DEVELOPMENT OF WELD PATTERN ANALYZER FOR QUALITY ANALYSIS OF ARC WELDING PROCESS

By

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1. **Vikas Kumar**, S. K. Albert, N. Chandrasekhar and J Jayapandian. *"Study of Manual Metal Arc Welding Using Digital Storage Oscilloscope"*, **National welding meet, Indian Institute of welding,** Mohamed Sathak Engineering College, Rameswaram, India, 2013.

2. **Vikas Kumar**, S. K. Albert, N. Chandrasekhar, J Jayapandian and M. Krishnamoorthy. *"Monitoring the Learning of Welding Skill using High Speed Data Acquisition System",* **National welding Seminar, Indian Institute of Welding,** Mumbai, India, 2015.

3. **Vikas Kumar**, S. K. Albert, N. Chandrasekhar, J Jayapandian and M.V.Venkatesan, "*Performance Analysis of Arc welding Parameters using Self Organized maps and Probability Distributions*" **IEEE First International Conference on Control, Measurement and Instrumentation (CMI)**, Kolkata, India, pp. 196-200, Jan 2016.

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5. **<u>Vikas Kumar,</u>** S. K. Albert, N Chandrasekhar and Jayapandian, "*Weld data analysis using Self Organizing Maps and Probability Density Distributions to evaluate the effect of welding current and welding power sources in SMAW process*", C-091, **IIW-International Welding Congress (IC),** Chennai, India, 2018

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Dedicated to my beloved parents

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Synopsis

1. Introduction

Arc Welding is one of the most widely used welding processes because of its versatility, simplicity in the operation and relative low cost. This process is extensively used in construction and fabrication of structural components in almost all type of industries. For a chosen material, joint design, welding position and welding process, the factors which can govern the quality of the weld are welding power source, welding consumables and skill of the welders. Currently, effects of these factors are evaluated by examining the quality of the weld produced and not by monitoring how welding process is affected by change in factors. For example, the present practice of monitoring and evaluation of learning of welding skill is done not by checking whether the welder is able to maintain constant arc gap while welding is in progress; but by visual examination of the weld bead (in the early stages of learning) and by destructive testing of the weld (in the final stages of learning) prepared by the trainee. This is an indirect method because skill of the welder is assessed from the quality of the weld produced. Further, this is expensive and time consuming as the assessment can be carried out only after the weld is completed. Hence, there is scope for developing a procedure to assess the quality of welding process which can be employed from the data acquired while welding is in progress.

The challenge in developing such a procedure is the random behavior of the welding arc due to various physical processes that happen across the arc in a very short time while welding is in progress. These include metal transfer, short circuiting, spatter, ionization, gas-metal reactions etc. In fact quality of a weld depends on how quickly a welding machine or a welder responds to these variations or a welding consumable is tolerant to these variations. During welding these variations are reflected as fluctuations in the current and voltage signals. If such dynamic variations that occur in voltage and current during welding can be acquired at the same rate as they occur, then this data can be analyzed to evaluate the welding power source, consumables and even skill levels of welder. However, such random variations in current and voltage which occur during actual welding process cannot be recorded with ordinary ammeter and voltmeter as they occur at very short intervals and requires high speed data acquisition system. Such welding monitoring systems have been developed by many researchers using advanced Field Programmable Gate Array (FPGA) **[1],** Microprocessor **[2]** or even Microcontroller **[3]**. In addition to high rate of data acquisition, appropriate filtering of noise is also necessary to ensure that the data obtained are true representative of the physical processes that occur during welding.

The data thus acquired have been used for a comprehensive analysis of actual welding process by many researchers. In [**1**] the authors have reported that various signal processing techniques can be used on electrically measured signals of high sensitivity to detect welding imperfections in real time. Similarly, welding imperfections in GMAW were identified from the instantaneous values of welding parameters acquired while welding is in progress **[4]**. Analyses of data using different statistical methods like PDD have been reported by many researchers for testing and optimizing the performance of arc welding process **[5-6]**. Data acquired was also subjected to Artificial Intelligence (AI) techniques to predict the quality of various welding parameters **[7-10].**

From the above discussion it is clear that data acquired using a system capable of recording all the electrical variations happening in actual welding process can be used to carry out an in depth analysis of random voltage and current signals, which in turn can be used to evaluate the arc welding-process.

In the present study welding voltage and current data were acquired using a commercially available general purpose Digital Storage Oscilloscope (DSO). Data thus acquired were used to develop procedures based on statistical and Artificial Neural Network (ANN) techniques to assess the arc welding process. This procedure was subsequently used to monitor progress of learning of the welder trainees, assess the skill of the welder, compare the performance of different welding power sources, study the differences in the performance of different welding electrodes in Shielded Metal Arc Welding (SMAW) and examine the effect of shielding gas in Gas Metal Arc Welding (GMAW) process. Finally, a dedicated standalone Programmable System on Chip (PSoC) based data acquisition system was also developed for this purpose and feasibility of using this system for studying the arc welding process is demonstrated.

2. Objectives

Arc welding is a process with lot of randomness; these variations if acquired properly can be used to understand arc welding process in detail. Hence, the main objective of the present is to develop a procedure to study arc welding process using the electrical signals acquired during welding. This involves high speed data acquisition of the welding data, its processing and subsequent analysis and demonstration of how this procedure can be used to study the arc welding process. Objectives also include development of a dedicated data acquisition system that can be used for this purpose.

These objectives are realized in the following steps:

1. Acquisition of random welding signals by using commonly available Digital Storage Oscilloscope and suitable voltage and current sensors at the time of actual welding.

2. Application of appropriate filtering technique to reduce the noise present in the welding signals.
3. Procedure development for evaluating the arc welding process using the acquired data.
4. Application of these procedures
    a) To monitor the progress of learning and evaluate the skill of the welders.
    b) To study the performance of arc welding power sources.
    c) To evaluate various welding electrodes and
    d) To study the effect of shielding gas composition in GMAW process.
5. Development of dedicated and cost effective data acquisition system which can be used along with arc welding power sources for on line monitoring and evaluation of the arc welding process.

3. Experimental setup

Procedure for studying the arc welding process from the voltage and current signals acquired online was developed using the data acquired with a DSO (*Agilent Technologies,* DSO7054B). This DSO has a band width of 500 MHz and maximum sampling rate of 4 GSa/s. Welding current was acquired using a high sensitive (selectable between 1mA/A or 10mA/A) Hall Effect based current clamp. For the voltage differential probe was used, which is optimized for acquiring differential signals. The entire data acquired by DSO was extracted into an external computer using an Ethernet cable and dedicated software provided by *M/s Agilent technologies.* For all our studies data acquisition was carried out while making bead-on-plate welding on carbon steel plate using suitable welding consumable. Both voltage and current signals were acquired simultaneously at a sampling rate of 100,000 samples/s for 20 seconds of duration. To ensure consistency of the data, three bead-on-plate welds were made and data was acquired for all the three welds. Data was subsequently filtered and then subjected to time domain, statistical and ANN analysis.

For demonstrating that the proposed technique can be used to monitor the progress of learning of various trainee welders, data was acquired from four trainee welders at three stages of their training, initial, middle and final. Data was also collected from an experienced welder for comparison. For demonstrating the use of this procedure to evaluate skill of the welders, data was acquired from a batch of trainee welders who have completed the welder training from a training institute.

In order to demonstrate that the procedure presented here is able to differentiate the performance of different power sources, voltage and current signals from different power sources were acquired while welding is in progress. These welds were prepared by the same welder and the same type of welding consumable. The f power sources chosen include rectifier, inverter and generator type.

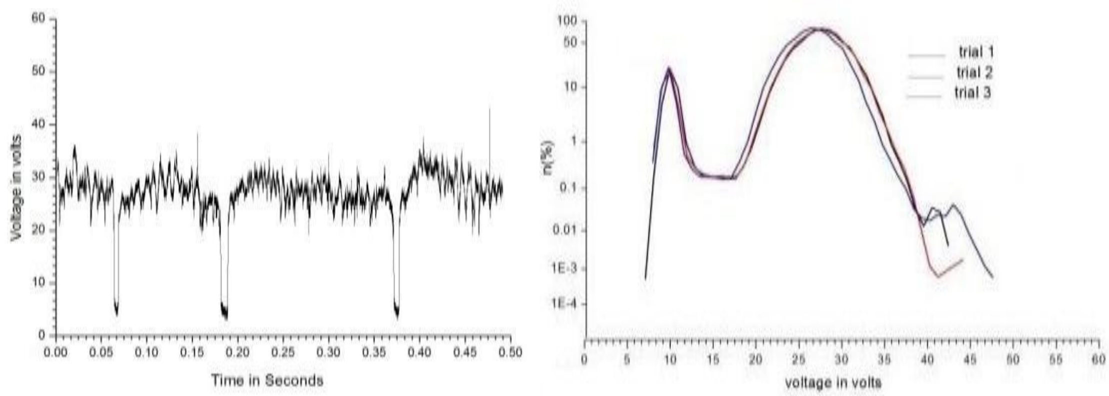
This procedure was also used to differentiate the metal transfer behavior of E 7018, E 6010 and E 6013 electrodes. For this purpose, bead-on-plate welds were made by a welder using these consumables and a single power source. r. Metal transfer during welding was monitored and recorded using high speed camera. The camera used was Fast cam MC2.1 photon focus. It has a maximum capturing speed of 10,000 frames per second. In the current experiment 4000 frames/second were used and the camera was equipped with a shutter whose value is minimum 1/100,000s. For the 4000 frames/s the high speed camera records the last 4.094 seconds of data from a total welding duration of 20 seconds in the current experiment. It is also demonstrated that change in flux composition also could be differentiated by this procedure by carrying out this study using welding consumables in which flux composition was varied systematically. Further, the effect of baking on the performance of electrodes could also be identified form the analysis of the data acquired during welding.

It is known that in GMA welding, shielding gas composition and welding parameters employed have a significant effect on the metal transfer. The data acquisition and analysis procedure developed is capable of studying this too. For this purpose, bead on plate welds are made with 100% Ar, 100% CO_2 and gas mixture of 80% Ar and 20% CO_2 using AWS ER 70S2 wires (1.2 mm dia.) on carbon steel plates at different voltage and current levels and the data acquired were analyzed. All welds were made using the same welding machine and the same welder.

After comprehensively demonstrating that the data acquisition and analysis, procedure can be used to study the arc welding processes for various applications, a standalone data acquisition system on PSoC-5 based platform, capable of acquiring welding data at sampling rate of 100,000 samples/s was developed indigenously. Then, it is shown that, this system can be used as an alternative to the DSO for data acquisition because the analysis carried out using this data produced similar results as that obtained from the analysis of data acquired from DSO. Thus at the end of this study, we have a standalone data acquisition system and a procedure to comprehensively study the arc welding process from the voltage and current signals acquired.

4. Results

The performance of different welding power sources, quality of the electrode, and skill of welder is evaluated using Time domain, Probability Density Distribution (statistical technique) and Artificial Neural Network Techniques. **Fig. 1(a,b)** represents typical time domain and PDD plot using basic type E 7018 electrode. These electrodes are coated with basic type flux and metal transfer across the arc from electrode to the molten pool takes place predominantly by short circuit mode **[11]**. This can be seen from time domain analysis of this data in **Fig. 1(a)** where sharp reductions in voltage correspond to short circuit metal transfer. Although data was acquired for duration of 20s; for clarity purpose, only 500ms data was shown in time domain analysis. Statistical (PDD) analysis of entire data of 20s duration was plotted in **Fig. 1(b)**; in this plot first peak is due to short circuit metal transfer happening in actual process, whereas second peak corresponds to the voltage displayed on the welding power supply at the time of actual welding (steady state).

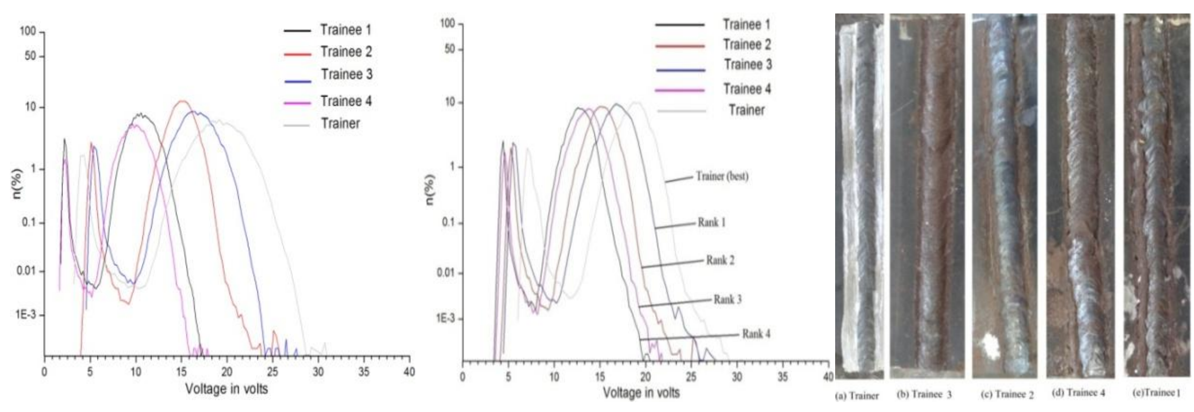


(a) Time domain oscillograms of welding voltage **(b) Voltage PDD plot.**

Fig. 1: Welding data acquired using DSO.

Welding skill was evaluated from the analysis of PDD's generated using the data acquired from different welders. It was found, for different welders, PDD shapes are different, the extent of these differences corresponds to difference in the skill level of the welders. **Fig. 2(a)** shows the voltage PDD generated from the signals acquired from the trainee welders during the early stage of training and that of an experienced welder. It may be noted that the two peaks in voltage PDD of an experienced welder is widely separated, whereas for trainee welders both peaks were close to each other with second peak at lower voltage values than that in the PDD of the experienced welder. However, as the training progresses, it is noticed that the PDD obtained from the welds made by trainees approaches to that of an experienced welder (**Fig. 2(b)**). Hence, by comparing PDDs of the welds made by the welder at different stages of the welding with that of an experienced welder, the progress of learning as well as the skill level of the welder can be assessed. The farther the PDDs of the trainees from that of an experienced welder, the less is the skill level of the trainee. The trainee whose PDD is closest to experienced welder's PDD is considered to be the best among all trainee welders. Based on this conclusion, ranking of various trainee welders are marked in **Fig. 2 (b)**. Ranking thus obtained for different trainee welders were found to be in consistent with visual examination of respective bead images **(Fig. 2(c))**. Quality of the butt welds produced by these welders using E7018 electrodes and 12 mm thick steel plates also matched with skill of the welders assessed using this procedure. PDD technique thus developed was subsequently used to grade 28 fresh welders passing out from a skill training institute and this grading matched fairly well with the independent grading given by the training institute based on the bead profile, straightness, consistency etc. Self-Organized Maps, an Artificial Neural Network (ANN) analysis was also employed for grading welding skill; but the grading of skill levels using this technique matched less with that of the training institute than with the PDD technique.

Having seen from the assessment of welder's skills that the separation of two peaks in the PDD is a criterion that can be used to assess the quality; this concept was also used for grading the quality of different power sources (i.e. rectifiers, inverters, generators, thyristors etc.). Quality of the weld bead produced using different power sources matched well with the grading of the power sources done by analyzing the PDDs generated from the welding data acquired while making bead-on-plate welds using these power sources. It is interesting to note that this correlation was independent of the type of power source used in this study, rectifier, inverter or generator. This procedure was also used to differentiate the mode of metal transfer in different type of welding consumables like AWS E 6010 (cellulose) and E7018 (basic)). It is known that short circuit transfer is the predominant mode of metal transfer during welding using E 7018 (basic type) where as both short circuit and spray transfer mode occur during welding using E 6010 (cellulose) electrode **[11]**. As already indicated, **Fig. 1(b)** is a typical voltage PDD for E 7018 weld, and **Fig. 3** is the voltage PDD of E 6010 electrode. A comparison of these two PDDs shows that in case of E 6010 in addition to the two peaks present in PDD for E 7018 weld, a third peak at higher voltage levels is also present. This peak corresponds to the spray mode of metal transfer happening in these electrodes. This was confirmed from the images of metal transfer taken during welding using high speed camera (**Fig. 4).** Both short circuit and spray transfer modes of metal transfer can be imaged during welding using E 6010 electrodes whereas only short circuit transfer could be seen in the case of welding by E 7018 **[11]**. It is also shown that for the same type of electrode, change in flux composition resulted in change in the voltage oscillogram and PDD.



(a) During training **(b) At the end of training** **(c) Bead image**

Fig 2. (a, b): PDD of trainees during different stages of training and (c) corresponding bead image.

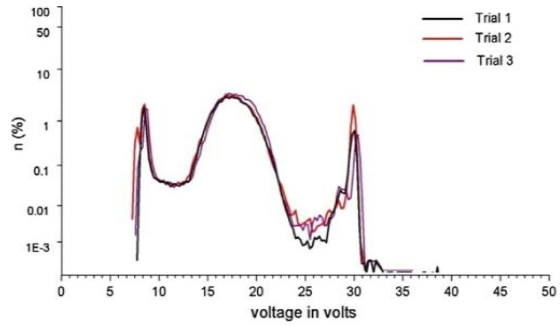
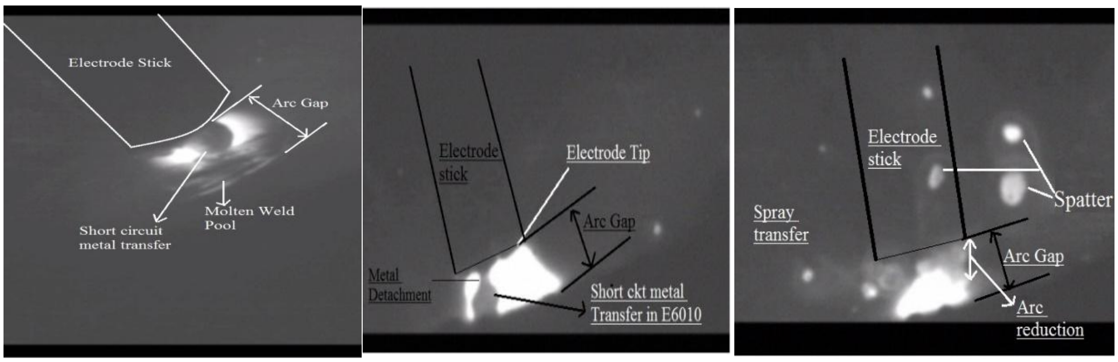


Fig. 3: PDD using E6010 electrode



(a) E7018 (Shrt ckt transfer) **(b) E6010 (Shrt ckt transfer)** **(c) E6010 (Spray transfer)**

Fig. 4: High speed imaging of different electrodes.

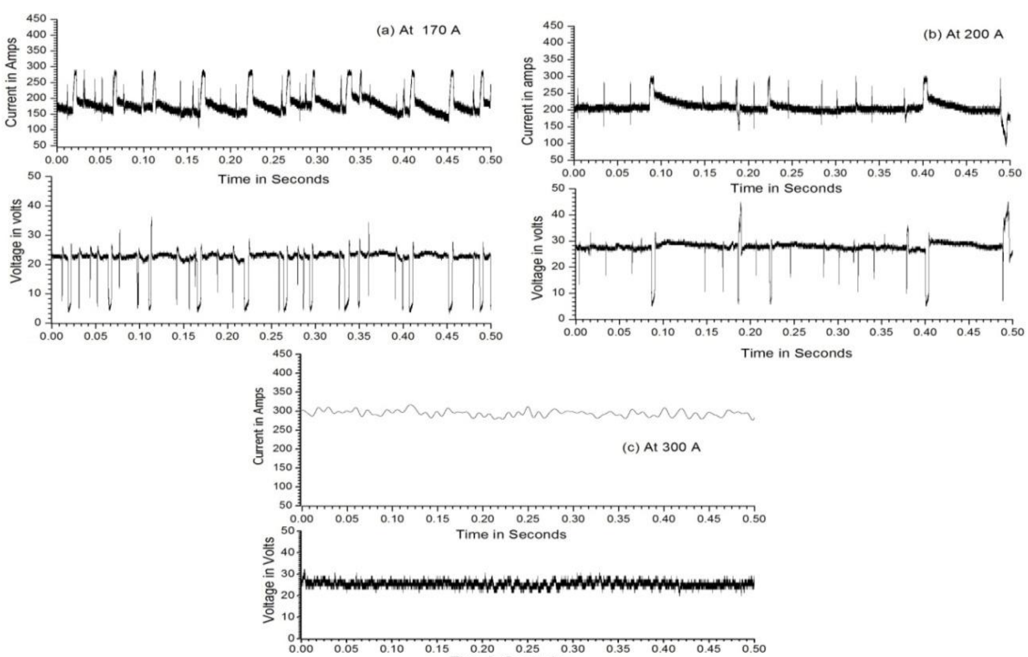


Fig. 5: Current and voltage oscillogram of GMAW welding using 80% Ar & 20% CO_2.

GMAW is a widely used arc welding process in which arc is protected by shielding gas. Composition of shielding gas, welding voltage and current employed determine the modes of metal transfer from electrode to molten pool. With time domain and PDD analysis of voltage and current signals it was shown that modes of metal transfer in GMAW can be studied. **Fig. 5** shows the voltage and current oscillograms of GMAW welding process using gas mixture of 80 % Ar and 20% CO_2 as shielding gas. This figure shows that at lower current of 170A, short circuit metal transfer dominates (frequent voltage dips in **Fig. 5(a)**). As current increases 200A, short circuit metal transfer becomes less frequent and changes to globular transfer **[12]**; Beyond a critical value of current only spray transfer occurs and this can be seen clearly in the oscillograms shown in **Fig. 5(c)** for 300A. Corresponding differences could also be seen in the PDDs of the voltage and current signals (not shown here). Difficulty in achieving spray transfer mode of metal transfer with 100 % CO_2 shielding gas could also be demonstrated using this analysis.

Having demonstrated a procedure which involves high speed data acquisition and subsequent analysis of data using appropriate statistical and ANN techniques can be used for online monitoring and evaluation of the welding process, a dedicated data acquisition system was developed for this purpose which can replace the Digital Storage Oscilloscope. This system, named as Weld Pattern Analyzer (WPA), was initially developed with Programmable System on chip 3 (PSoC-3). Throughput limitation of this design was eliminated by modifying the hardware with PSoC-5 design using Successive Approximation (SAR) type Analog to Digital Converter (ADC) and by reducing the sampling time with separate hardware counters with auto incrementing addressing scheme (**Fig. 6**). WPA can acquire the weld data for any desired duration to analyze a welding process. Results obtained from the analysis of data acquired with

WPA were on par with that carried out using data acquired by DSO proving WPA can be used as a standalone tool, which can be used for comprehensive analysis of welding process. It is also possible to integrate WPA with welding power source for on line data acquisition to study the welding process.

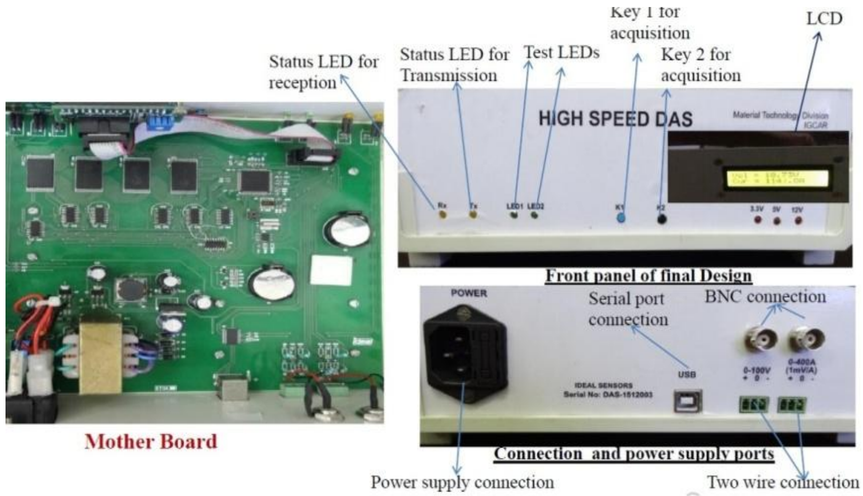


Fig. 6: Mother board with front and back panel of final WPA.

5. Organization

This thesis is organized into following 6 chapters including the introduction chapter.

Chapter 1: - Introduction

Chapter 1 describes the research problem about the study of arc welding process by the analysis of electrical signals acquired during welding, significance of the work and the various research questions considered. This chapter further discusses how the methods developed in the present work can be used as an alternative to the procedures currently employed for evaluating the welding process.

Chapter 2: - Literature survey

In chapter two a detailed survey of weld parameter evaluation has been discussed. In this chapter initially, the online monitoring of weld parameters was discussed which enabled researchers to visualize the dynamic variations in welding data. To have any meaningful analysis of the acquired data, the next essential thing is filtering of noise. Hence, this chapter then discusses different methods of noise filtering using FFT and wavelet filtering mechanism. Then a separate section is presented about the detailed study of welding data using time domain and statistical analysis. Usage and implementation of PDD technique by various researchers is discussed in this section. A separate section on ANN is also provided, which discusses the importance of ANN in weld data analysis. This section further discusses various algorithms and networks that are used for this purpose. Based on the detailed survey of the literature, scope of the present work is given at the end of the chapter.

Chapter 3: -Welding data acquisition and procedure development

Chapter 3 initially provides details of data acquisition which include use of DSO, selection of current and voltage probe and choice of sampling rate for acquisition. Then it provides how the data acquired by DSO is transferred to PC for subsequent filtering and analysis. Various filtering techniques are considered to filter out noise from the signal and final choice of filter is also presented. Subsequently, processing of data for time domain and statistical analysis are presented in detail. The oscillogram used for time domain analysis and Probability Density Distribution (PDD) generated for statistical analysis is described using the current and voltage signals acquired for bead on plate welds made using E7018 electrodes on carbon steel plates by SMAW process.

Chapter 4: - Evaluation of arc welding process

Procedures developed to evaluate the arc welding process and presented in detail in Chapter 3 was applied to evaluate skill of the welders, power sources and consumables. Experimental details and results of these studies are presented in this Chapter. In addition to time domain and statistical analysis, ANN techniques were also used for this evaluation. Details of this procedure and the results obtained are also presented in this chapter. Based on all these results, it is shown that the procedure presented here can be used reliably for evaluating the arc welding process in a comprehensive way to evaluate various welding parameters (Welding Power sources, Consumables, welder's skill etc.).

Chapter 5:-Development of PSoC-5 based weld pattern analyzer

This chapter deals with the development of PSoC Based High speed DAS (Weld Pattern Analyzer, WPA) for the acquisition of welding data, which could replace DSO for data acquisition. To meet the throughput requirement, how design evolution of PSoC-3 to PSoC-5 based system took place is shown in this chapter. Then a separate section has been presented about the development of Human Machine Interface (HMI) to process the voltage and current signals using Lab-view and Mat lab programming. Finally, this system was used to demonstrate how oscillograms and PDD of voltage signal vary with skill of welder and flux compositions of welding electrodes. These results are also compared with those obtained from data acquired with DSO.

Chapter 6: - Conclusion, contributions and scope for future research

In this chapter summary of each work carried out along with the important Contributions from the present research work are presented. Also, recommendations for further study are made.

6. Contributions

Major contribution of this research work is mention below.

1. A procedure which involves high speed on-line data acquisition and subsequent analysis of the acquired data has been developed to study the arc welding process. It is

demonstrated that this procedure can be used to evaluate the skill of welders and performance of power sources. Modes of metal transfer with different welding consumables in SMAW process and with different shielding gas composition in GAMW process can also be studied using this procedure.

2. Though this procedure is initially developed using the data acquired with DSO, subsequently Weld Pattern Analyzer (WPA), a dedicated, affordable and innovative hardware tool based on PSoC-5 has been developed for data acquisition which can replace DSO for data acquisition.
3. The Weld Pattern Analyzer and the procedure are so simple and cost effective that they can be incorporated into welding power sources for the purpose of on-line data acquisition and subsequent analysis.
4. This procedure has the potential of replacing the current practice of assessing skill of the welder and performance of consumables and power sources etc. from testing of the welds produced.

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1

Introduction

Arc Welding is one of the most widely used welding processes because of its versatility, simplicity in the operation and relatively low cost. Due to its inherent merits, this process is extensively used in construction and fabrication of structural components in almost all type of industries. Random arc behavior and various modes of metal transfer in an arc welding process leads to dynamic variations in voltage and current while welding is in progress and hence, monitoring of this process is difficult. For a given material, joint design, welding position and welding process, three important factors which govern the quality of the weld are welding power sources, welding consumables and skill of the welders. Till date, the practiced methodology to evaluate the effects of these factors is to examine the quality of the weld produced but and not to monitor the real time changes of these parameters during the welding process itself. For example, at the time of welding we are not able to record arc gap variations happening during the actual welding process. The fact just presented can be further understood by analyzing the present practice towards qualifying a welding consumable, procedure or a welder. At present this is done by testing the weld produced using these consumables, procedure and welders, but not by monitoring the welding process. This is an indirect method and is just based on the requirement for welds of acceptable quality. However, this practice is expensive, time consuming and the assessment can only be carried out only after the weld is completed and it is inspected or tested. On the contrary, if we can record the variations that occur during actual process itself at the same rate as they are happening then (real time monitoring); welding process can be understood in a much better way than it is done at present. Hence, in this thesis work a mechanism to evaluate the skill set of various welders, performance of different welding power sources, quality of the welding consumables and role of shielding gases in an arc welding process is proposed (here, it should be noted that the final weld quality is highly dependent on weld deposit properties as a function of heat input per unit length, prior substrate temperature and cooling rate; these factors were taken into account but not used in the analysis as they are outside the scope of present research).

The challenge in developing such a mechanism is the random behavior of the welding arc due to various physical processes that happen across the arc in a very short time while welding is in progress. These include metal transfer, short circuiting, spatter, ionization, gas-metal reactions etc. In fact, quality of a weld depends on how quickly a welding machine or a welder responds to these variations or a welding consumable is tolerant to these variations. During welding these variations are reflected as fluctuations in the current and voltage signals. If such dynamic variations that occur in voltage and current during welding can be acquired at the same rate as they occur, then this data can be analyzed to evaluate the welding power source, consumables and even skill levels of welder. However, such random variations in current and voltage which occur during actual welding process cannot be recorded with ordinary ammeter and voltmeter as they occur at very short intervals and this require high speed data acquisition systems. Such systems have been developed by many researchers using advanced Field Programmable Gate Array (FPGA) **[1],** Microprocessor **[2]** or even Microcontroller **[3]**. In addition to high rate of data acquisition, appropriate filtering of noise is also necessary to ensure that the data obtained are true representative of the physical processes that occur during welding.

The data thus acquired have been used for a comprehensive analysis of actual welding process by many researchers. In [**1**] the authors have reported that various signal processing techniques can be used on electrically measured signals of high sensitivity to detect welding imperfections in real time **[1]**. Similarly, welding imperfections in Gas Metal Arc Welding (GMAW) were identified from the instantaneous values of welding parameters acquired while welding is in progress **[4]**. Analyses of data using different statistical methods like Probability Density Distribution (PDD) have been reported by many researchers for testing and optimizing the performance of arc welding process **[5-7]**. Data acquired was also subjected to artificial Intelligence (AI) techniques to predict the quality of various welding parameters **[8, 5-6]**

From the above discussion it is clear that data acquired using a system capable of recording all the electrical variations happening in actual welding process can be used to carry out an in depth analysis of random voltage and current signals, this in turn can be used to evaluate the arc welding process.

In the present study random variations happening in an arc welding process were acquired and subsequently processed to understand the arc welding process in detail. Hence, the objective is to develop a comprehensive procedure to study arc welding process using the electrical signals acquired during welding. This involves high speed data acquisition of the welding data, its processing and subsequent analysis and demonstration of how this procedure can be used to study the arc welding process.

Objectives also include development of a dedicated data acquisition system that can be used for this purpose.

These objectives are realized in the following steps:

1. Acquisition of random welding signals by using commonly available Digital Storage Oscilloscope and suitable voltage and current sensors at the time of actual welding.
2. Application of appropriate filtering technique to reduce the noise present in the welding signals.
3. Procedure development for evaluating the arc welding process using the acquired data.
4. Application of these procedures
    a. To monitor the progress of learning and evaluate the skill of the welders.
    b. To study the performance of arc welding power sources.
    c. To evaluate various welding electrodes and
    d. To study the effect of shielding gas composition in GMAW process.
5. Development of dedicated and cost effective data acquisition system which can be used along with arc welding power sources for on line monitoring and evaluation of the arc welding process.

To achieve above objectives, filtering of noise was the first step after the acquisition of the random voltage and current data. This was done by the use of Fast Fourier Transform Low Pass Filter (FFT-LPF). Filtered data were subsequently processed using various methods like time domain, statistical and Artificial Neural Network (ANN) techniques. The procedures thus developed were subsequently used to monitor progress of learning of the welder trainees, assess the skill of the welder, compare the performance of different welding power sources, study the differences in the performance of different welding electrodes in Shielded Metal Arc Welding (SMAW) and examine the effect of shielding gas in Gas Metal Arc Welding (GMAW) process. Finally, a dedicated standalone Programmable System on Chip (PSoC) based data acquisition system was also developed for this purpose and feasibility of using this system for studying the arc welding process has been demonstrated.

1.1 Thesis structure

This thesis is organized into 6 chapters including the introduction chapter. In Chapter 2 detailed literature review about welding process, weld parameter evaluation and online monitoring of weld parameters is presented. A detailed literature survey on study of welding process using time domain, statistical and ANN analysis is also presented in this chapter. Chapter 3 provides the details of data acquisition using Digital Storage Oscilloscope (DSO). Welding data thus obtained using DSO was subsequently filtered and processed using time domain, statistical and ANN analysis to develop various procedures for weld parameter evaluation. The oscillogram used for time domain analysis and Probability Density Distribution (PDD) generated for statistical analysis is described using the current and voltage signals. In Chapter 4 procedures developed to evaluate the arc welding process and presented in detail in Chapter 3, was applied to evaluate skill of the welders, power sources and consumables. Chapter 5 deals with the development of PSoC Based High speed DAS (Weld Pattern Analyzer, WPA) for the acquisition of welding data, which could replace DSO for data acquisition. A separate section has been presented about the development of Human Machine Interface (HMI) to process the voltage and current signals using Lab-view and Mat-lab programming. Finally, this system was used to demonstrate how oscillograms and PDD of voltage signal vary with skill of welder and flux compositions of welding electrodes; results obtained were also compared with those obtained from data acquired with DSO. Finally, chapter 6 presents the summary, contributions and scope of further work.

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2

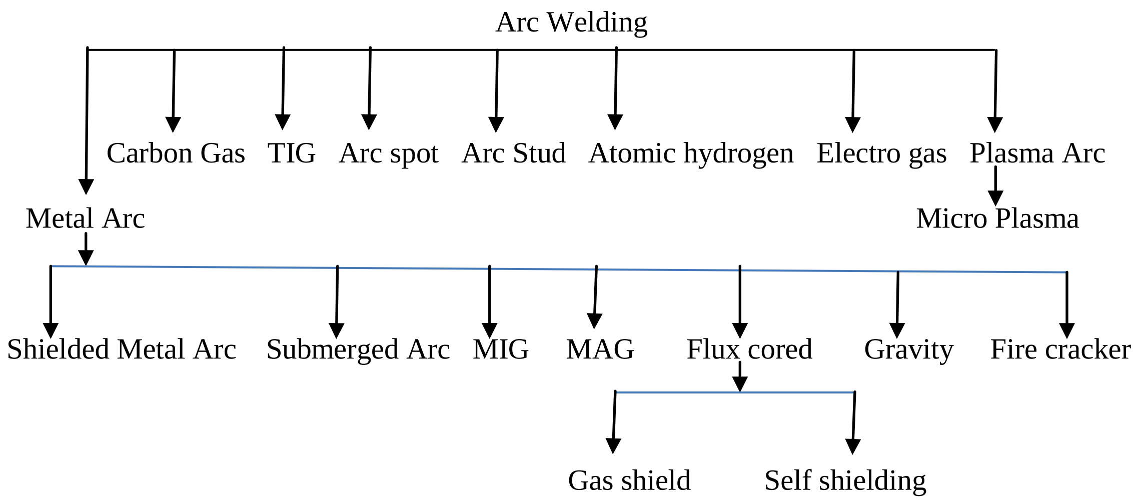
Literature survey

From the Introduction chapter it is clear that the weld data acquisition and its subsequent analysis can be used to study various aspects of an arc welding process. In this chapter a detailed review of the literature available on weld data acquisition and its subsequent analysis is provided. Initially, a brief review of arc welding process with focus on welding power sources, consumables and skill level of welder which ultimately determines the quality of the final weld is provided. Then the online monitoring of actual welding processes reported in the literature is discussed along with various methods/tools used for analysis of this data. Weld data acquisition enabled researchers to visualize the dynamic variations happening in actual welding process. As Digital Storage Oscilloscope (DSO) and a Programmable System on chip (PSoC) based platform were employed for weld data acquisition, detailed information on DSO and PSoC is then presented. To have any meaningful analysis of the acquired data, the next essential thing is filtering of noise. Hence, different methods available for noise filtering using FFT and wavelet filtering mechanisms are then presented. Recently Artificial Neural Network (ANN) techniques have been used for feature extraction and decision making; hence, a brief introduction about this with special emphasis on ANN in weld data analysis is provided. Based on this review, scope of the present work is formulated and provided at the end of this chapter.

2.1 Arc welding

Arc welding is one of the several fusion processes for joining metals. In this process the heat required for fusion is generated by an electric arc formed between a metallic electrode and the base metal (cathode and anode). The arc thus formed consists of thermally emitted electrons and positive ions from electrode, work piece and those formed from the ionization of the gases in the arc atmosphere. These electrons and positively charged ions are accelerated in the potential field (arc voltage) between the electrode and the work piece, which are typically connected to the terminals of the welding power source and produce heat when they convert their kinetic energy by collision at the electrode or work piece. Consequently, due to intense heat produced by the arc, both work piece and the electrode melts in the arc (except in Gas Tungsten and Plasma Arc Welding processes in which electrode is not a consumable and hence not allowed to melt) and form the weld metal for the joint. Arc welding has many variants **[1]**; which are listed in **Table 2.1.** The primary differences between the various arc welding processes are the methods by which molten metal is protected from atmosphere.

Table 2.1: Arc welding process chart



2.1.1 Shielded Metal Arc Welding (SMAW)

Among all the welding process, shielded metal arc welding, is the most common, versatile and inexpensive one and accounts for 30% of the total welding in advanced countries and over 70% of the total welding in India [**1**].

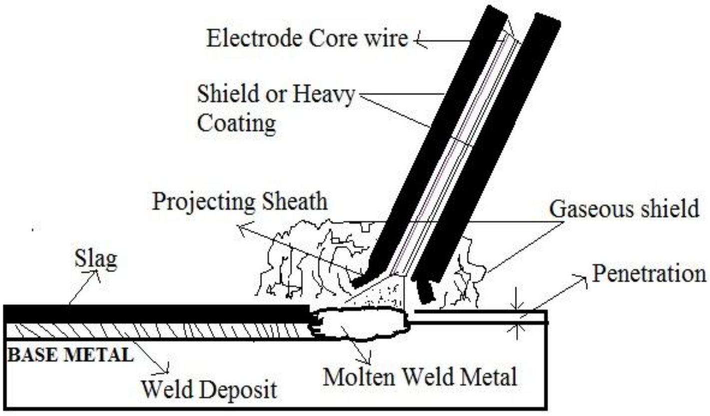


Fig. 2.1: Shielded metal arc welding.

It is also known as Manual Metal Arc (MMA) welding process and as the name suggests, it is a manual process hence, it is highly dependent on the skill and experience of welder. The power sources used for SMAW can be either AC or DC and it can be a simple transformer, generator, rectifier or invertors. This type of welding is performed by striking an arc by touching or scratching the work-piece with the arc-striking end of the electrode which is having a covering with flux. This electrode melts and get transferred into the molten metal formed at the work piece. The flux coating provided in the electrode reacts with molten metal as well as the atmosphere to produce a gas shield and slag cover which protect the weld metal from atmosphere.

2.1.2 Arc Welding Electrodes

From the time of the first modern covered electrode invented by Oscar Kjelberg of Sweden in 1907 [**1**], numerous research has been done on flux coatings provided to electrodes to improve the weld quality. This led to the evolution of different type of coatings on electrodes.

2.1.2 .1 Types of electrode coating

The type of coating given to the electrodes can vary widely; but the most popular among them are rutile, basic and cellulosic types. As the name suggests, rutile (TiO_2) and cellulose respectively are the main constituent in the flux of the rutile and cellulose coated electrodes and the major constituent of the flux in basic coated electrodes are $CaCO_3$ and CaF_2.

Flux of rutile electrodes contains, in addition to ~50% rutile, Ferro-manganese, mineral carbonates and other chemicals which are held together with approximately 15% of sodium silicate, also known as water glass. The advantages of rutile electrodes include ease of striking arc, arc stability, low spatter, good bead profile and ease for slag removal from the electrode. The electrode can operate on both AC and DC currents and in all positions if the formulation of the coating is so designed. Major disadvantages of these electrodes are that the oxygen content in the weld metal is high and hydrogen levels in the electrodes are not controlled.

As already mentioned, basic electrodes contain calcium carbonate and calcium fluoride in place of the rutile. Arc stability, slag detachability and bead appearance for the weld produced by these electrodes are poor and hence not very popular with the welders. However, oxygen content in the weld metal is less than those produced with other type of electrodes and this provides good mechanical properties for the weld metal. These electrodes are baked just before its use to remove the moisture content and this brings down hydrogen level in the weld metal thus the risk of cracking. CO_2

formed by the dissociation of the carbonates present in the flux protect the arc from external atmosphere.

Cellulosic electrodes contain a high proportion of organic material, and this produces a fierce, deep penetrating arc and a faster burn-off rate. Cellulosic electrodes are more prone to spatter than rutile types. As hydrogen and carbon are major constituents of cellulose, the arc is protected from the external atmosphere mainly by hydrogen and CO_2 gas formed during burning of cellulose. Hence, hydrogen content in the welds produced by these electrodes is usually high. As hydrogen causes cracking in high carbon or high alloy steel welds, this type of electrodes is available only for welding of mild steel and some low-alloy steels.

As the arc atmosphere is affected by the flux coating, it has significant influence on the characteristics of the welding arc and the mode of metal transfer from electrode to the molten pool of weld metal. Three major modes of metal transfers reported in SMAW process are short circuit transfer, free flight transfer and spray transfer [**1**]. In each metal transfer mode, there is a group of forces that act on the arc [**2**] and provide the characteristics of the transfer. Depending on the balance of these forces, the mode of transfer, size of droplets, rate of transfer, amount of spatter, etc., may be different. Several models were proposed to explain metal transfer during welding using bare electrode and covered electrode [**3-8**]. Hence, a careful examination of these modes of metal transfer can provide very useful insight about actual welding process. However, viewing the metal transfer during welding is not easy, because of the intensity of the welding arc. Special purpose high speed cameras with proper filters and illumination are required to view the modes of metal transfer that takes place during welding.

As per the specifications of AWS for welding consumables we can get the information about the type of flux coating on the welding consumables. This specification contains 4-digit number and the last digit of this number indicates the type of coating for a particular welding electrode [**1**]. The flux coating provided to these electrodes protects the molten metal from atmospheric contamination. Additionally, the constituents of flux also stabilize the welding arc, act as de-oxidizers, helps in alloy addition etc. Hence, flux coating provided to the electrode is an important aspect of SMAW process.

2.1.3 Gas Metal Arc Welding (GMAW)

The American Welding Society (AWS) defines gas metal arc welding (GMAW) as "an arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal electrode and the work piece. Shielding is obtained entirely from an externally supplied gas". The essential elements of a basic GMAW process are shown in **Fig 2.2**.

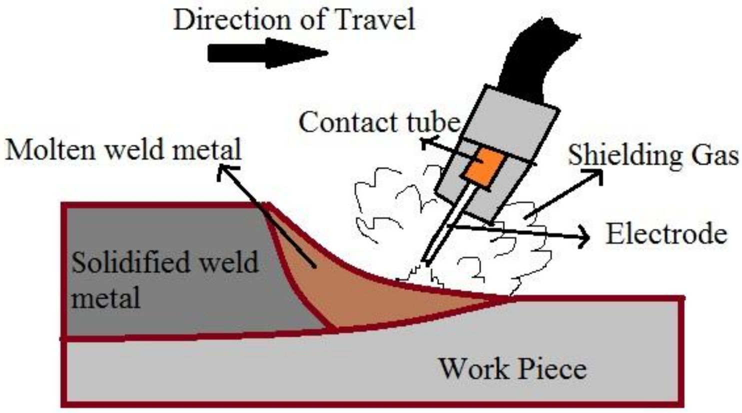


Fig. 2.2: GMAW process.

GMAW is an arc welding process that incorporates the automatic feeding of a continuous, consumable electrode that is shielded by an externally supplied gas.

Reverse polarity (electrode is connected to positive terminal) is preferred because it gives better melting, deeper penetration and better cleaning action.

2.1.3.1 Shielding gas in GMAW process

The primary function of a shielding gas is to protect the molten weld metal from atmospheric contamination and the resulting imperfections **[9];** the role of shielding gas in GMAW process is similar to the role of electrode flux in SMAW electrodes. In addition to its shielding function, shielding gases in GMAW process has unique physical properties that can have a major impact on mechanical properties, welding speed, weld appearance, weld shape, and even on arc stability. The primary gas combinations used in this process are Ar + 1-2% O_2, Ar + 3-5% O_2, Ar + 15-20% CO_2, 100% CO_2 etc. The composition and purity of the gas or gas mixture should be properly adjusted to meet the application requirements.

In the GMAW Process there are presently 6 modes of metal transfer [**10-11**] are available, short circuit, globular, spray, streaming, streaming rotating and pulse. Short circuit and globular transfer occur at relatively low current, with further increase in the current the globular mode transforms to spray mode. If the current value is further increase the spray in turn will transform to streaming mode of metal transfer. In this mode due excess heat and higher current, the wire volume above the arc-wire coupling is heated enough to become plastic, resulting in the *"tapered"* shape of the electrode end **[10]**. Beyond "streaming spray", the "streaming rotating" transfer mode can be achieved by a further increase in the current level. The wire electrode tapering effect is more pronounced with overheating, resulting in an extended metal filament **[11]**. In pulsed transfer a long arc length is used and the welding current is cyclically pulsed from a low value (base current), sufficient, however, to maintain the arc, to a high value (pulse current) and sufficient to form and detach a droplet **[11]**.

From the above discussion it is clear that with varying current different modes of metal transfer can be achieved however, in the conventional power sources only three modes of metal transfer are most popular (i.e. short circuiting, globular and spray type) hence, in the present work we have considered only these three modes of metal transfer. For shielding gas mixture of 80% Ar and 20% CO_2, all the three modes of metal transfer occur; low current and voltage combination results in short circuit metal transfer which changes to, globular mode of metal transfer with increase in current, and once current exceeds transition current, spray mode of metal transfer will take place **[12]**. However, with more than 20% CO_2 in the shielding gas, spray transfer does not occur and hence when 100 % CO_2 is used as a shielding gas only short circuiting and globular transfer occur **[13].**

In addition to SMAW and GMAW process there are other arc welding processes like Tungsten Inert Gas (TIG) welding, Submerged Arc Welding (SAW), Flux-cored arc welding (a variant of GMAW process in which tubular wire filled with flux is used instead of solid wire), etc. In addition to these, plasma welding is also essentially an arc welding process. In TIG, plasma and flux cored arc welding, the welding arc is protected by shielding gas while in submerged arc welding, bare wire is used as electrode and flux in powder form fed to the arc protects the arc. In TIG and plasma welding, electrode is not a consumables and autogenous (without melting of electrode or filler metal) welding can be carried out using these processes. In TIG welding, filler wire, if required can be added separately.

2.2 Power sources for arc welding

Various arc welding process shown in **Table 2.1** and briefly explained in above paragraphs require special electric power of relatively low voltage and high current to produce and sustain an arc capable of making good weld. Machine designed to deliver such electric power are known as power sources for arc welding. Ever since the welding process entered the engineering field continuous improvements are taking place in the field of welding power sources. The choice of a welding power source depends upon the process of welding.

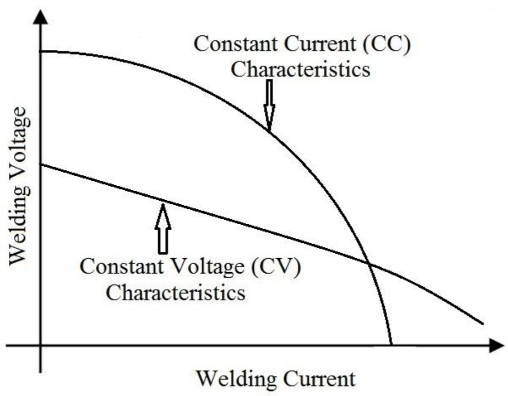


Fig. 2.3: Characteristic curve for welding power source.

Depending on the variation of voltage and current under static loading condition the welding power sources are classified as constant current (CC) type or constant voltage (CV) type (**Fig. 2.3**). A power source giving a small change in current for a relatively large change in voltage is known as CC type power source. This means that current does not vary much (or more or less remain constant) irrespective of changes in the voltage. CC power supply internal control system is designed to control the current fluctuations. This type of power sources is used for manual welding processes like SMAW and TIG welding. In these processes changes in arc voltage occurring due to fluctuation in the arc gap, produces only minor variation in current; hence the name constant current type.

A power source with relatively flat curve is described as constant voltage (CV) type power source because in this case small variation in voltage produces large change in current. Alternately large change is current results in little change in voltage and hence the name constant voltage (CV) type. These type of power sources responds instantly for dip transfer with a high current flow through the welding circuit. In welding power source this rate of current rise is controlled by inductance coil [**14**] (**Fig. 2.4**). Increasing the inductance will increase the arc time and decrease the frequency of short-circuiting. For each electrode feed rate, there is an optimum value of inductance. Too little inductance results in excessive spatter [**14**]. If too much inductance is used, the current will not rise fast enough and the molten tip of the electrode is not heated sufficiently causing the electrode to stub into the base metal. Modern electronic power sources automatically set the inductance to give a smooth arc and metal transfer [**14**].

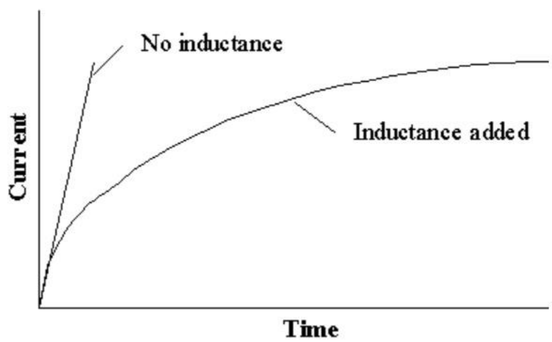


Fig. 2.4 Effect of inductance on welding current.

Flat or constant-voltage type power sources are conventionally used for semi-automatic and fully-automatic processes involving a continuous electrode fed at a constant rate, such as GMAW process, FCAW and submerged-arc welding. The flat type power source together with a continuous electrode fed at a constant wire-feed speed form a self-regulating arc. The arc length and weld current are interrelated in such a way as to correct sudden changes. For example, arc length variation is determined by the difference between melting rate and feeding rate of the electrode wire. The voltage drop across the arc is directly proportional to arc length. A small decrease in arc gap results in corresponding decrease in arc voltage which in turn leads to a large increase in the welding current. As a result, melting rate of the wire increases which in turn restores the arc gap to the original value.

2.2.1 Classifications of arc welding power sources

As arc welding power sources are low voltage and high current devices, step down transformer is an important component of any power sources that draw power directly from the main supply. Alternately, generator power sources, driven by internal combustion engine or motor are also available. Accordingly, power sources are classified as welding transformers, generators, rectifiers, inverters etc.

2.2.1.1 Transformer power source

Among various welding power sources, the welding transformer is one of the most popular types due to its low cost, simple construction and ease of maintenance. This welding machine which always delivers AC output for welding is mainly a step down type of transformer which converts the high voltage low current industrial supply into low voltage and high current required for welding. It generally operates in single phase supply, i.e. 220 V single phase, or two lines of 440 V three phase supply [**1**].

Fig. 2.5 shows schematic of a welding transformer having thin primary windings with a large number of turns. On the other hand, the secondary has more cross-sectional area and less number of turns meaning, less voltage and very high current in the secondary. One end of the secondary is connected to the welding electrode, whereas the other end is connected to the pieces to be welded. Arc is struck between the electrode and the work piece and the heating produced at the electrode tip and work piece are sufficient to melt both and maintains as steady weld pool. Arc extinguishes and restarts at every half cycle of the AC power supply. For re-ignition of the arc, flux constituents of the electrodes shall contain elements that facilitate easy ionization. Further, arc re-ignition is difficult if the welding current set is low. Hence, welding current cannot be lowered below this value, which means transformer power sources will not be useful for welding thin sections.

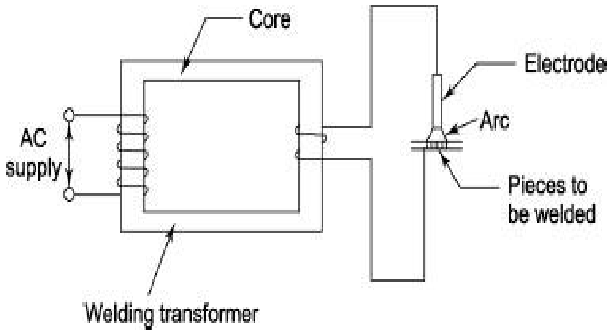


Fig. 2.5: Welding transformer.

2.2.1.2 Generator power source

The welding generator was the first power source successfully developed for industrial use. As already mentioned, it is a rotary type machine driven by an electrical motor or an internal combustion engine. The welding motor generator, whether driven by a motor or an engine forms a single integral unit. In this configuration the utility power is converted first into mechanical energy then back into electrical energy to achieve the step-down effect similar to a transformer. Because the output of the generator can be DC or AC current, these power sources can produce DC from AC without any need for rectifiers.

The working principle of the generator is: when a conductor moves in a magnetic field, it cuts the magnetic lines of force (flux) and, as a result alternating voltage is generated in the conductor. This alternating voltage is then converted to direct voltage by means of a device called commutator and collected together by a set of carbon brushes to get the required output. The welding generators which were developed earlier were basically DC generators with carbon brushes and commutators. Now welding generators are available with latest brush technology **[15]**. A unique advantage of this generator power source based on internal combustion engine is that, it can be used even in remote location where electric power is not available.

2.2.1.3 Rectifier power source

The welding rectifier provides DC power for welding and it has no moving parts. It consists of a step down voltage transformer with means to rectify AC to DC. The transformer can be single pass type, which converts the main supply to a low voltage supply on the secondary side. On a three phase machine, the primary is connected in delta or star, but the secondary is connected in delta. This is because delta connection is more convenient for low voltage and high current. The method of controlling the current is usually in the AC section between the transformer and the rectifier set. The welding rectifier can be designed for constant current as well as for constant voltage. In CC type rectifier the current is controlled through variable inductance or impedance. A CV type rectifier is usually designed to give a slightly sloping instead of a perfectly flat volt ampere curve. The slope is usually achieved by changing tapes on reactors in series with the AC part of the circuit.

2.2.1.4 Inverter power source

Since the arrival of high end semiconductors such as the insulated gate bipolar transistor (IGBT), now it is possible to build a switched-mode power supply (SMPS) capable of withstanding the high loads of arc welding process. Power sources based on this technology are commonly referred as invertors. A schematic of this type of power source is shown in **Fig. 2.6**. These devices first rectify the utility AC power to DC; then they invert the DC power into a step down transformer to produce the desired welding voltage or current. The switching frequency is typically 10 kHz or higher. Although the high switching frequency requires sophisticated components and circuits, it drastically reduces the bulk of the step down transformer. Power control and overload protection are also provided by an inverter power source. The high frequency inverter-based welding power sources are typically more efficient and provide better control of variable functional parameters than non-inverter welding machines.

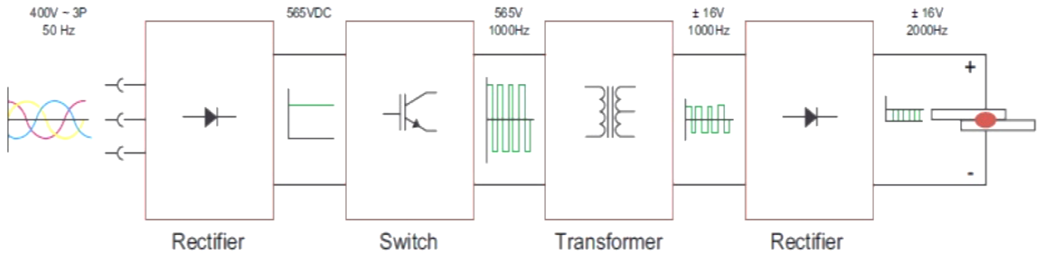


Fig. 2.6: Block diagram for inverter technology.

The IGBTs in an inverter based machine are controlled by a microcontroller, so the electrical characteristics of the welding power can be changed by software in real time, even on a step by step basis, rather than making changes slowly over hundreds of cycles. Typically, the controller software will implement various controlling parameters in these types of power sources. Additionally, it is possible to add new features to a software-controlled inverter machine, through a software update.

From a brief description of arc welding processes given above it is clear that there are different types of consumables, shielding gases and power sources used for welding. In addition to this, in the case of welding processes carried out manually like

SMAW and TIG welding, skill of the welder would be an additional variable. In order to ensure a good quality weld, performance of the welding consumables, response of the power source to various physical processes like metal transfer that take place during the weld and ability of the welder to maintain constant arc gap, melting rate, speed etc while welding is in progress are important. However, under normal circumstances that exist in a welding work shop monitoring the welding voltage and current displayed on the welding machine and monitoring the speed of welding are the two actions that can be carried out without any difficulty. However, processes like metal transfer, fluctuations in the arc gap and response of the welding machines to these variations are too rapid to be displayed by an ordinary voltmeter and ammeter. Hence, it is not possible to evaluate performance of welding power source or consumable or skill level of a welder without an appropriate weld monitoring system. In the absence of such a system, performance of consumable or skill level of welder is evaluated by assessing the quality of the welds produced using the consumable and the welder **[16]**. In this case the assumption is that if the weld is good, then the consumable and the welders are qualified. Performance of the consumable or welder during welding is not monitored. Power sources are tested by applying a resistive load and measuring the voltage and current using calibrated equipment and comparing with those displayed on the machine. Reference [**17**] prescribes that a power source can be evaluated on the basis of the specified RMS voltage value, type of insulation, types of grounding provided to the power source etc. As per this document for a good power source the value of the no-load RMS voltage of the supply must not exceed 80 V, or the peak of 113 V for direct-current machines; and for no-load the RMS value should reduce to 48 V if the arc welding takes place in environments with increased risk of electric shock (the peak value for dc machines remains instead the same also in this case). [**17**] further recommends that a good power source should be doubly insulated (i.e. basic insulation plus supplementary insulation), or, they should have reinforced insulation [**18**]. This reference further emphasizes that the circuit within the power source must not be internally connected to the enclosure of the welding machine (which may be connected to ground via a protective conductor (PE) (also referred to as *equipment grounding conductor*)). This is basically to assure that in the case of contact with either the electrode or the clamp, only a modest touch current will circulate (this touch current is due to the parasitic distributed capacitance) between the welding circuit connections and the PE (**Fig. 2.7**).

In none of these evaluations, signals collected from welding arc are used. Hence there is lot of interest in on line acquisition of the weld data while welding is in progress as that would reveal dynamic variation in current and voltage that occur during welding. Once a reliable data acquisition is carried out, the data can be suitably analyzed to understand the performance of welding power source or consumable or skill of a welder. Accordingly, many research groups across the world have attempted this and brief review of the published literatures in this area is given below.

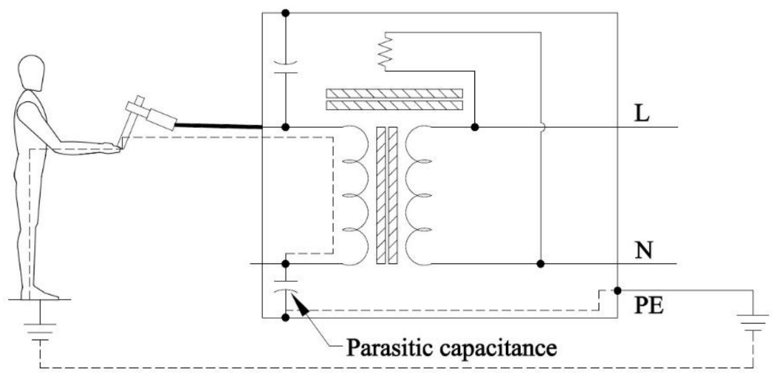


Fig. 2.7: Torch Current between welding circuit connections and PE.

2.3 Evaluation of arc welding parameters using weld data analysis

Hardware employed for real time dynamic measurements of welding variables are commonly referred as Weld Monitoring System (WMS) which consists of data acquisition unit, display and processing unit and relevant sensors. Data from WMS is subjected to appropriate filtering and analysis for understanding of the arc welding process. In the following sections, different weld monitoring systems used by different researchers for data acquisition and results of subsequent analysis of this data are presented.

In the recent past many research groups have developed WMS and the data acquired have been used to study the processes, detection of welding defect, recording the weld data etc. However, the processing units employed in these WMS vary widely from Field Programmable Gate Array, microcontrollers, microprocessors, Analog to Digital (A/D) card etc. Lanzoni et.al. developed their own weld monitoring system in which they have used advanced field programmable gate array (FPGA) and measurements and processing of electrical signals from sensors placed on the welding transformer and electrodes has been proposed for detecting faults in real time and with high sensitivity [**19**]. In [**20**], the authors designed and developed a microprocessor based controller system for real-time collection and display of welding parameters and this system was used to detect welding imperfections in gas metal arc welding by recording the instantaneous values of welding parameters. Development of welding process monitoring system based on a microcontroller platform capable of data acquisition, aggregation, and wireless transfer to a data server and presentation of this data in the form of a welding diary have also been reported [**21**]. This system could monitor and record all the relevant welding data and hence is capable of substituting the tedious manual filling of the welding data sheet. In a separate study Adolfsson, S. et al. has designed a WMS setup which uses a welding torch, a welding table and instrumentation for acquiring welding signal (i.e. voltage and current). They have used LEM Module LT 500-S current sensor for sensing the welding current. For voltage measurement instrumentation amplifier was used by them. The output of current and voltage sensors was connected to a DAQ system where the signals were filtered, sampled, digitized and stored temporarily. With this setup the authors acquired the welding data and by subsequent analyses they proposed a method of automatic detection of burn through in a GMAW process **[22]**. S.Adolfsson, A.Bhrami, G.Bolmsjo and I.Claesson used the same system to study the weld quality produced by robotized short-arc welding (in GMAW process) and developed a simple statistical change detection algorithm for this purpose **[23]**. In [**24**] the authors have used an analog to digital (A/D) converter card and Hall Effect sensors to capture various welding parameters to an external computer. With detailed analysis of the acquired welding data (voltage and current) they have shown that in a GMAW process, even though a gas mixture that promotes a stable transfer is used spatter can still appear in the welded joint area. In **[25]** a WMS experimental setup was established using an A/D card, a robot carrying a welding torch, and an industrial PC. The welding voltage and current signals are continuously sampled by the PC at a sampling frequency of 10 kHz. For filtering purpose, a low pas filter was used by them. Subsequently, they have shown that in a GMAW process, various statistical parameters can be correlated with the process disturbances. In another study [**26**] the authors have used ADC to acquire welding voltage and current at the rate of 200 khz. The acquired data is transferred to an external computer and subsequently filtered using a Low Pass Filter (LPF) which has a cutoff frequency of 200 khz. Filtered data thus obtained was used to develop a multiple regression model which can predict the arc stability.

Voltage and current data acquired using a WMS have been subjected to detailed analysis to demonstrate the various applications of this procedure in the study of arc welding processes. Many researchers have used statistical tools like Probability Density Distribution [**27-31**], signal processing, ANN techniques for this purpose. PDD technique was used in [28] to show that the arc stability is improved with the use of nano powders of $CaCO_3$ in the flux coating. In another study, welding data was acquired and current histogram plotted to explain the phenomenon of metal transfer by observing the current deviation from the histogram curve [**32**]. Recently, acquisition of CO_2 welding (GMAW) signals using a data acquisition system and their subsequent analysis using VC++ and MATLAB mixed programming to obtain PDD and power spectral density (PSD) has also been reported [**30**]. Very recently, evaluation of welding power source and filler wires through signature analysis has been reported, where authors evaluated dynamic characteristic of the arc welding power source and used welding current PDDs to analyze and evaluate the instantaneous fluctuations that appears in flux cored wire arc welding [**29**].

In another study the authors have derived the range of parameters from the welding data. The parameters thus obtained were used for fault discrimination by using independent component analysis for separating the sampled data from the arcing and short circuiting mode of metal transfer [**33**]. Further, voltage and current signals acquisition has also been used to study the alloy enrichment in the weld metal deposited using cellulosic electrode as function of welding parameters [**34**].

In a separate study [**35-36**] Statistical Process Control (SPC) technique was used to extract the range of various statistical parameters like mean and standard deviation. Changes in these statistical parameters are displayed using control charts and are correlated with weld quality using trending analysis, tolerance analysis, and sequential analysis techniques.

In [**37**] the authors have studied arc voltage behavior in pulse gas metal arc welding (GMAW-P) under different drop transfer modes in which experimental measurements were made to investigate effect of drop transfer mode on change in voltage during GMAW-P process. It is shown that the welding arc is significantly affected by the molten droplet detachment and sudden change in voltage just before and after this event can be used to understand the characteristics of molten metal transfer in GMAW-P.

Many authors have used signature image technique to demonstrate that fault recognition in a GMAW process is possible on real time basis **[38-42]**. Further, it is also shown that the signature image technique is useful to identify unknown faults occurring in a welding environment **[38-39]**. In a separate study **[40]** the same authors have further utilized the signature images for real time computation for quality monitoring and fault detection in automated welding in an industrial production environment. This method employs a basic set of orthonormal signatures to describe good quality reference welding according to process specifications, followed by a statistical estimation. The estimates allow a determination of whether the production signatures belong to the reference set for good welding or not. In another study the same author proposed a method for determining a stability index during welding. In aforementioned work signature images were obtained using welding voltage and current data. It is then shown that, with a reasonable choice for the signature image window scaling, the stability index agrees with welding experience in the GMAW transfer modes of short circuiting and spray transfer. The effect of changing welding consumables, wire and shielding gas is illustrated and the connection between the stability index and metal transfer phenomena is investigated **[41]**.

A technique for detecting flaws in GMAW process was proposed in **[43]**. In this study the authors have used various signal processing methods to identify the signal parameters which were sensitive to irregularities in the weld. Further, techniques were suggested to identify defective welds. The authors also describe a technique which can be used to evaluate the quality of a weld from any sensing system for use in automatic welding of mass production parts. In another study signal processing technique is used in resistance spot welding to identify some of simple faults [**44**].

Welding data acquired has also been processed using Artificial intelligence techniques to study various arc welding processes. In [**45**] the authors have predicted the quality of pulsed metal inert gas welding by taking various process and statistical parameters of arc signals and provided these parameters as an input to neural network model to predict the weld qualities. Intelligent monitoring and recognition of short circuiting in Gas metal arc welding (GMAW) process by fuzzy kohonen clustering has been done by the authors in **[46]**. In another study fuzzy logic and neural network technique has been adapted for recognizing GMAW process disturbances [**47-48**]. Strength of weld joint has been predicted for pulsed metal inert gas welding by analysis of acquired welding current through wavelet packet transform analysis **[49]**.

In [**50**] the authors have presented the methods for automatic detection of weld defects of short-circuit gas metal arc welding. It is based on the extraction of arc signal features as well as classification of the features obtained using Self-Organize Feature Map (SOM) neural networks in order to get the weld quality information and for finding the defects in the product. This is important for on-line monitoring of weld quality especially in Robotic welding and lays the foundation for the further real-time control of weld quality.

In [**51**] the authors have discussed the identification of weld imperfections in the welds produced by Gas Metal Arc Welding process using arc sensing. Authors further discussed a monitoring method for defects in the welds produced by GMA welding process. It is based on the principle of feature extraction from the arc signals by classifying signal histogram in the welding process using Self Organized Maps (SOM) technique. In a separate study different control algorithms were used to develop a computer animated GMAW process emulation module using MATLAB SIMULINK package. This was used to train welding personals so that they can gain sufficient insight about GMAW process and learn this technique [**52**]. Similarly, in [**53**] an advanced welding simulation trainer system is presented which is designed to provide welding training and also to be used as a testing, recruitment and engagement tool for educational institutes and industry.

Hence, it is clear from the information provided above; weld monitoring system is being used by many research groups to monitor the arc welding processes in situ. Attempts have been made correlate the data acquired with modes of metal transfer, defects, weld penetration etc. However, most of these studies are carried out in laboratories using data acquisition system specifically designed for this purpose.

There is hardly any literature that discusses use of such system in actual welding fabrication. This is because development of WMS and data analysis procedures still remains in R&D and yet to reach the welding shop floor. Further, cost of WMS is significantly higher than a welding equipment and expertise required for analysis is much different from expertise of a shop floor welding engineer. In recent times, welding equipment manufacturers have come up with weld data acquisition system, which can be integrated with welding power source and acquire the voltage and current data at reasonable speed which can be used to verify whether welding parameters confirm to those provided in welding procedure specification **[54]**.

2.4 Data Acquisition System (DAS)

As already stated, one of the most important units of a weld monitoring system is its DAS unit; various researchers have used different hardwares for this purpose [**19-21, 24-25, 29]**. A DAS is a system designed to acquire physical signals from the actual process to a device. The main aim of this device is to measure, process and to store these physical signals. Actually, the DAS needs various modules to do these activities. These modules can be seen as stages, where each stage has a concrete task in the acquisition of the real world signal. **Fig. 2.8** shows the common stages in a DAS.

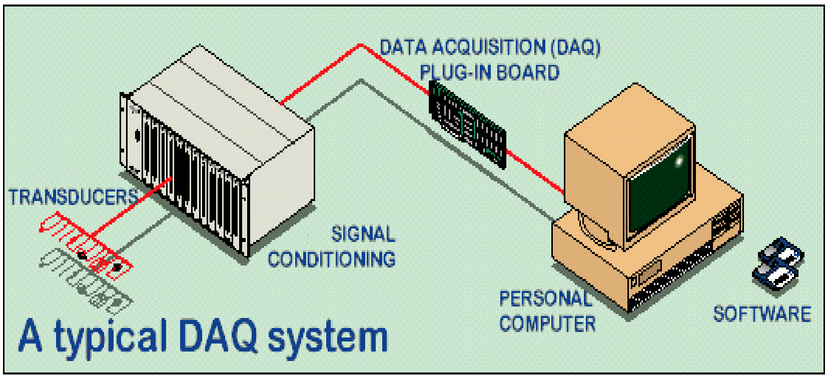


Fig. 2.8: Various stages in a DAS [55].

DAS are designed for the acquisition of real world signal coming from various sensors which are represented in electrical quantity (usually in the form of voltage). A sensor can be classified in many ways which actually depends on how a sensor senses incoming signal and the kind of output it provides. In a DAS irrespective of the source, the signals will be converted in digital format by an Analog to Digital Converter (ADC); this ADC is the key component of a DAS. Among various types of ADC available most common are the Flash ADC, the Successive Approximation Register (SAR), the integrating ADC and the Sigma-Delta ADC. The main difference between them is how they sample the incoming signal; due to different mechanism of quantization they provide varying sampling rate.

The incoming signal is initially sampled and once they are quantified each signal level are assigned to a binary value which is the representation of analog signal in digital format. Sampling of the input signal will be triggered by the DAS main clock at a periodic rate. Hence, the performance of DAS will depend on the performance of ADC parameters which includes resolution, dynamic range and the sampling rate.

The resolution of the ADC is determined by the number of bits (N) of the ADC, this actually give the number into which incoming analog signal can be quantized into. Consequently, N corresponds to the size of digital code.

In an ADC, its dynamic range and its Full Scale Range (FSR) are determined by a voltage which is known as voltage reference. This is helpful in determining the minimum voltage variations that can be detected at the input side of an ADC, this is termed as Least Significant Bit (LSB) and is given by: -

$$1\text{LSB} = \frac{FSR}{2^N}$$

The sampling rate is the rate with the incoming analog signal can be sampled or quantized. In order to have faithful reproduction of the quantized signal (in digital format), the sampling rate should be greater than double the bandwidth of the analog signal.

Another important step in the process of signal acquisition is signal conditioning module (Analog Front End). Signal conditioning module is used to adapt the signal coming from the sensing element to the input of DAS so that dynamic range can be matched. Offset, common mode and bandwidth are some of its common key parameters. This module is prior to DAS input. This module plays an important role because it ensures the quality in the conversion.

Amplifying/attenuating allows the level of the signal match the DAS dynamic range. This is done to maximize the usage of number of bits offered by the DAS.

Multiplexing the signal will depend on the quantity of signal that needs to be acquired. Multiplexing allows the DAS to acquire several signals in parallel.

Once the signal is matched to the DAS input, it is converted to digital format and is transferred to the final computer. The computer used should have powerful and reliable software to show this data which in turn is used for post processing to measure or to study the behavior of some process.

2.4.1 Digital Storage Oscilloscope (DSO) as a DAS

An oscilloscope can be used to acquire instantaneous values of voltage and current. It does this by measuring the voltage drop across a resistor and in the process draws a small current. The voltage drops thus obtained is amplified and used to deflect an electron beam in either the horizontal X axis or vertical Y axis using an electric field. The electron beam creates a bright dot on the face of the Cathode Ray Tube where it hits the phosphorous. The deflection, due to an applied voltage, can be measured with the aid of the calibrated lines on the graticule.

A digital storage oscilloscope is an oscilloscope which stores and analyses the signal digitally rather than using analogue techniques. It is now the most common type of oscilloscope in use because of the advanced trigger, storage, display and measurement features which it typically provides [**56**]. The input analogue signal is sampled and then converted into a digital record of the amplitude of the signal at each sample time. The sampling frequency should not be less than the Nyquist rate to avoid aliasing **[57]**. These digital values are then turned back into an analogue signal for display on a cathode ray tube (CRT), or transformed as needed for the various possible types of output—liquid crystal display, chart recorder, plotter or network interface.

2.4.2 PSoC based data acquisition system

PSoC (Programmable System-On-Chip) is a family of microcontroller integrated circuits by Cypress Semiconductor. These chips include a Central Processing Unit (CPU) core and mixed-signal arrays of configurable integrated analog and digital peripherals [**58**].

The PSoC system used in this work has been developed by Cypress Micro System Company. From the point of hardware, it is both cost and power efficient, considering the software point of view, the designer can use the presetting “PSoC creator” to easily design the system of his choice.

2.4.2.1 PSoC architecture

There are three families of PSoC: PSoC 1, PSoC 3 and PSoC 5. The principal difference is the Micro Controller Unit (MCU) that feeds the core, which increases its performance in terms of clock rate and therefore the calculation rate. Also, the instruction length is incremented from 8 to 16 and 32 bits. **Fig. 2.9** shows a comparison between them.

Depending on the PSoC model, the digital and analog systems may have 16, 8, or 4 digital blocks and 12, 6, 4 analog blocks. Also, the number of pins and the memories size may differ from each other categories. PSoC devices are formed by a core, a configurable system based on analog and digital blocks, and a programmable routing and interconnect. In its simplest configuration it consists of: An Arithmetic Logic Unit (ALU), Seven on-chip registers, a serial interface, two 16 bit timers, function registers, Support for 64K of external memory (code and data), Four 8-bit I/O ports and 210 bit-addressable locations.

Fig. 2.10 and **Fig.2.11** shows detailed architecture of PSoC-3 and PSoC-5. These figures show the necessary blocks of a PSoC platform.

The PSoC architecture is widely used for numerous applications. Fernando et. al. [**60**] has used the PSoC architecture to design data acquisition system for educational purpose. In an another study [**61**] the authors have designed Data acquisition, Controlling and Wired Remote Display system using PSoC. Similarly, in [**62**] PSoC-5 based system was used by authors to demonstrate a technique to design a low-cost, highly accurate ECG data acquisition system.

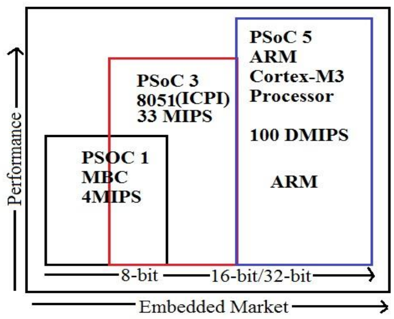


Fig. 2.9: Comparison of PSoC family.

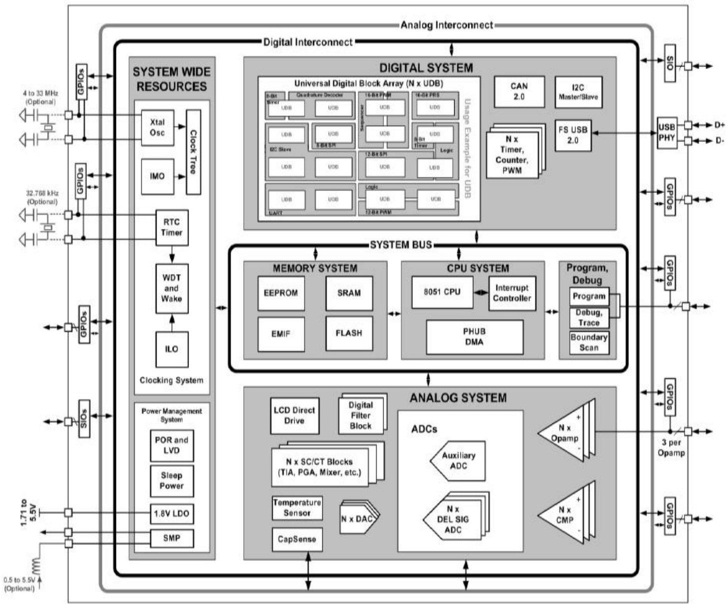


Fig. 2.10: PSoC-3 architecture [59].

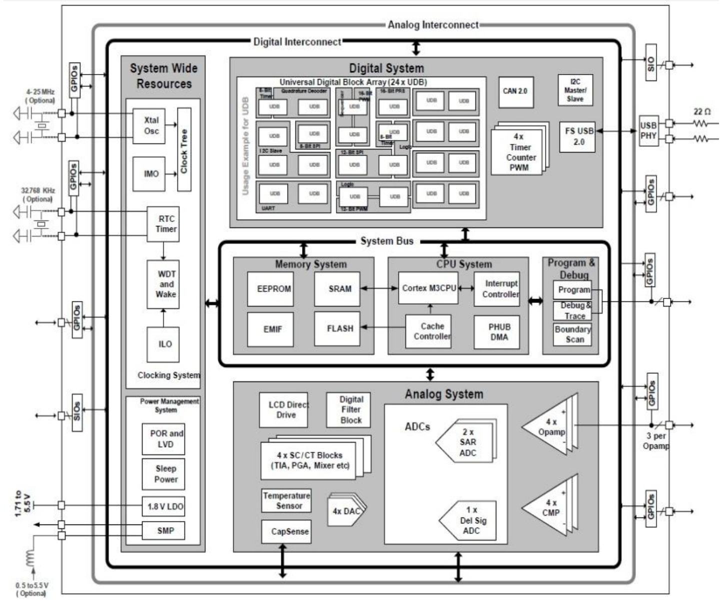


Fig. 2.11: PSoC 5 architecture [59] (LCD- Liquid crystal display, OpAmp-Operational Amplfier, RTC –Real time control, SRAM-Static Random Access Memory, XTAL Osc- External Oscillator, EEPROM- Electrically Erasable Programmable Read-Only Memory).

In a separate study [**63**] analog system of PSoC-1 was used by the authors to realize a reconfigurable filter stage. This system can adapt itself as per the incoming signal. Usage of PSoC in wireless sensor node was proposed in **[64],** here the authors have used the reconfigurable capabilities of the hardware to minimize the power consumption.

2.4.2.2 Programmable System on Chip (PSoC) Vs Micro Controller Unit (MCU)

The difference between PSoC and micro-controller is that PSoC includes both analog and digital module, and can have hundreds of built in functions. Consequently, there is a drastic decrease in the design time [**65**]. **Fig. 2.12** shows a typical MCU that contains a Central Processing Unit (CPU) and a set of peripheral functions such as Analog to Digital Convertor (ADC), Digital to Analog Converter (DAC), Universal Asynchronous Receiver/Transmitter (UART), Serial Port Interface (SPI), and general I/O, all linked to the CPU's register interface. Within the MCU, the CPU is the "heart" of the device – the CPU manages everything from setup to data movement to timing. Without the CPU the MCU cannot function. **Fig. 2.13** shows that PSoC is quite different from MCU. The Central Processing Unit, analog, digital, and Input / Output units are equally important in PSoC system. In a PSoC, CPU is not the most important unit. Instead, systems interconnect and programmability forms the heart of a PSoC based design. The analog and digital peripherals are interconnected with a highly configurable routing matrix, which allows users to create custom designs to meet desired application requirements. We can program PSoC to emulate an MCU, but we cannot program an MCU to emulate PSoC.

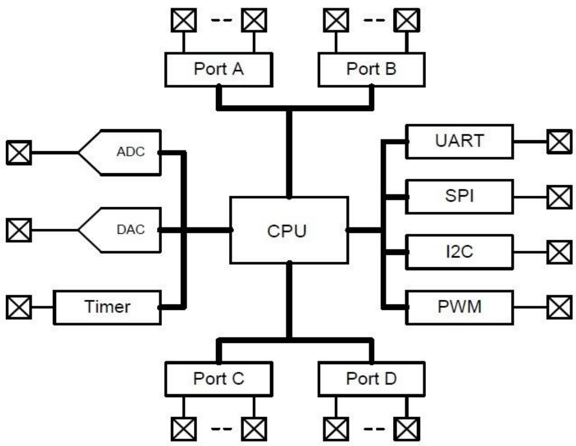


Fig. 2.12: Block diagram of typical MCU [66] (DAC-Digital to Analog Converter, SPI-Serial Port Interface, PWM-Pulse Width Modulation).

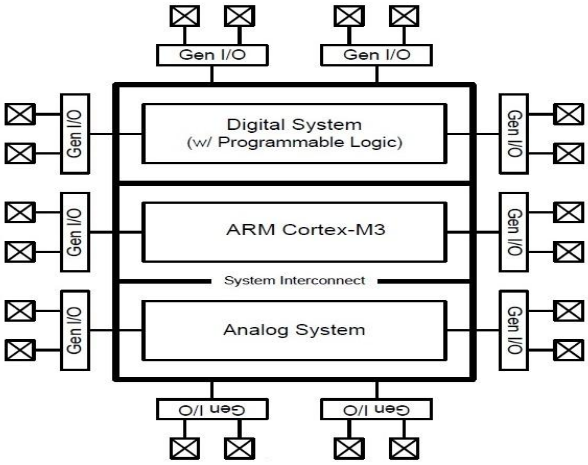


Fig. 2.13: PSoC-5 LP block diagram [66].

From the above discussion it is clear that a PSoC based system can be used to acquire the data for various applications. The rate of data acquisition and filtering of noise from a data acquisition system are necessary to ensure that the data thus acquired are the true representative of the physical process. Hence, for reliable acquisition of welding signal using PSoC and to have any meaningful analysis of the data thus acquired a thorough understanding of noise emanating in a welding environment is required and the same is presented in the next section.

2.5 Noise in a welding environment

Electrical noise and or interference can be defined as undesirable electrical signals, which distort or interfere with an original (or desired) signal [**66**]. Noise could be transient or constant. Transient noise is caused, for example, by lightning. Constant noise may occur due to the predictable 50 or 60 Hz AC 'hum' from power circuits or harmonic multiples of power frequency close to the data communications cable [**67**]. The contribution of all these noises affects the system's design.

In a welding environment noises are basically of two types:

Internal noise

1. Thermal noise (due to electron movement within the electrical circuits)

2. Imperfections (in the electrical design).

External noise

1. Natural origins (electrostatic interference and electrical storms)

2. Electromagnetic interference (EMI) - from currents in cables

3. Radio frequency interference (RFI) - from radio systems radiating signals

4. Cross talk (from other cables separated by a small distance).

Basically there are three contributing factors for an electrical noise problem to exist: -

1. A source of electrical noise

2. A mechanism coupling the source to the affected circuit

3. A circuit conveying the sensitive communication signals.

In a Welding equipment which produce quick changes (spikes) in voltage or current or harmonics, these noises are unavoidable and due to switching surges welding equipment is prone to such noise. This may distort the desired voltage and current signals. Additionally, welding equipments which comprises of silicon-controlled rectifiers, noise due to 'notching' also occurs **[67]**. The switching of these devices causes sharp inverted spikes during commutation. **Fig. 2.14** shows the typical waveform with this type of disturbance.

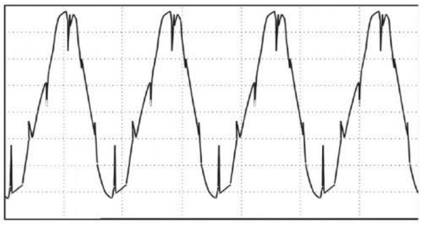


Fig. 2.14: Waveform distorted by notching [67].

Faults in power systems can cause voltage disturbances. Distortions and disturbance thus produced can easily affect sensitive electronic equipments by finding a way to electronic circuitries via main power supply. In addition to these factors directly communicated disturbances, arcing generated in power-switching devices, sparks and high-frequency harmonic current components may produce electromagnetic interference. Hence, proper isolation is essentially required to avoid these kinds of disturbances. **Fig. 2.15** shows diagrammatically the reasons for noise from the equipment within a facility.

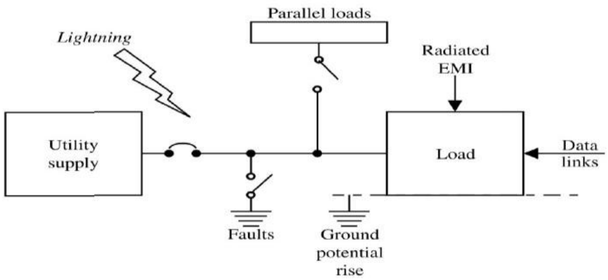


Fig. 2.15: Noise emanating from electrical systems within a facility [67].

From the above discussion it is clear that due to the presence of electrostatic and electromagnetic noises in a welding environment, the raw data obtained with a data acquisition system contains unwanted noise. Hence, the electrical signal thus acquired should be filtered with appropriate filtering mechanism so that noise can be minimized before further processing. There are conventional frequency domain methods, like FFT **[57]** and many recent techniques like Wavelet Transform [**68**]. In this work to filter the noise, signal to noise ratio (SNR) is chosen as the parameter that can be used for selecting the appropriate filtering technique. Detailed description about this technique and results obtained will be discussed in **chapter 3**.

Literature survey presented above reveals that weld data acquisition and analysis of the same using time domain and statistical analysis are used for online weld process evaluation, defect identification and quality monitoring. Evaluation of welding process using ANN and fuzzy logic is also reported in the literatures. Based on the findings of the literature, it is observed that most of the WMS were developed for a specific application and it is seldom used for other applications. A possible exception to this is the analysator Hannover **[31]** developed at Lebniz University, Hannover. Further, use of general purpose equipment like digital storage oscilloscope as DAS in WMS has never been explored; in fact, most of the DAS are specifically designed for the intended applications. Similarly, recent technologies like System on Chip have not been exploited as potential DAQ unit in WMS.

2.6 Scope of the thesis

Scope of the present work is to develop a procedure to acquire dynamic variation in voltage and current signals at the same rate as they occur while welding is in progress and use this data for comprehensive understanding of the arc welding process. This procedure is first developed using DSO as a data acquisition system in WMS and subjecting the data to time domain, statistical and ANN analysis. Capability of this procedure to assess the skill level of the welders, differentiate the performance of different welding power source and consumables and study the role of shielding gas in different modes of metal transfer in GMAW process are then demonstrated. Subsequently, a PSoC based DAQ system, which is very cost effective is developed that can replace DSO in the developed WMS. PSoC based system was used for various applications and its capabilities are demonstrated.

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3

Weld data acquisition and procedure development

This chapter provides the details of data acquisition setup which include DSO, and current and voltage sensing probes, processing It is important to optimize the data acquisition rate by many trials and examination of the acquired data to ensure that the data acquired accurately represents the physical processes that occur during weldng Then it provides details of how the welding data was acquired by DSO for duration of 20 seconds for every welding trial and transferred from DSO to PC for subsequent filtering and analysis. Various filtering techniques are considered to filter out noise from the signal and final choice of filter is also presented. Subsequently, processing of data for time domain and statistical analysis are presented in detail. The oscillogram used for time domain and Probability Density Distribution (PDD) analyses are generated using voltage and current signals. Details of the PSoc based DAS which is developed as an alternative to DSO is also provided.

3.1 Experimental setup

3.1.1 Data acquisition setup

Fig. 3.1 shows the schematic of arc welding machine setup with data acquisition system. For all our studies data acquisition was carried out to acquire the instantaneous values of voltage and current by maintaining an identical condition while making bead-on-plate welding on carbon steel plate using suitable welding consumable.

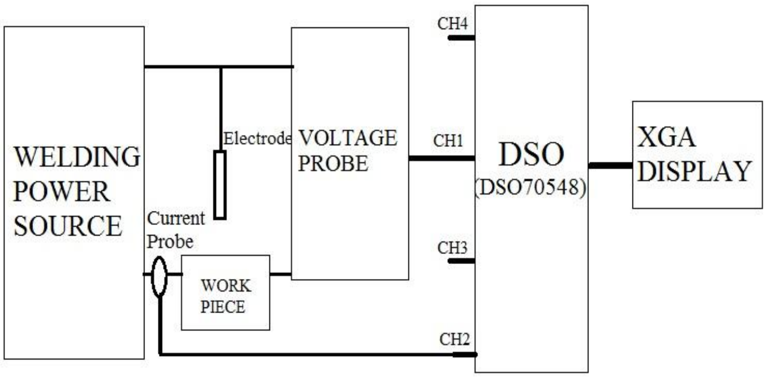


Fig. 3.1: Block diagram of data acquisition setup.

For recording the welding data (i.e. voltage and current) online, a DSO (Agilent Technologies, DSO7054B) of 500 MHz band width and maximum sampling rate of 4 GSa/s is used. It has 4 channels and A.C to D.C coupling. The DSO has an extended graphic array display (XGA) of 12.1 in. The in depth memory of the DSO is 8 Mega points and it has an input impedance of 50 ohms – 1M ohm. The oscilloscope allows real time collection and display of welding parameters and also enables data to be taken out of it for post processing.

For measuring welding current, high sensitive (selectable between 1 mA/A or 10 mA/A) Hall Effect based current clamp was employed. With this probe it is possible to measure DC current up to 600 A and AC current up to 100 A. True RMS measurement with DC components is also possible. For contact less measurement with the clamp ring this device uses Hall Effect to measure the axial magnetic field generated in the cable by current flowing through it. This clamp also provides electrical and physical isolation with good dynamic response. For the voltage measurement a 500MHz band width high voltage differential probe was used. These probes were optimized for acquiring differential signals and are connected across the positive and negative terminals of the welding power source for measuring the instantaneous values of the potential difference that occurs during welding. Two signal paths are provided for achieving high value of common mode rejection ratio and matching of overall attenuation and frequency response. Impedance matching was done for the most accurate measurement as reflections are minimized along the signal path. The system input capacitance is 2.5 pF and a propagation delay of 6.1 ns. The attenuation accuracy of the probe is 100:1 and it has an input resistance of 40MHz. The maximum input voltage is 1000Vrms.

The entire data acquired by DSO was extracted into an external computer using an Ethernet cable and dedicated software provided by M/s Agilent technologies, the supplier of the Oscilloscope. The software has the option to extract either all the data acquired by the oscilloscope or to manually select only desired number of data points as per the requirement. The welding time was set to 20 s and 2,000,000 samples were acquired during this time. The data thus obtained were filtered and analyzed.

3.1.2 Welding setup

The instantaneous values of voltage and current data were acquired while bead-on-plate welding on carbon steel is in progress with an inverter power source and E 7018 electrode of 3.15 mm diameter in SMAW process. Photograph of welding setup along with data acquisition unit are shown in **Fig. 3.2**.

Current chosen for welding and the corresponding voltage displayed in the machine while making these bead-on-plate welds are 120 A and 25 V respectively. For each condition, three sets of data were acquired from three different beads-on-plate welds for duration of 20 s.

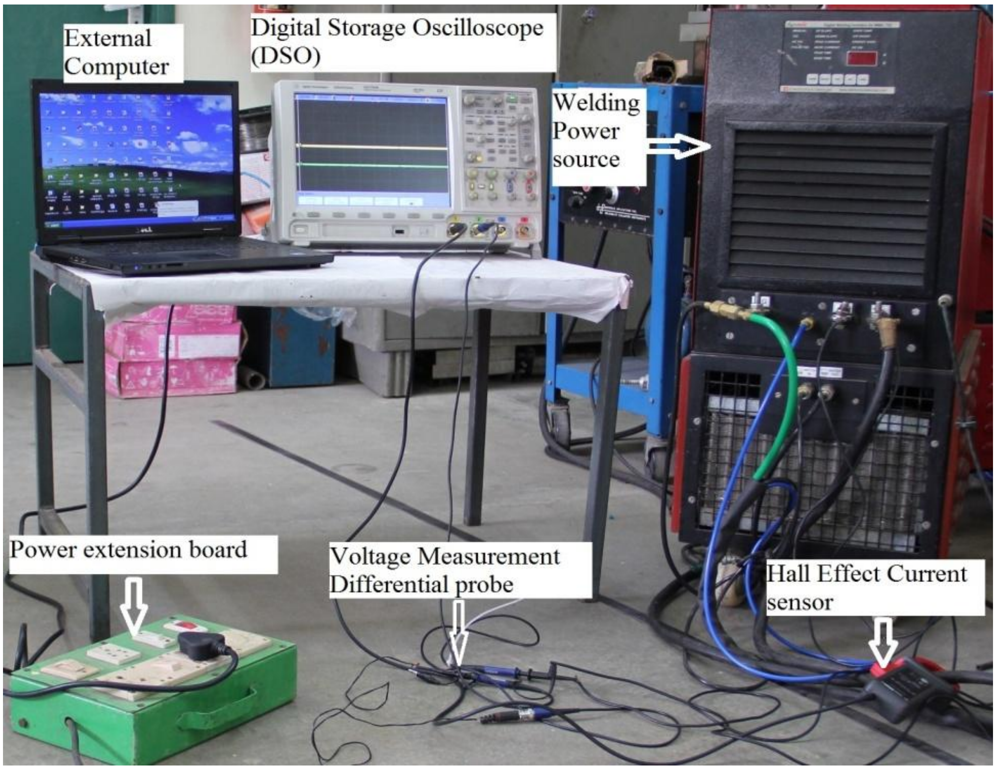


Fig. 3.2: Photograph of welding setup with data acquisition unit.

3.2 Data processing

The prime task to be carried out after acquiring the welding voltage and current signals is to subject them to an appropriate filtering so that noise can be minimized before further processing.

3.2.1 Signal filtering

There are conventional frequency domain methods, like FFT and many recent techniques like Wavelet Transform [**1**]. To filter the noise, signal to noise ratio (SNR) is chosen as the parameter that can be used for selecting the appropriate filtering technique. SNR of the signal was estimated both before and after filtering and the filtering technique that gives highest value for the ratio of SNR at the output to SNR at the input is chosen.

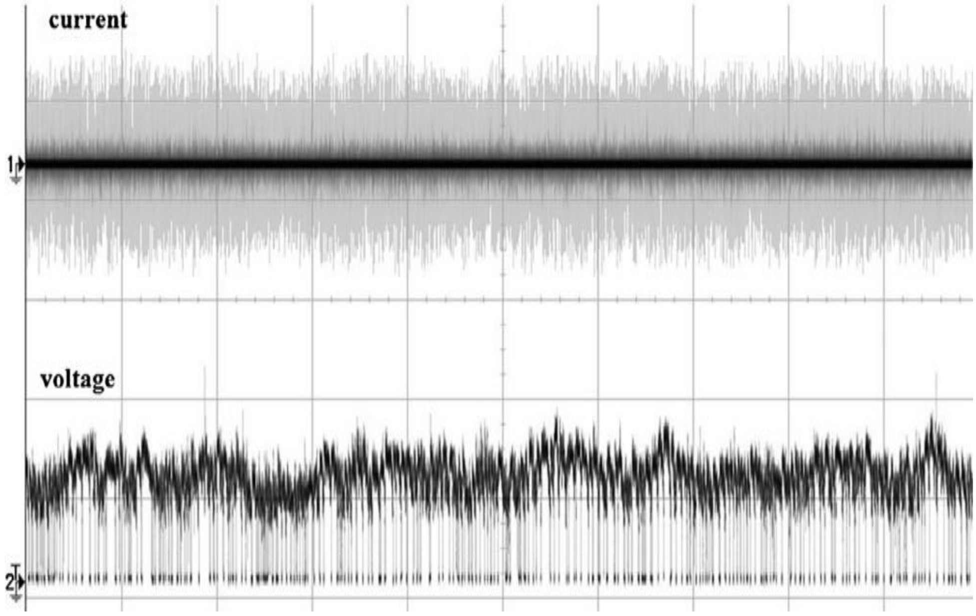


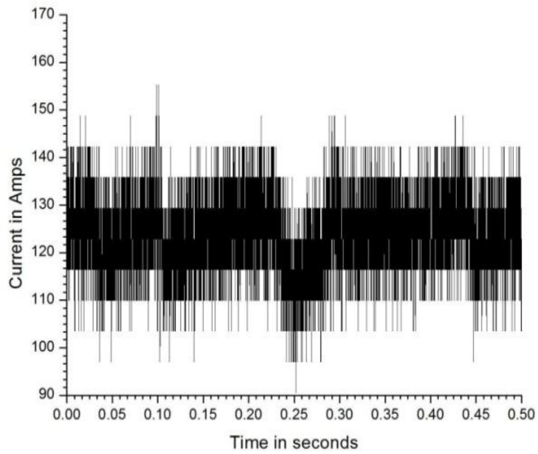
Fig. 3.3: Raw data of current and voltage of 20 s duration.

Fig. 3.3 shows typical voltage and current signals (without filtering). Noise level is too high to study the actual variations in the voltage and current signals and hence, use of appropriate filtering techniques is necessary before these signals are subjected to further analysis.

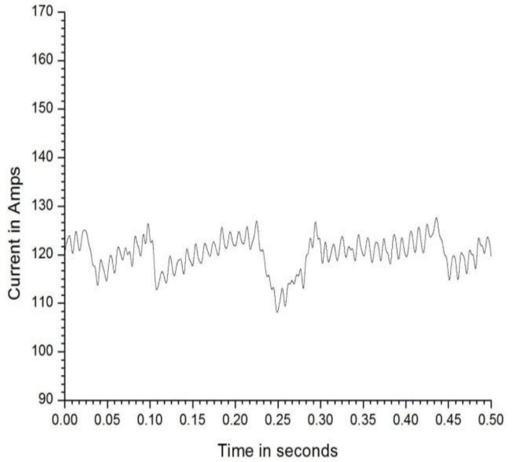
3.2.1.1 Current filtering

3.2.1.1.1 Filtering method based on the Fast Fourier Transform

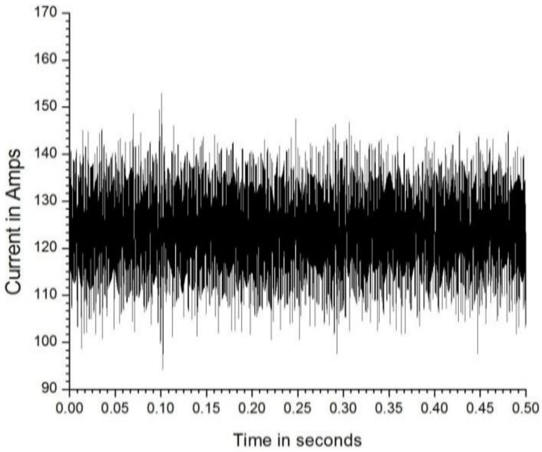
FFT filters which includes FFT low pass filter, FFT high pass filter, FFT band pass filter and FFT band stop or band elimination filter were first applied on signal acquired. **Fig. 3.4** and **Fig. 3.5** show the output from various filters with 500 ms of current signals shown in **Fig. 3.3** as their input. Aim here is to identify the best filtering technique for our application; hence random data of 500 ms was taken for this purpose. The output waveform corresponding to each and every filter is shown, which gives the extent of filtering achieved by each filtering technique.



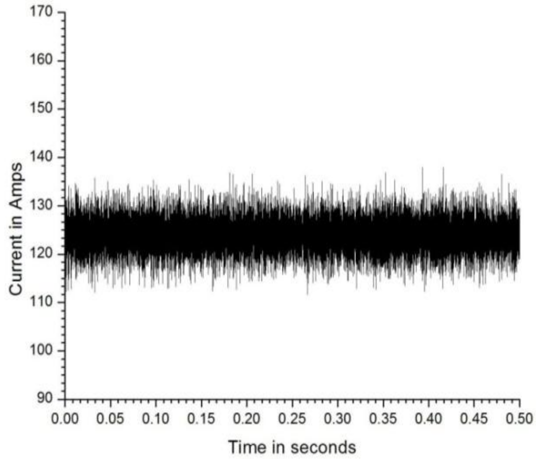
(a) Input signal with noise



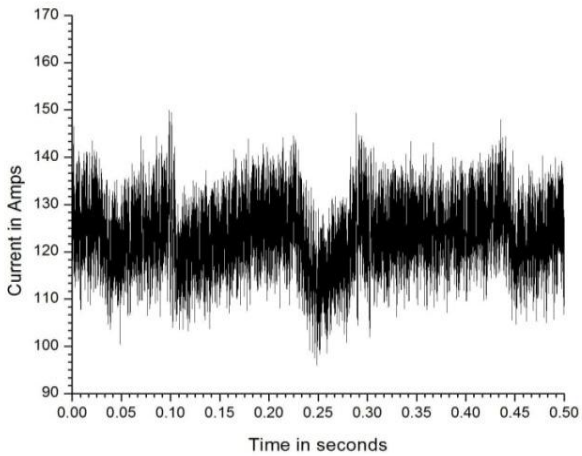
(b) Low pass filter



(c) High pass filter



(d) Band pass filter

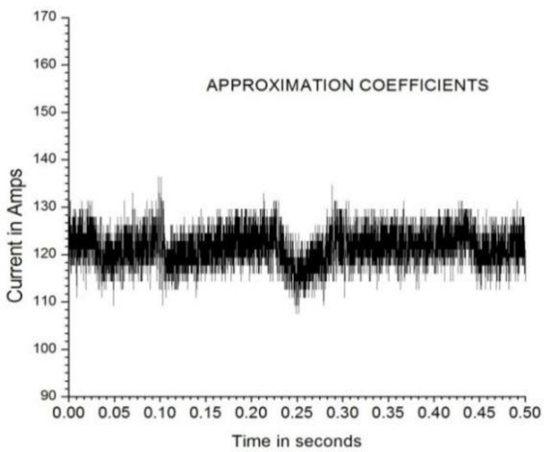


(e) With band elimination filter

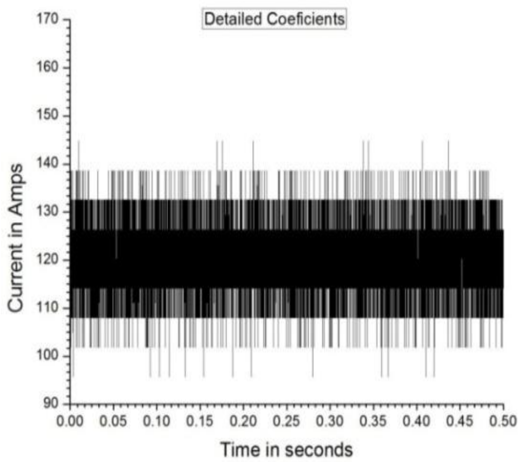
Fig. 3.4: Samples of filtered welding current with various filtering techniques (a) shows input signal with noise, (b) filtered input with low pass filter, (c) with high pass filter, (d) with band pass filter, (e) with band elimination filter.

3.2.1.1.2 Filtering method based on the discrete wavelet transform

The wavelet transform is a multiresolution analysis (MRA) technique that can be used to obtain the time-frequency representation of the Welding signal. This transform is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal. Wavelet transform is one of the most popular techniques for processing non-stationary signal in both frequency and time domain. MRA is designed to give good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. Performance of wavelet transform depends on the type of wavelet basis used, it can be effectively used for suppressing the noise and to find desired signal. Frequency component are kept at certain threshold and the wavelet coefficient are used to recover desired signal. Depending on the application wavelet basis can be selected because it analyzes the signal at different frequencies with different resolutions. Every spectral component is not resolved equally.



(a) Wavelet approximation coefficient



(b) Detailed coefficient

Fig. 3.5: Samples of filtered welding current with DWT filtering techniques (a) with wavelet approximation coefficient and (b) with detailed coefficient.

The data was separately subjected to wavelet transform filtering technique using Haar wavelet as candidate wavelet (**Fig. 3.5**). Haar wavelet has been found to have the optimal value in terms of SNR. Frequency component are kept at certain threshold and the wavelet coefficient are used to recover desired signal [**1-2**]. The threshold value is predicted based on trial and error method till the desired signal has been extracted. Filtered signals thus obtained were subjected to time domain and statistical analysis to evaluate arc welding process.

Different techniques of wavelet signal processing include DE noising, smoothing with zero padding extension, Smoothing with periodic extension, Multi scale DWT and Continuous wavelet analysis. Welding signal with noise was processed using all these techniques and corresponding SNR values are tabulated in **Table 3.1**.

3.2.2 Signal to Noise Ratio (SNR) calculation

Signal to Noise Ratio (SNR) is defined as the ratio of signal power to the noise power, which is usually expressed in decibels. A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise.

SNR, both at the input and at the output for all filtering techniques mentioned above were estimated and tabulated in **Table 3.1**. This table also gives the ratio of these two SNRs.

Although frequency domain in wavelet transform was revealing the patterns, it was noted that the SNR for signal at output to those at input, which is the criteria for selection of the filtering technique, is considerably low for this technique (**Table 3.1**),. Hence in spite of many advantages that wavelet transform technique is having over the FFT filtering technique, wavelet transform is not selected for the filtering purpose in the present study. From **Table 3.1**, it is concluded that FFT low pass filter is having maximum SNR value. One can come to the same conclusion also from the various output signals shown in **Fig. 3.4** and **Fig 3.5.**

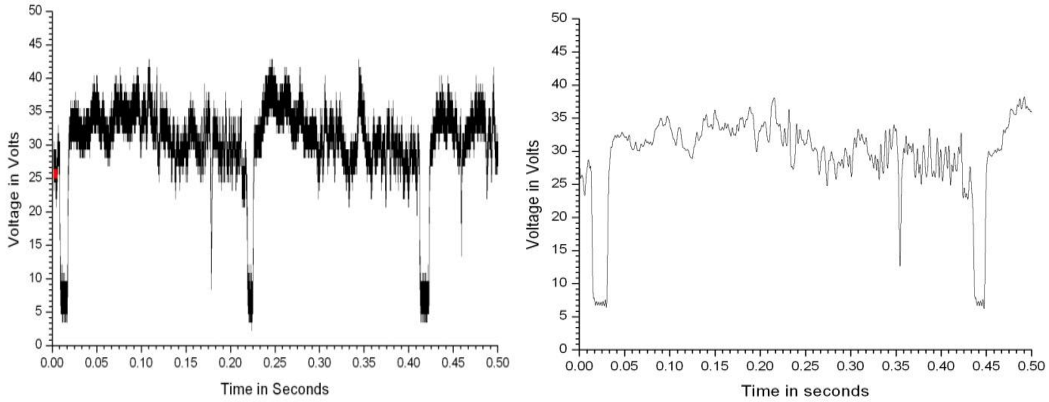
Table 3.1: SNR for input and output for the filtered signal

Type of filters adopted	Signal to Noise Ratio (decibels)		
	Input	Output	Ratio (Output to input)
FFT pass filters			
Low Pass	44.9104	62.0484	1.381604
Band pass	44.9104	60.0188	1.336412
High Pass	44.9104	47.4336	1.056183
Band block	44.9104	46.9242	1.04484
Wavelet Transformation Technique (Haar wavelet)			
Denoise	44.9104	47.0000	1.046528
Smooth with zero padding extension mode	44.9104	46.3104	1.031173
Smooth with periodic extension	44.9104	46.2102	1.028942
Multi scale DWT Smooth	44.9104	46.0114	1.024515
Continuous wavelet	44.9104	45.041	1.002908

Hence, from now onwards for all the analysis of weld parameters FFT LPF will be used.

3.2.3 Voltage filtering

Techniques presented above for current filtering were also used to filter the voltage data and it was found that in case of voltage data also FFT LPF provided maximum SNR value. Hence, to filter both current and voltage data similar technique using FFT LPF was employed. **Fig. 3.6(b)** shows the filtered output of voltage signal for the raw signal shown in **Fig. 3.3** after subjecting to FFT LPF.



(a) Shows input signal with noise **(b) filtered input with low pass filter**

Fig. 3.6: Samples of filtered welding voltage.

3.3 Welding signal/data analysis

Once the acquired signals are filtered, Signal analysis was carried out using following techniques: -

1. Time domain and
2. Statistical analysis (Probability Density Distribution (PDD analysis)) techniques.

3.3.1 Time domain analysis

Time domain analysis of filtered data enabled us to visualize the welding signal qualitatively. In this analysis variation in voltage and current were observed with respect to time. **Fig. 3.7** represents a typical time domain plot for E 7018 electrode acquired at different sampling rates. From this figure we can observe the extent of variations taking place in actual welding process. The variations around steady state value (recorded value of ~ 25 V) will take place due to the random arc gap variations in SMAW process. Consequently, in these figures steady state voltage values are varying from ~ 18 – 35 V (**Fig. 3.7**). Figures further show sudden dips in voltage values, duration of these sudden dip in voltage and the way they occur can be correlated with the actual welding process. Detailed explanation of these oscillograms will be provided in the next chapter. It may also be noticed that there is change in the signal with change in rate of sampling (acquisition rate).

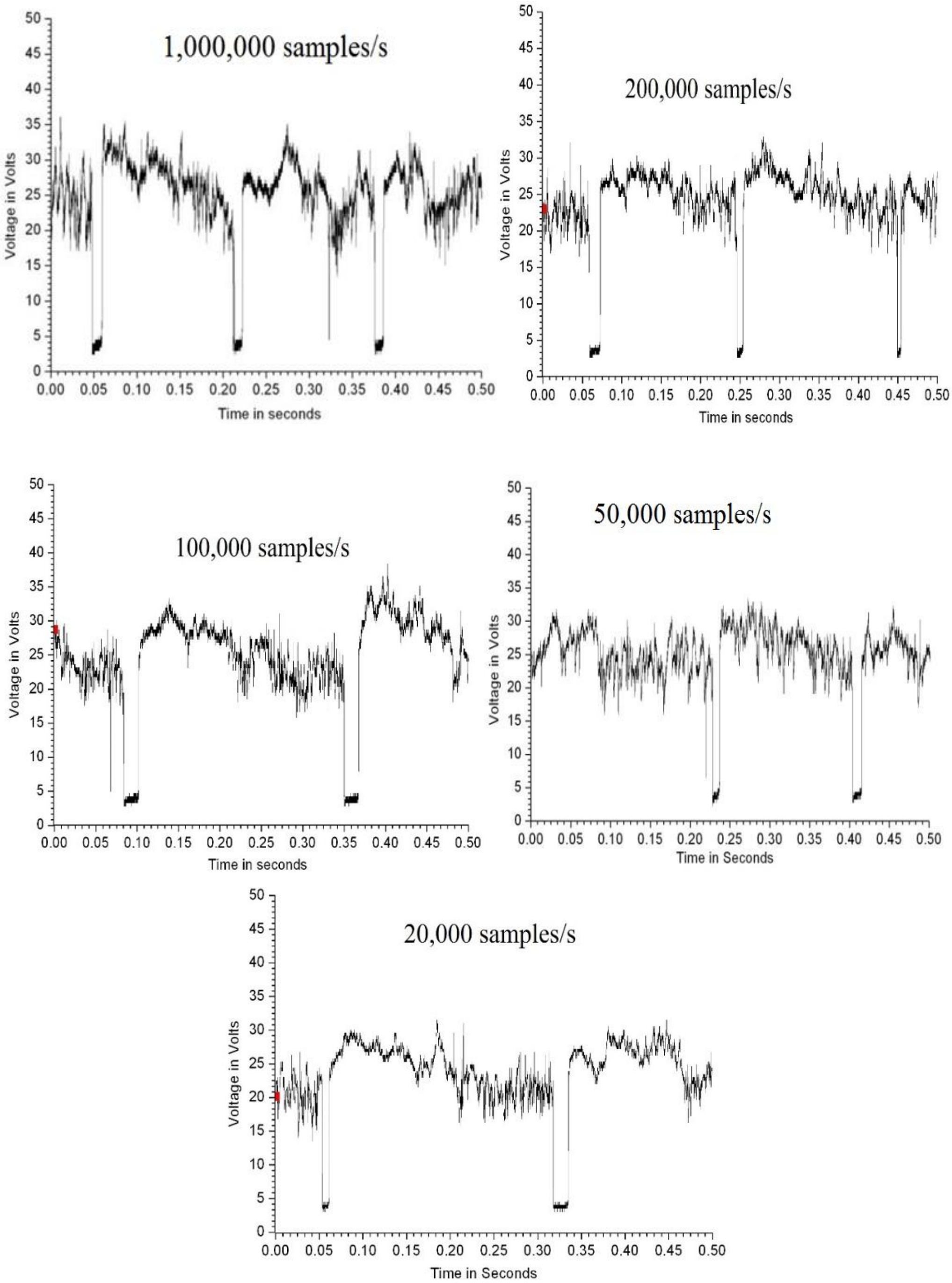
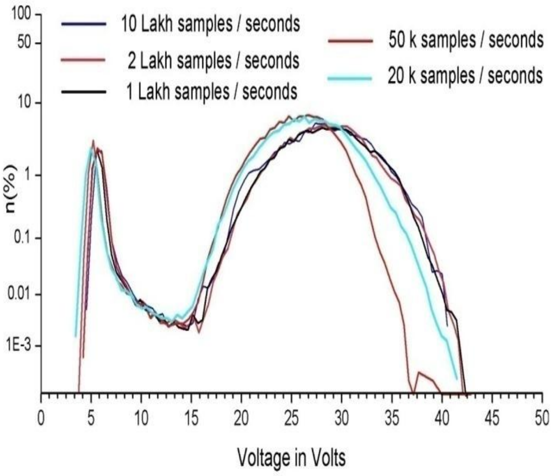


Fig. 3.7: Time domain analysis of welding voltage acquired at different acquisition rates.

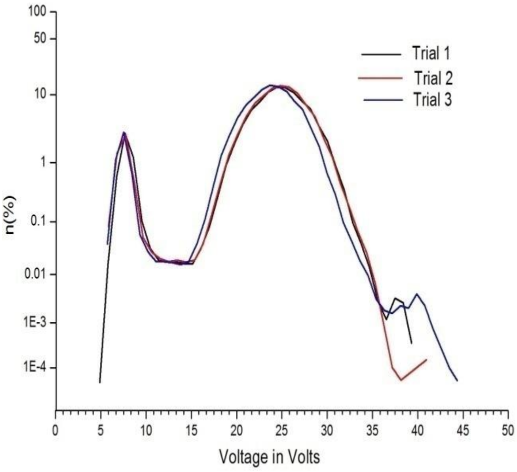
3.3.2 Statistical analysis (Probability Density Distribution (PDD analysis))

Though data was acquired thrice for each trial, and each acquisition was carried out for duration of 20 s each, only 500 ms data from one of the three acquisitions is used for time domain analysis. PDD analysis [**3-8**] enables us to use the entire data acquired for the 20 s to study the arc welding processes. PDD is the plot of the percentage of the total data acquired for each of the discrete values. **Fig. 3.8(b)** represents typical PDD plot using basic type E7018 electrode. From figure, it is seen that voltage PDD for the weld made by E7018 electrode has two distinct peaks, one at the low voltage and the other at the high voltage. First peak in this PDD corresponds to sudden voltage dips noticed in the time domain analysis of voltage signals (**Fig. 3.7),** whereas the second peak in the voltage PDD corresponds to the steady state voltage value (recorded value of ~25 V).

Rate of weld data acquisition is extremely important as acquisition of data at a speed lower than that of the actual events occur during welding would result in modification of the actual signals. Hence, this data acquisition rate should be sufficiently high compared to variations taking place in actual process. Hence, to arrive at appropriate data acquisition rate voltage data was acquired at various rates to collect different quantum of data. This in turn was analyzed using time domain and PDD curve. It should be noted that current data was not utilized for this purpose because the SMAW process essentially utilizes CC type of power source in which only voltage variations will be significant. From the time domain analysis of voltage data (**Fig. 3.7**), acquired at different rates, effect of sampling rate can be noticed. However, from the PDD analysis of voltage data in **Fig. 3.8 (a)** influence of data acquisition rate can be clearly seen. From this figure it is clear that voltage PDD attains saturation after around 100,000 samples/s. This means that above this acquisition rate further increase in data sampling rate is not making much difference in the acquired data. Consequently, 100,000 samples/s is chosen as a standard data acquisition rate for weld parameter analysis. To show the repeatability of acquired data, three trials from each acquisition rate was performed and analyzed. It was found that data was repeatable for a particular acquisition rate. The fact just presented can be understood by observing **Fig. 3.8(b)** where all the three trials of voltage PDD acquired at 100,000samples/s shows excellent repeatability.



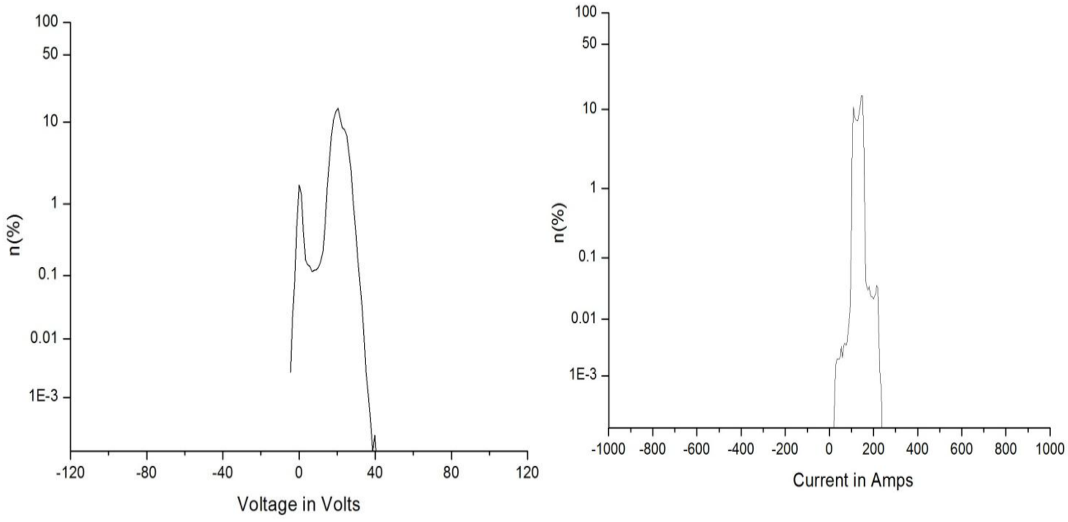
(a) PDD with varying acquisition rates.



(b) Three trials of PDD at 100,000 samples/s.

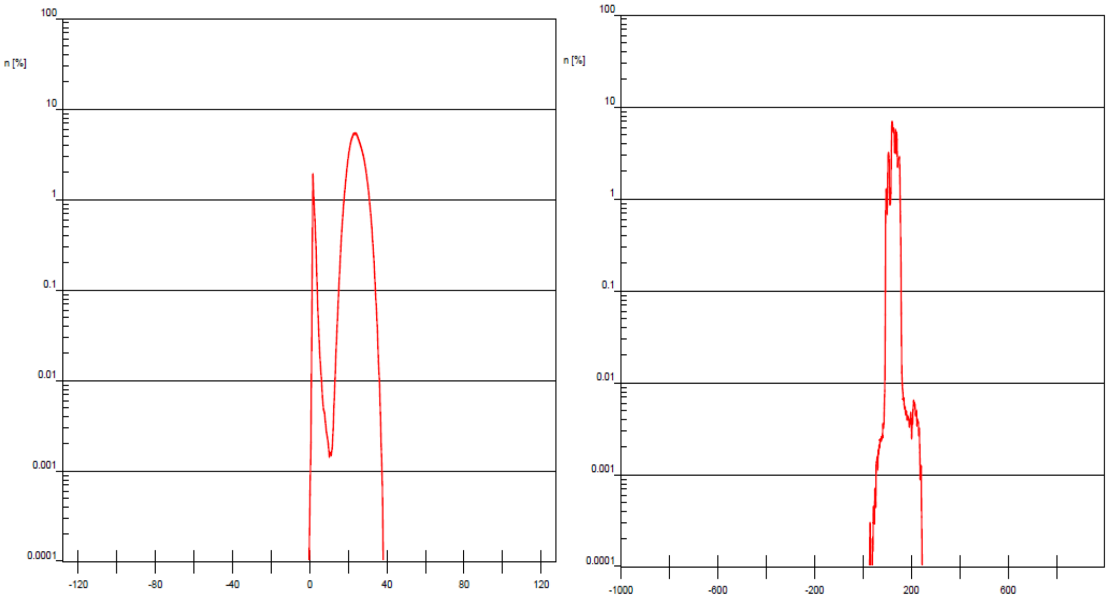
Fig. 3.8: PDD analysis of voltage data.

PDD analysis of the voltage and current data obtained using DSO (in **Fig. 3.9**) were compared with the PDD of the voltage data acquired using analysator Hanover (in **Fig. 3.10).** For the comparison purpose these data were acquired for weld beads made using same type of electrode (E 7018), same welder and same inverter power source. Very good correlation between the PDDs obtained with DSO and the PDD obtained with analysator can be seen from these figures.



(a)Voltage PDD **(b) Current PDD**

Fig. 3.9 PDD analysis of the voltage and current data acquired using DSO.



(a)Voltage PDD **(b) Current PDD**

Fig. 3.10: PDD analysis of the voltage and current data acquired using Analysator Hanover [4].

Hence, with the exercise just presented we tried to optimize time domain and PDD techniques for our application. These techniques will be used to evaluate different welding parameters in upcoming chapters.

Summary

In this chapter it is shown that how a commercially available general purpose DSO using suitable current and voltage sensors can be used for high speed data acquisition of the arc welding process. A suitable mechanism for noise analysis in welding signals is presented and it is shown that FFT Low pass filter is appropriate for filtering the weld data. Then a technique for choosing suitable data acquisition rate was presented, and it was concluded that for faithful and reliable acquisition of welding data, data acquisition rate should be at least 100000 samples/s. Finally, PDD and time domain techniques were optimized to study various aspects of arc welding process in upcoming chapters.

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4

Evaluation of arc welding process

Procedures developed to evaluate the arc welding process and presented in detail in Chapter 3 were applied to Shielded Metal Arc Welding (SMAW) and Gas Metal Arc Welding (GMAW) and it is shown that this procedure can be used to evaluate these two processes. In the case of SMAW process, welder skill, quality of power source and quality of consumables are the factors that influence the quality of the weld joint. In case of GMAW, in addition to these factors, shielding gases employed also play a major role in deciding the final quality of the weld. Hence, it is demonstrated that the procedure developed to evaluate the arc welding process can be effectively used for evaluation of welders’ skill, performance of the power sources and differentiating different welding consumables. Effect of shielding gas composition and current on different modes of metal transfer in GMAW process is also demonstrated using this procedure. Experiments carried out using SMAW and GMAW processes to realize these objectives are explained and the results obtained are presented and discussed in this Chapter.

In the introduction chapter it is already mentioned that welding is a stochastic process in which there are dynamic variations in voltage and current while welding is in progress will takes place. For a given welding power source and welding consumables, the fluctuations observed in the voltage and current signals for different welders can be contributed to the difference in the skill level of the welders. A major cause of these fluctuations during welding is coming from the variation in the arc gap during welding, and ability of the welder to maintain a constant arc gap depends critically on the skill of the welder which improves through continuous learning. Hence, it is shown that using the voltage and current signals acquired using DSO; it is possible to monitor the progress of acquiring welding skill during training period and also to differentiate skill levels of different welders

Welding power sources are classified based on whether they are DC (direct current) or AC (alternating current) and whether it is constant current (CC) or constant voltage (CV) [**1**]. Manual welding processes like SMAW and GTAW use CC type power sources while automatic welding processes like GMAW and SAW use CV type. DC power sources are more widely used than AC power sources and these DC power sources can be generators, rectifiers or invertors and capabilities of the power sources can vary depending on the type. For example, in the case of SMAW process, for a change in arc voltage arising from the change in arc gap an inverter power source is expected to respond faster than other type of power sources to maintain the CC characteristics of the power source. It is shown that by analyzing the voltage and current signals acquired from different welding power sources while welding is being carried out using same welder and welding consumables, it is possible to differentiate the performance of different power sources and even grade them. Similarly effect of flux coating on the electrodes on arc characteristics is also demonstrated using this procedure which can in turn be used to differentiate between the performances of different type of electrodes.

In case of GMAW, shielding gases employed have significant effect on the mode of metal transfer during welding. Depending on the shielding gas and the current employed, modes of metal transfer can be short circuit, globular or spray. It is shown that the procedure developed for evaluation of the arc welding process is able to differentiate the modes of metal transfer in GMAW as a function of composition of the shielding gas and the arc welding current. It should be noted that if the higher current densities are obtained other modes of transfer (i.e pulse, streaming and streaming rotating) can also be achieved **[2]**.

4.1 Monitoring and evaluation of skill levels of welders

4.1.1 Experimental setup

Two separate studies were carried out to demonstrate the use of arc monitoring procedure to evaluate the welders' skill. First one was the usage of this procedure to monitor the progress of learning by the welder trainees during the progress of training. The second one was to grade the skill levels of a batch of welders who had just completed their training. For monitoring the progress of learning, the instantaneous values of voltage and current data were acquired while bead-on-plate welding on carbon steel is being made by the trainee welders. A Constant Current (CC) generator type power source and E 7018 (3.15 mm dia.) electrodes were used for this study. Current chosen for welding is 120 Amps and corresponding voltage displayed in the machine while making these bead-on-plate welds is ~20 volts. At a given time of acquisition three sets of data were acquired from three different beads-on-plate welds for duration of 20 s for each of the trainee welder. Data was acquired from four trainee welders at three stages of their training, initial, middle and final. Data was also collected from an experienced welder for comparison.

Although both voltage and current data has been acquired, only voltage data was used to evaluate the skill level of welders as welding voltage varies with the arc gap and maintaining uniform arc gap throughout welding depends on the skill of the welder. CC power sources are so designed that current variation that accompanies voltage fluctuation is effectively suppressed and hence, current signals are not used for the evaluation. Data was subjected to time domain and PDD analysis and the results demonstrated the progress of learning by the trainees with the progress of training. Further, at the end of the training, the bead-on- plate welds and butt welds prepared by trainees are subjected to visual and radiographic inspection respectively to assess the quality of welds and correlated with the results from the assessment of skill levels of different trainees. These results are compared with those obtained from the analysis of the voltage data.

For demonstrating the usage of this procedure to grade the skill level of welders, data was acquired from a batch of 28 welders who have completed the welder training from a training institute. Bead-on-plate welds were made by these welders on a carbon steel plate using E7018 electrodes and an inverter power sources and voltage and current data were acquired. Voltage data was subjected to time domain and statistical analysis to grade the welders based on their skill levels. Skill of the welders was assessed independently by the training institute from the dimensional measurements of the bead-on-plate and the examination of bead profile and the results were compared with those obtained from the analysis of the voltage signals.

The voltage and current data acquired was also analyzed using Self Organizing Map (SOM) technique which is a known Artificial Neural Network (ANN) technique. For this analysis only 100,000 data were used. Results thus obtained were compared with those obtained from statistical analysis. Before going to the results and practical implications of these techniques a brief description of Self-Organizing Map (SOM), the AI technique used in this study is given below.

4.1.2 SOM analysis

SOM is the one of the most popular neural network models that is used in AI techniques. While dealing with artificial neural network (ANN) model an important aspect that initially encounters is whether guidance is required for learning or not. In our application we required a technique in which little needs to be known about the characteristics of the input data, because we are dealing with data that have completely random behavior. ANN of the unsupervised learning type, such as the self-organizing map, has been used for clustering the input data and finding features characteristic to this data.

4.1.2.1 Network architecture of SOM algorithm

SOM network includes input of 'n' units (X1, 2...Xn) which is actually the length of training vectors and 'm' output units (Y1, Y2….Ym) as number of categories. Each input units are fully connected with outputs units as shown in **Fig. 4.1**.

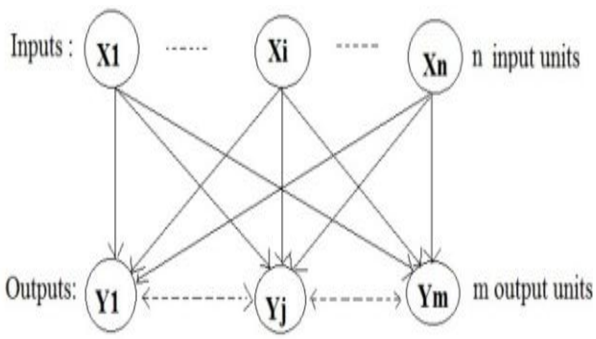


Fig. 4.1: SOM network architecture.

SOM belongs to the category of competitive learning, but it is having an organization, which means having a lattice of output neurons that can be arranged in 1, 2 or even higher dimensional space (**Fig. 4.2a**). When we feed the input patterns (**Fig.**

4.2b), these patterns acts as stimuli to randomly distributed neurons to assign random weights and organize themselves based on the statistical distribution of the input data (**Fig. 4.2c**). Weight updation will take place for all iterations in such a way that the Euclidean distance between input vector and the weight vector is minimized. Consequently, one of the neurons will emerge as winner (black dot in **Fig. 4.2**). Due to the weight adjustment, winning neuron will move closer to input lattice and hence is indicative of statistics of input distribution.

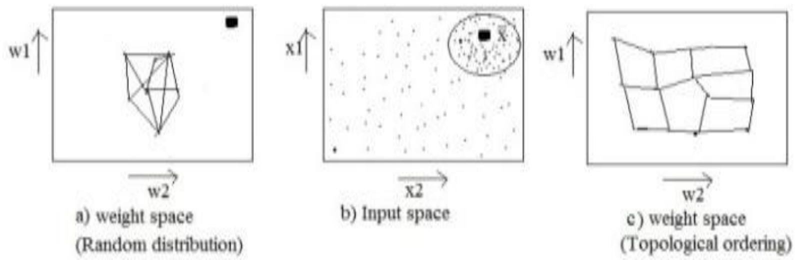


Fig. 4.2: Topological ordering in SOM.

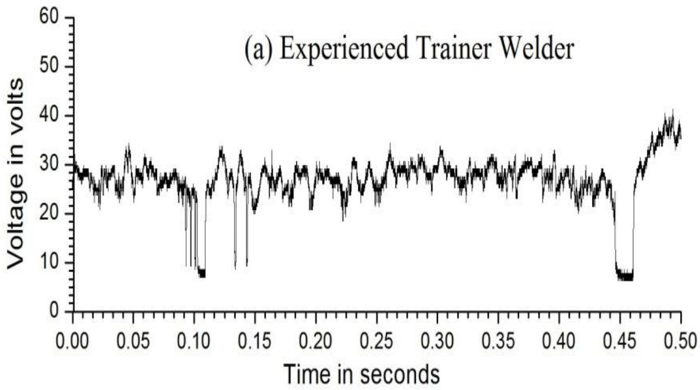
This property perfectly suits the application of grading the skill of welders and quality of different power sources, as a good welder can maintain a stable arc gap, consequently data obtained will be such that more data will be accumulated near the steady arc voltage. Hence, position of winning neuron can easily reflect the skill of the welders. Description of SOM Algorithm is given in **Appendix A**.

4.1.3 Monitoring the progress of learning of welding skill

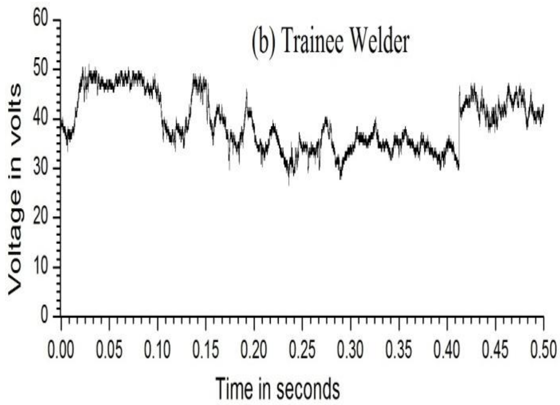
4.1.3.1 Time domain analysis

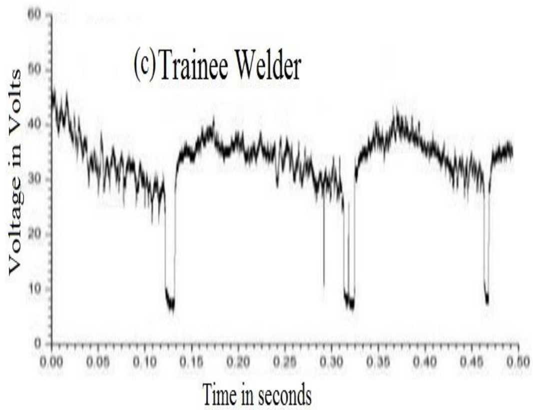
Fig. 4.3 shows the variation in voltage recorded as a function of time for 500 ms (time domain analysis) for an experienced welder in **Fig. 4.3(a)** and a trainee welder at the early stage of training in **Fig. 4.3(b)** and at the end of the training in **Fig. 4.3(c)**. Time domain analysis of these figures reveals steady state voltage and frequent drops from the steady state. Drops in voltage corresponds to metal transfer from the electrode to the molten weld pool by short circuiting mode, which is the major mode of metal transfer while welding with E7018 electrode.

A comparison of **Fig. 4.3(a)** and **Fig. 4.3(b,c)** reveals that voltage fluctuation is more for the trainee welder than for the experienced welder. At the time of joining in **Fig. 4.3(b)** trainee welder was finding it difficult to maintain a stable arc gap and hence the large fluctuations in the voltage were noticed. As the training progressed**,** voltage fluctuations in the time domain analysis for trainee welder gets reduced **(Fig. 4.3(c))**. This means that towards the end of the training trainee welder learned how to maintain a steady state welding.



(a) Time domain analysis of skilled welder





(b) During initial stages of training **(c) Towards the final stages of training**

Fig. 4.3: Time domain analysis of Skilled (Trainer) and less skilled (Trainee) welder.

4.1.3.2 PDD Analysis

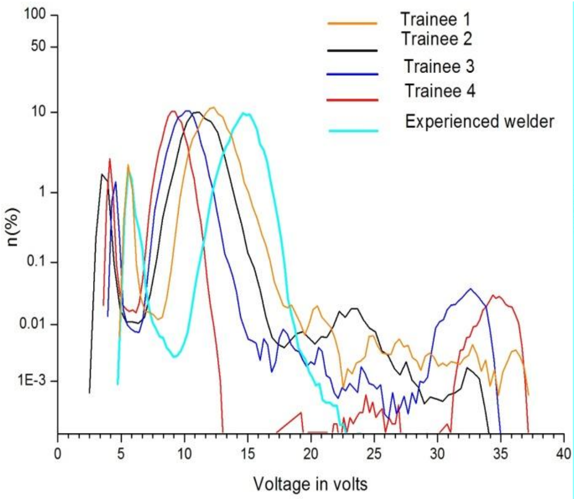
As already mentioned in **chapter 3**, voltage PDD in **Fig. 3.8** for the weld made by E7018 electrode has two distinct peaks, one at the low voltage and the other at the high voltage, the latter corresponding to the average voltage displayed by the voltmeter in the welding power source and this is equivalent to the steady state condition as shown by the time domain analysis. The low voltage peak corresponds to short circuit metal transfer that takes place for E7018 electrode. Hence, for a good weld made by E 7018, voltage PDD should have two distinct peaks, a sharp low voltage one that corresponds to short circuit transfer and a broad high voltage one corresponding to the steady state condition. Now the voltage PDDs generated for trainee welders at different stages of their learning can be compared with this PDD to monitor progress of their learning.

Fig. 4.4(a) shows PDD analysis of four trainee welders at the time of their joining along with the PDD of the experienced welder. These PDDs of the trainee welders are different from that of the experienced welder with difference between two peaks significantly less in the latter than in the former. Further, there is large number of random variations recorded at high voltages. These differences can be attributed to lack of skill in the case of trainee welders when compared with that of an experienced welder.

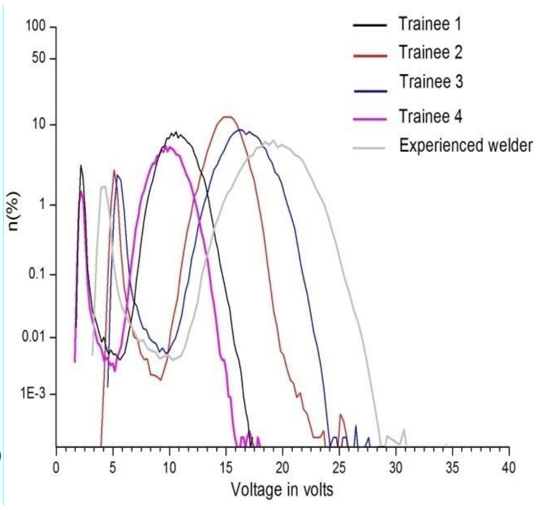
Fig. 4.4(b) shows the PDD of trainee welders during intermediate stage of their training along with PDD of an experienced welder. A comparison of this figure with **Fig. 4.4(a)** reveals significant improvement in the PDDs of all the trainee welders and these PDDs are more similar to that of the experienced welder than before. High voltage fluctuation reduced considerably which means that the ability of the welder to maintain stable arc gap has improved.

Fig. 4.4(c) shows the PDD of trainee welder at the end their training along with the PDD of the experienced welder. Further improvement is noticed as PDDs of all the trainee welders are now similar to that of the experienced welder; two peaks in each PDD can be clearly differentiated and high voltage signals reduced considerably. This clearly indicates that the progress of learning of the welders can be monitored by looking at the PDDs generated from the voltage signals acquired during different stages of the training of the welders. In fact, one can even conclude that the trainee welder whose voltage PDD that matches closely with that of the experienced welder is more skilled than the other trainees. Accordingly, from **Fig. 4.4(c)**, one can assume that trainee welder 3 is more skilled than other trainee welders. Welder 1 is less skilled than the others at the end of the training.

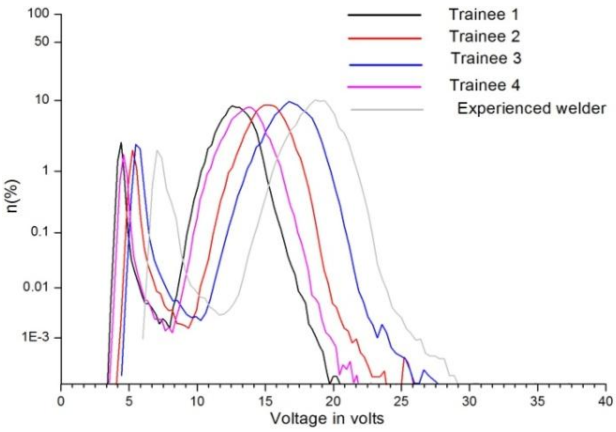
If the assumption that trainee welder 3 is more skilled and trainee welder 1 is less skilled than other trainees at the end of the training is valid, then it should be reflected in the quality of the welds produced by them. In order to confirm this, bead-on-plate welds by them at the end of their training was compared. Similarly, radiographs of the butt welds made by them were also compared.



(a) During their joining

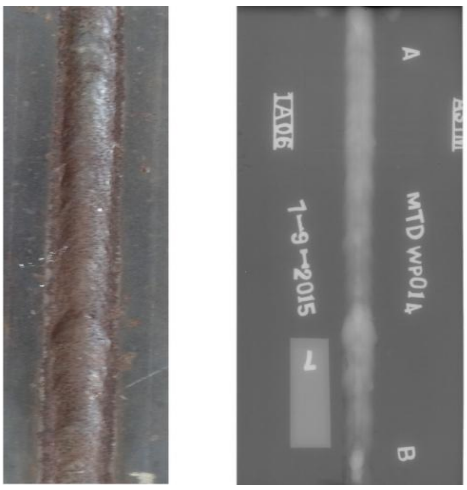


(b) During intermediate stage of their training



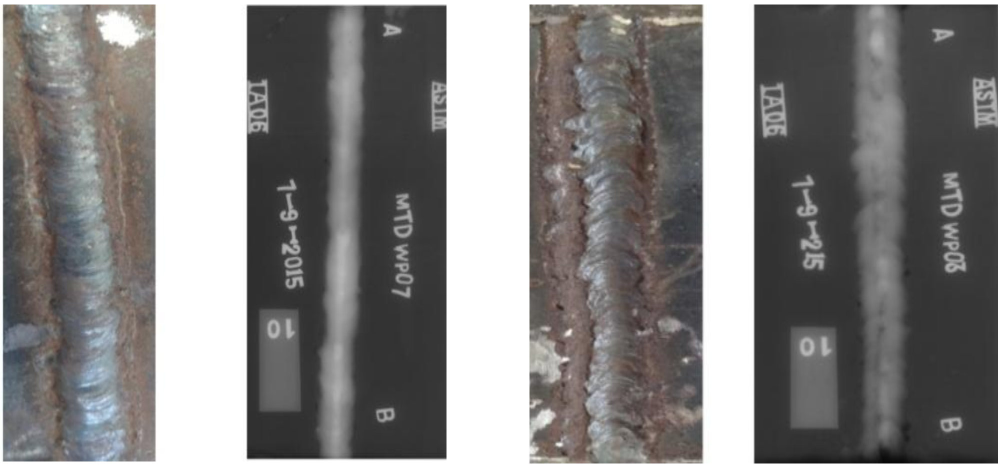
(c) At the end of their training

Fig. 4.4: PDDs of trainees during different stages of training.



Trainee 3

Trainee 2



Trainee 4 **Trainee 1**

Fig. 4.5: Bead images of weld pad and corresponding radiograph image (arranged in decreasing order of their quality).

Fig. 4.5 shows the photographs of the bead-on-plate welds made by the trainees and digital images of the radiographs of the butt welds produced by these trainees. From the straightness and uniform width of the bead and minimum spatter around the weld, the bead on plate weld produced by the trainee welder 3 is the best and that produced by trainee welder 1 is the worst. Similarly welding defects revealed in the radiography of the welds are minimum in the butt welds produced by the trainee welder 3 and maximum in that of the trainee welder 1. These results are in agreement with the conclusions drawn from the PDD analysis of the voltage signal.

From the results presented above one aspect is clear; for a good weld made of E7018, two peaks in voltage PDD will be widely separated with fraction of voltage values recorded in between the two peaks significantly low. Further, fraction of voltage recorded significantly above the second peak shall also be negligible.

4.1.4 Skill assessment of welders

PDD analysis presented above clearly showed that statistical techniques can be used to monitor the progress of learning by trainee welders. Though it is shown that one could even differentiate the skill levels of different welders, data from only four welders is too small to prove this aspect. Hence, to evaluate the skill of the welders, PDD analysis was carried out on data collected from 28 welders who were passing out from a welding skill training institute**.** **Fig. 4.6** shows PDD generated for the welders ranked 1-4 and 25-28 among the 28 welders who participated in this exercise. The welder who produced a weld having its voltage PDD with two peaks most widely separated and having minimum fraction of random voltages higher than that of the second peak is taken as the most skilled one while the one who produced a weld with minimum separation between the two peaks is taken as the least skilled.

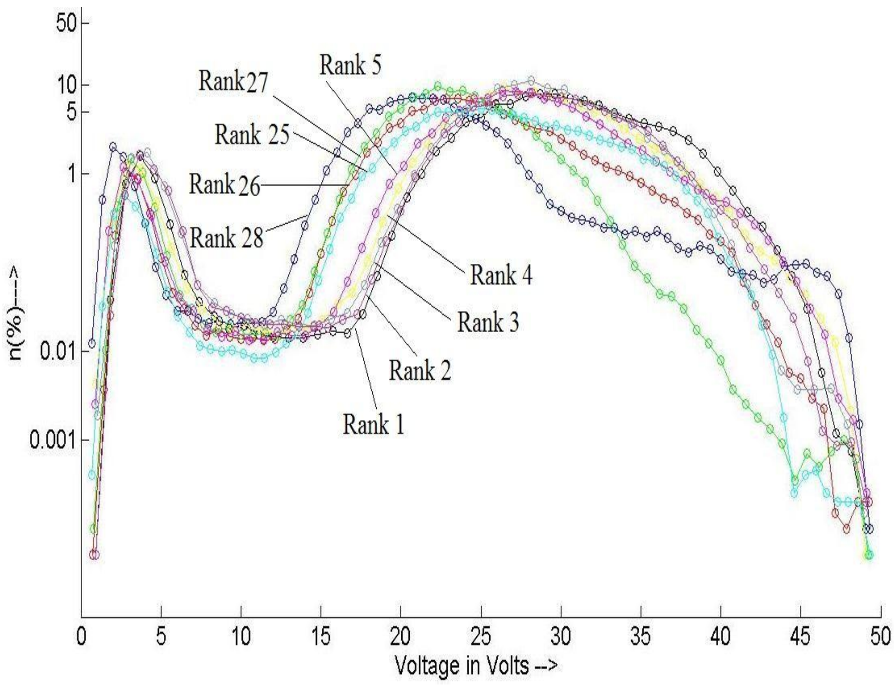
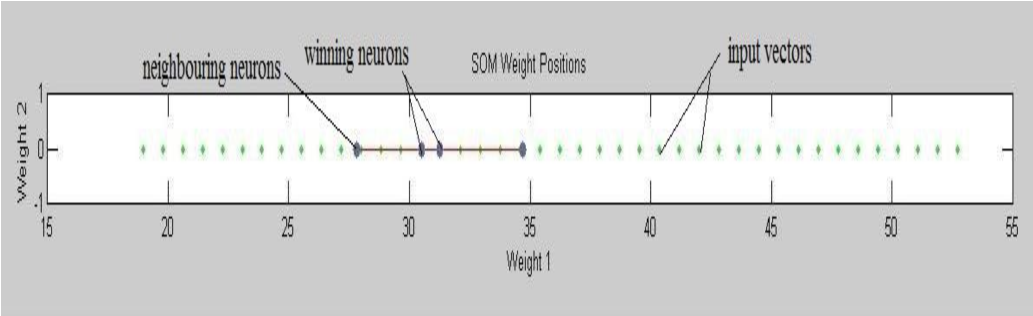


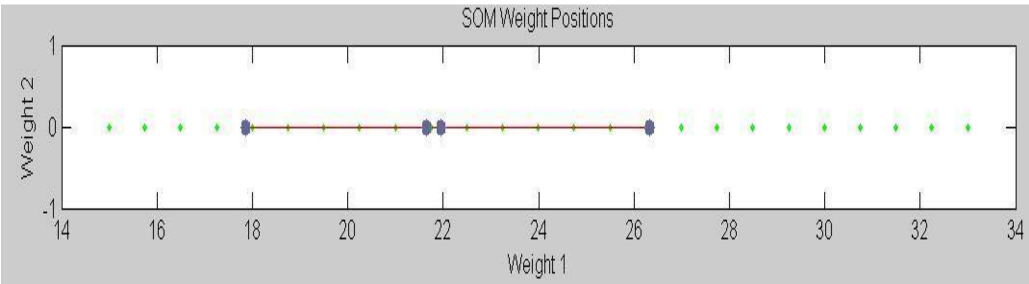
Fig. 4.6: PDD analysis of various welders' data from skill training institute.

4.1.5 SOM analysis for progress of learning and evaluation of welding skill

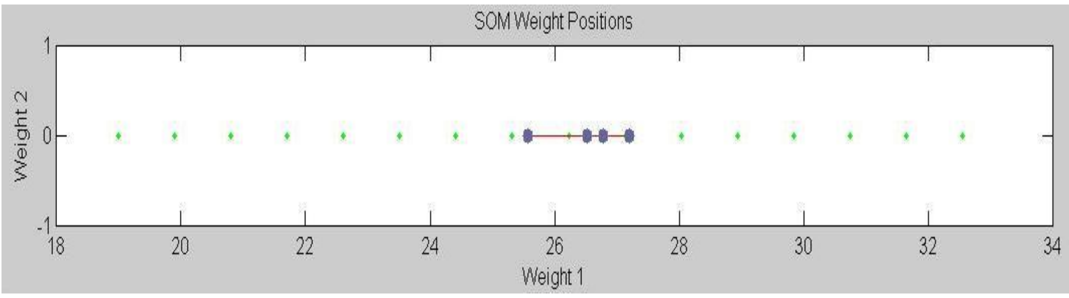
SOM analysis was applied on data acquired while monitoring the progress of learning and also on data acquired to evaluate the skill level of batch of welders who completed the welder training. **Fig.4.7** shows the results of the SOM analysis for monitoring the progress of learning; in this the input vectors are represented as green dots and SOM classifies the input space by showing blue dots for each neurons weight vector which are connected by neighboring neurons with red lines. In order to reduce the processing time for analysis, only 100,000 data was used for the analysis, not the entire data acquired for one bead on plate weld. In the Figure weight 1 is the voltage value whereas weight 2 refers to random weight assigned by SOM Algorithm. The winning and neighboring neurons can be seen as they are connected to each other with red line. In each case winning neuron tries to adjust its value near to the average voltage recorded during welding, which is nothing but the classification of the input data based on the clustering mechanism. Skill of a welder depends upon his ability to maintain a stable arc gap which ultimately leads to stable arc voltage. For a skilled welder, variation in arc gap and consequently the variation in arc voltage will be less. Hence, large number of input data points will accumulate near the voltage displayed by the power source which in turn depends on the set current. As we can clearly observe from **Fig. 4.7**, initially for a trainee welder (one of the trainee welder from the welding workshop whose analysis is shown in **Fig. 4.4**) the voltage value corresponding to winning neuron deviates from recorded value of 25V by 6V. As he undergoes training his performance improved. Consequently, the deviation from recorded value in SOM analysis has decreased, finally at the end of training this deviation was very less (~1 V), which is the indicative of the fact that welder's skill increases with training. Hence, using SOM analysis of the data acquired by DSO, it is possible to monitor the progress of learning of welders who undergoes training.



(a) SOM analysis at the time of Joining.



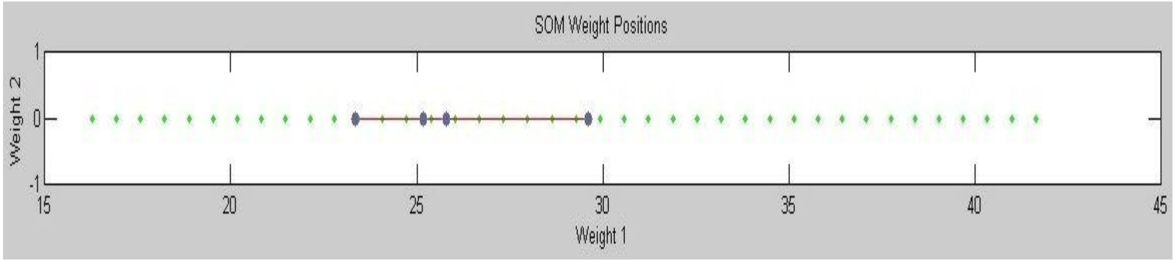
(b) SOM analysis at intermediate stage.



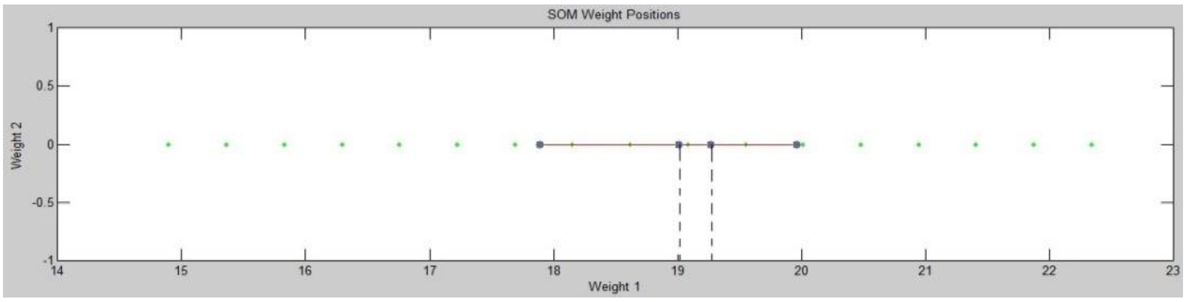
(c) SOM analysis at the end of the training.

Fig. 4.7: SOM analysis of a trainee welder at three different stages.

From the SOM analysis carried out for assessing the skill level of 28 welders from a training institute, results of welder ranked 1 and welder ranked last based on PDD analysis (in **Fig. 4.4**) are shown in **Fig. 4.8** It may be noted that the winning neurons for the welder ranked 1 is close to the voltage displayed (25 V) on the welding power source while for the welder with least skill it is far away from the displayed voltage.



(a) SOM analysis of welder ranked 1



(b) SOM analysis of welder ranked 28

Fig. 4.8: SOM analysis of welder's data obtained from skill training institute.

Consequently, based on the extent the deviation of winning neuron from the recorded voltage value, skill level of the entire 28 trainee welders from the skill training institute were graded using SOM analysis. Gradings thus obtained using PDD and SOM analysis are compared with the independent ranking provided by skill training institute in following section.

4.1.6 Comparison of the ranking of welders' skill

In order to confirm the ranking of the skill of welders by PDD and SOM techniques, the results were compared with ranking provided by the skill training institute where these welders had undergone training. The procedure adopted by skill training institute to grade the welder's skill involves measuring the straightness and bead width across the length of the welds (**Fig. 4.9**).

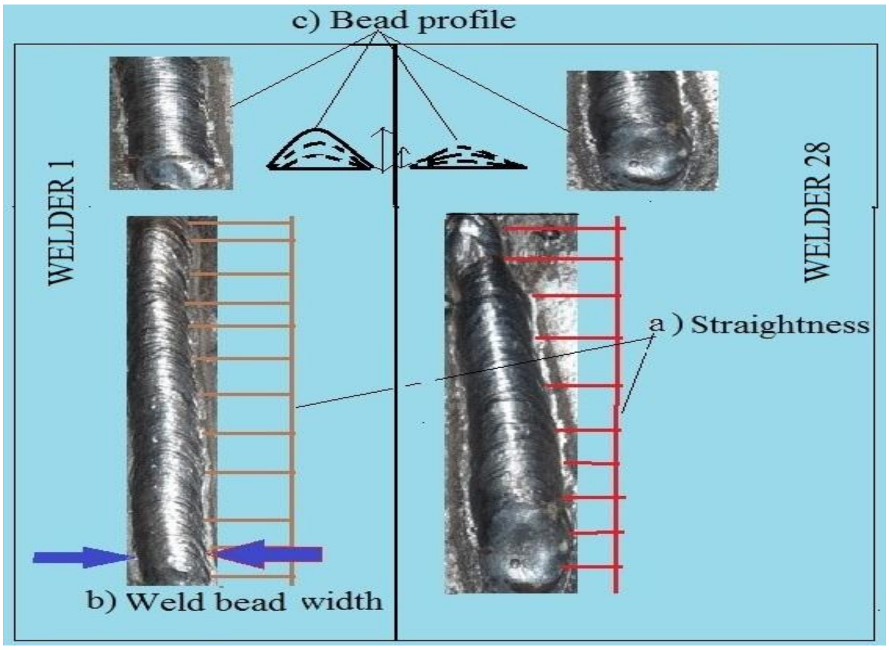


Fig. 4.9: Technique adopted by skill training institute for grading welding skill.

Weld profile is also checked for the convexity. Ranking given by the training institute based on these parameters is compared with the ranking obtained from PDD and SOM analyses (**Table 4.1**) respectively. Only in the case of Welder13 and Welder 17, the ranking arrived at by PDD analysis differed significantly that of the training institute. For SOM analysis ranking differed significantly from that of the welding institute for the welder 13, welder 17, welder 22 and welder 27. However, as a whole correlation between the current practice and the proposed procedure are reasonably good with PDD analysis giving better results than the SOM analysis.

Table 4.1: Comparison of ranking done by SOM and PDD with respect to existing practice.

	Ranking by PDD analysis	**Ranking by Current practice**	**Ranking by SOM analysis**
Welder 1	4	4	5
Welder 2	2	2	1

Welder 3	20	22	21
Welder 4	25	28	26
Welder 5	8	10	11
Welder 6	18	21	13
Welder 7	27	28	27
Welder 8	9	8	8
Welder 9	7	9	10
Welder 10	6	7	7
Welder 11	23	23	23
Welder 12	21	20	20
Welder 13	22	27	4
Welder 14	19	19	19
Welder 15	14	6	6
Welder 16	26	24	22
Welder 17	17	18	24
Welder 18	1	1	2
Welder 19	3	3	3
Welder 20	10	12	14
Welder 21	13	14	17
Welder 22	12	13	18
Welder 23	24	25	25

Welder 24	15	15	15
Welder 25	16	16	12
Welder 26	5	5	5
Welder 27	11	11	16
Welder 28	28	28	27

Results just presented here clearly show that high speed data acquisition during welding and subsequent analysis of this data can be used effectively both to monitor progress of learning and assessment of the skill for welding. In fact, this can be developed as an alternative or complimentary to the current practice of monitoring the training or for evaluating the skill of the welder. At present skill of the welders is evaluated either by inspecting the weld using non-destructive techniques or by testing of welds by destructive testing. As already mentioned, these are time consuming, expensive and can be carried out only after completion of preparation of the weld. In contrast, using the procedure presented here, one can evaluate the skill of the welders as soon as welder makes a weld bead from the welding data acquired using a data acquisition system and subsequent analysis. Further, progress of learning of a trainee welder can be monitored almost continuously using this procedure and this can in turn help in altering the training schedule depending on the ability of the trainee to learn the skill. Trainees can see their learning progress which makes learning more interesting to them. A trainee with better skill set can learn fast and another who is slow to learn can be given more attention by trainers. There could be a permanent record of the training which could be used during recruitment drives and assessment. One can also use PDD or SOM analysis for screening out unskilled welders from skilled during recruitment drives of large number of welders. This procedure can also be effectively used to short listing candidates during recruitment drives in which large number applications have to be handled in a short time.

At present there is a lot of interest on skill development throughout the world and welding is one of the major skills identified by various industrial sectors. Hence, a cost effective and reliable procedure for monitoring training and assessment of welding skill presented here would complement the efforts of developing skilled welders as envisaged by skill development initiative across the world.

4.2 Evaluation of welding power sources

4.2.1 Experimental setup

In order to demonstrate that the procedure presented here is able to differentiate the performance of different power sources, instantaneous values of voltage and current data from six different power sources were acquired while welding is in progress. For this purpose, bead-on-plate welding was carried out using E 8018 electrodes of 3.15 mm diameter on a carbon steel plate of dimensions 12x300x300 mm using these power sources by the same welder. During welding, voltage and current signals were acquired at a sampling rate of 100,000 samples/s for 20 s using DSO. To ensure consistency of the data, three bead-on-plate welds were made using each power source and data was acquired for all the three welds. Data was subsequently filtered and then subjected to time domain and statistical analysis. Among all the six power sources that has been used in present study two of them were rectifier power source (Machine 1 and Machine 2), one was generator power source (machine 3) and remaining three (Machine 4, Machine 5 and Machine 6) were Inverter power sources. Among the invertors, machine 6 can be operated as both in constant current and constant voltage mode so that it can be used for SMAW and GMAW while all others can be used only in constant current mode.

4.2.2 Time domain analysis.

Voltage and current oscillograms obtained for the rectifier power sources, while making bead-on-plate weld using E 8018 electrode are shown in **Fig. 4.10**. They consist of a steady state condition with random dip in voltage with corresponding change in current. It is evident from **Fig 4.10** that even in the steady state condition there is significant variation in the current and this variation is more in machine 2 than in machine 1. The sharp reduction observed in the voltage in both oscillogram correspond to short circuit metal transfer, which takes place in basic coated electrodes of the type E8018 used in the present study. However, response of current to this voltage reduction is different in both the power sources. In the machine 1, for the voltage drop observed there is corresponding increase in current, while in machine 2, there is a drop in current. This clearly shows the circuits in the two power sources employed to suppress the current surge that accompany short circuit metal transfer in welding are different and the time domain analysis of the acquired data is able to reveal this clearly.

Fig. 4.11 shows the time domain analysis for machine 3 which is a generator power source. The current variation in the steady state condition of the arc is similar that observed in the rectifier power source machine 1; but during voltage drop corresponding to short circuit transfer, there is a sharp increase in current. This rate of this sharp rise in the current is basically controlled by the inductance coil present in these types of machines which can be easily controlled using software programming **[3]**. The current travelling through an inductance coil creates a magnetic field. This magnetic field creates a current in the welding circuit that is in opposition to the welding current. Increasing the inductance will also increase the arc time and decrease the frequency of short-circuiting.

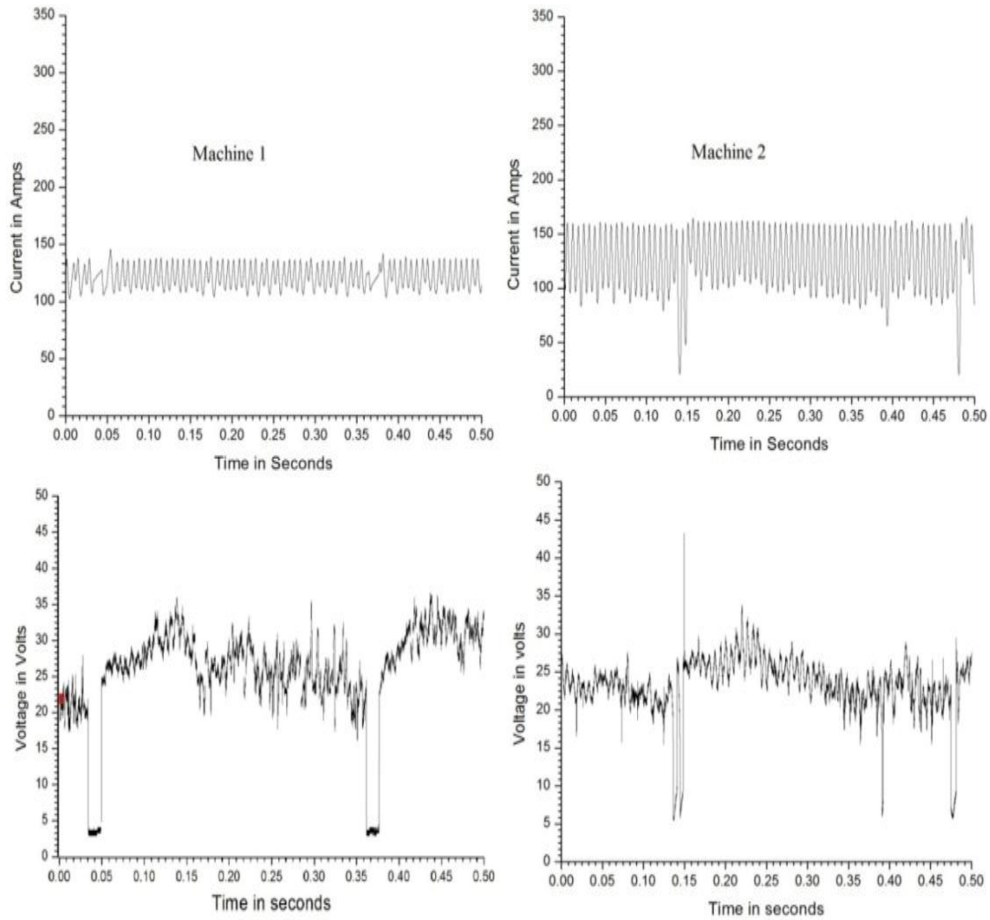


Fig. 4.10: Time domain analysis of voltage and current data obtained from different rectifier power sources.

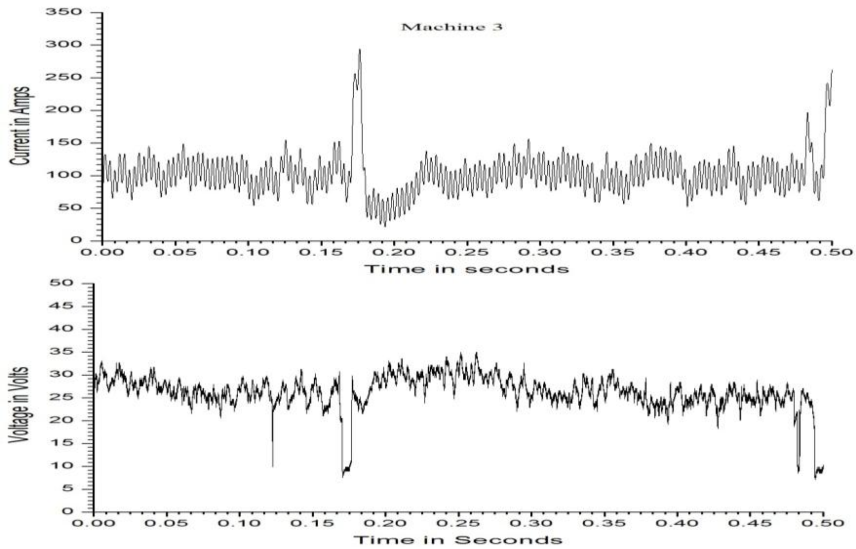
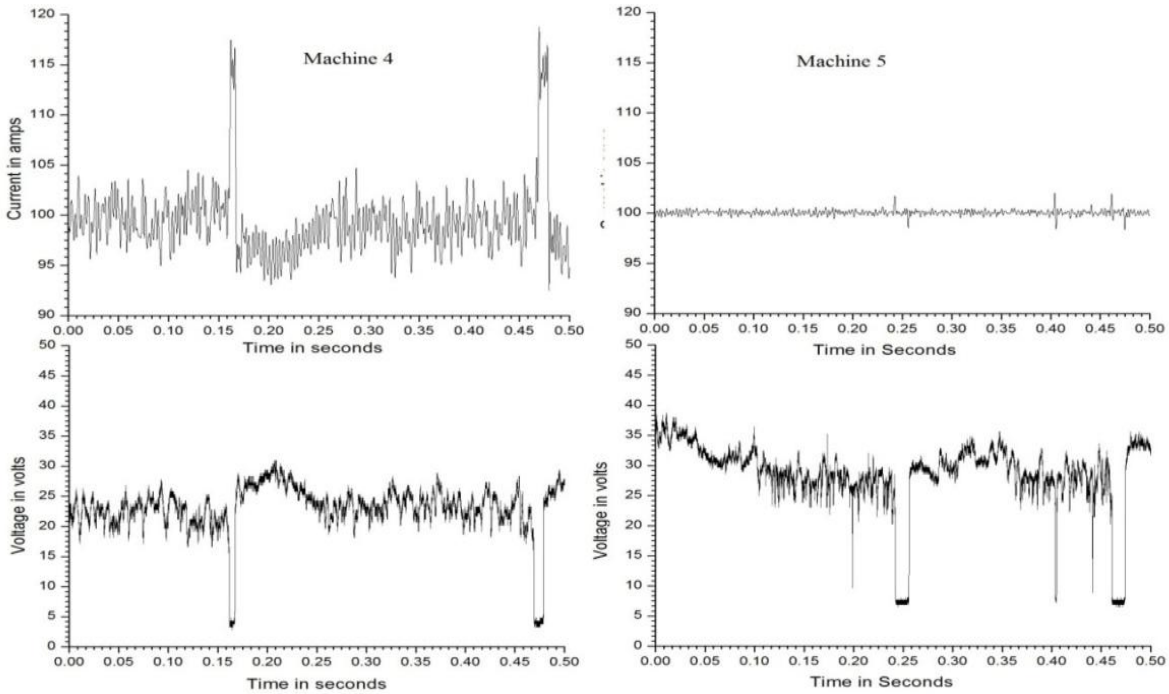


Fig. 4.11: Time domain analysis of voltage and current data obtained from a generator power source.

Fig. 4.12 shows time domain analysis of both voltage and current signal for three different inverter power sources (machine 4, machine 5 and machine 6). As the current variation in inverter power source is considerably lower than that in other power sources, range of current in y-axis is much smaller than in **Fig. 4.10** and **Fig. 4.11**.



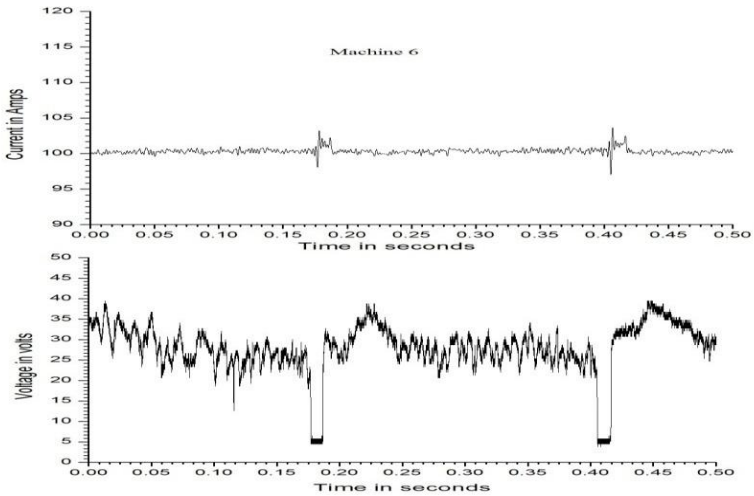


Fig. 4.12: Time domain analysis of voltage and current data from different inverter power sources.

A comparison of the current oscillograms for three different invertors shows that they are significantly different and for machine 4, the current variation during steady state is considerably higher than in the other two. Further, current increase corresponding to voltage decrease associated with short circuit transfer is also high in machine 4. For machine 5, the current variation recorded during short circuit transfer is as low as 3 A and the response time for the current to return to the set value is short indicating this power source is more effective in maintaining constant current (CC) characteristic of the power sources than other power sources.

Thus, it can be seen that the variation of current with change in arc voltage is more for rectifiers (**Fig. 4.10**) and generators (**Fig. 4.11**) than inverters. A careful comparison of all the power sources (machine 1-6 from **Fig. 4.10, 4.11 and 4.12**) it can be noticed that for inverters current variation from the set value is small (especially in machine 5 these variations are as low as ~3 A). Additionally, although Machine 4, Machine 5 and Machine 6 all are inverters, Machine 4 shows large current variations among all the inverters. Machine 6 which is another inverter shows a sudden variation in current before coming to steady state value. These variations clearly show that with the proposed technique differentiation among power sources of same type is also possible.

4.2.3 Statistical (PDD) analysis

PDD technique enabled us to grade various power sources qualitatively. Although both voltage and current data was acquired only voltage data were used for all PDD analysis. PDDs generated for voltage signals of all six power supplies are shown in **Fig. 4.13**.

While grading the skill level of various welders in the previous section, separation between the two peaks in the voltage PDD was correlated with the quality of the weld produced; the appearance of weld was better and separation of the two peaks in the voltage PDD was higher for the better skilled welders than the others. Hence, a similar criterion was adopted for grading the performance of different power sources by comparing the voltage PDDs of the welds produced using these power sources. In all the cases welding is carried out using same welder and E 8018 electrode which is also basic coated like E7018 used for evaluation of the skill level of welders. **Fig. 4.13** shows PDD generated for the Power sources ranked 1-5.

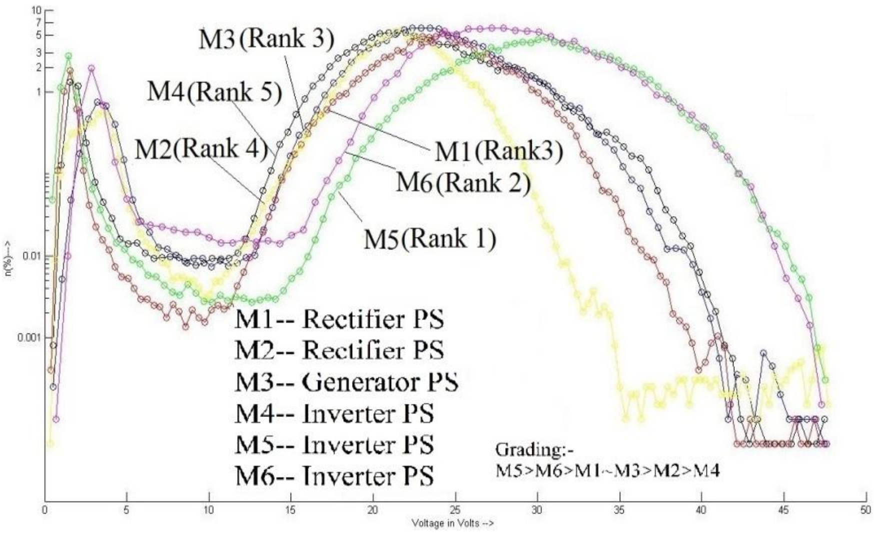


Fig. 4.13: Voltage and current PDDs of various welding power sources.

Based on the criteria mentioned above, it can be seen from **Fig. 4.13** that performance of Machine 5, an inverter power source is the best and then followed by Machine 6. It may be noted that, performance of Machine 4, which is also an inverter power source appears to be worst and ranked last as fifth. This is surprising because inverter power source is expected to perform better than other type of power sources. The performance of the generator power source and that of one of the rectifiers are almost similar and both are ranked 3 and that of the second rectifier is ranked fourth.

If grading of the performance of the power sources is correct, it is reasonable to expect that this is reflected in the appearance of the weld bead produced by these power sources. **Fig. 4.14** shows the photographs of the weld beads produced by all these six power sources with an increasing order of weld bead appearance. It is clear that the appearance of the weld bead made by Machine 4, which is ranked last, is the worst among all. Similarly, weld bead for machine 5, which is ranked 1 is smooth and uniform, so is that of machine 6 which is ranked 2. Appearance of the weld beads produced by the other power sources fall in between in accordance with the grading given based on the appearance of the PDDs.

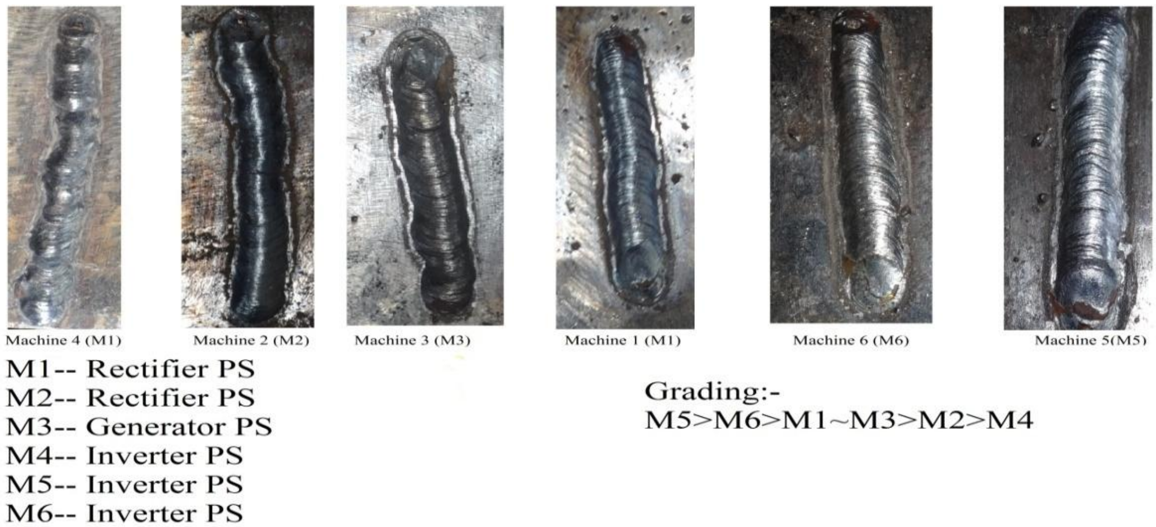


Fig. 4.14: Weld beads obtained by welding from various power sources.

Thus from the results presented above it is clear that the procedure involving high speed data acquisition using a DSO and subsequent analysis of the data is able to clearly differentiate between different welding power sources. The significant fact is that not only power sources of different types, but also different power sources of the same type can be differentiated using this procedure. Practical implications of this are significant. By a simple procedure, it is possible to choose the best one from a large number of choices available. It is also possible to use this technique to monitor the performance of a power source over a period of time.

4.3 Comparison of welding consumables

4.3.1 Experimental setup

For comparing different welding consumables and to show that the procedure developed in this study can be used to differentiate the arc characteristics of different electrodes data was acquired while welding using basic coated, rutile coated and cellulose coated electrode and analyzed. Bead-on-plate welds were made using an inverter power source and E7018 (basic coated), E6013 (rutile coated) and E6010 (cellulose coated) electrodes on carbon steel plates by the same welder. Diameter of the electrodes employed for welding was 3.15 for the first two while the cellulose electrode was of 2.5 mm diameter. Constant current of 100A was set for E 7018 and E 6013 type electrode whereas 50A current was set for E 6010 type of electrodes. Voltage and current signals were then acquired for 20 s of duration using DSO setup. To ensure consistency of the data, three bead-on-plate welds were made using each type of electrode and data was acquired for all the three welds. Data was subsequently filtered and then subjected to time domain and statistical analysis.

As welding is carried out for all the three types of electrodes using same welding and power source, the difference in their arc characteristics should be related to differences in the metal transfer behavior across the arc in these electrodes. Hence, this metal transfer across the arc is viewed using high speed camera with laser illumination and suitable filters. Fastcam MC2.1 photon focus was the camera used which has a maximum capturing speed of 10,000 frames per second and the minimum shutter opening time of 1/100,000s. In the current experiment images were acquired at 5000 frames/s. The camera comprises of the filtering system, macro optical system, capture board and synchronizing module. Images are acquired via camera to PC. For the 5000 frames/s the high speed camera records the last 4.094 seconds of data from a total welding duration of 20 seconds in the current experiment.

The schematic of the system configuration is shown in **Fig. 4.15.**

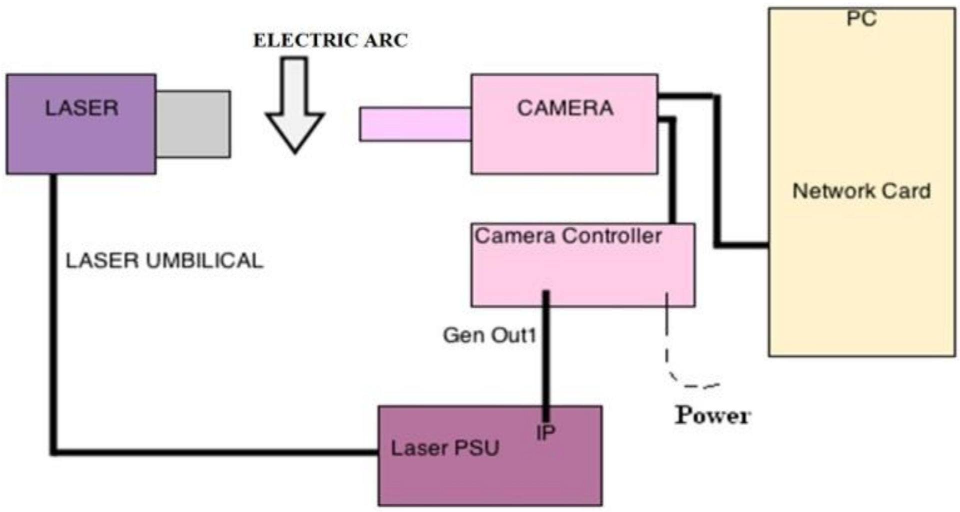


Fig. 4.15: Schematic of high speed camera assembly.

Though electrode fluxes are classified broadly as cellulose, rutile, basic etc, the exact composition of the flux can vary within the same type of flux. For example, basic coated electrode may contain some rutile to improve the arc characteristics or slag detachability. Similarly, depending on other constituents of the flux, the exact wt.

% of the major constituent of the flux can also vary. It is expected that these variations should result in changes in characteristics of the welding arc. It is demonstrated that arc data acquired using DSO is able to differentiate the differences in the arc characteristics caused by subtle changes in the flux composition. In order to demonstrate this welding data was acquired from the two sets of electrodes; one is E 7018 type electrode in which rutile content is varied from 0-7 wt.% and another is E 6013 type electrodes in which rutile content is varied from 45-55 wt.% (**Table 4.2**). Data was acquired for each of these electrodes while making bead-on-plates with 120A current and 25 V by the same welder and same power source.

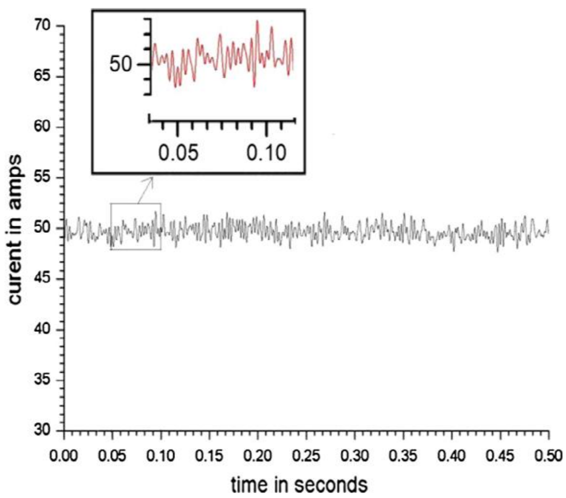
Table 4.2 Rutile content variations in E7018 and E6013 electrodes.

Electrode type	Rutile /Rutile sand variation
E 7018	nill
E 7018	3%
E 7018	7%
E 6013	45%
E 6013	50%
E 6013	55%

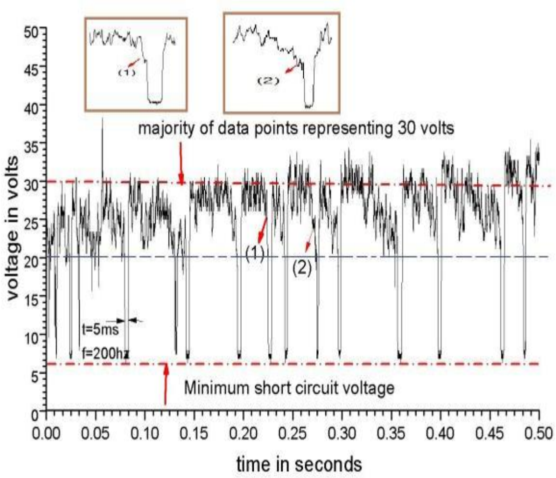
When using E7018 for welding, this electrode is used after baking at 300-350°C for 2-3 h. It is expected that arc characteristics of the baked electrode to be different from that of unbaked electrode. One set of experiment was also conducted to demonstrate that this difference in arc characteristics could also be revealed from the analysis of weld data acquired using DSO.

4.3.2 Variation in the arc characteristics of different electrodes.

Fig. 4.16 (a,b) show the current and voltage variation respectively that occur during welding using E 6010 electrode. Comparison of oscillograms shown in these figures with those of obtained using E 7018 (**Fig. 4.17)** and E 6013 (**Fig. 4.18)** reveals the differences in the arc behavior during welding using these three electrodes. For a given duration of 500 ms, more number of voltage drops (with shorter duration) occurs in E 6010 than in E 7018 and E 6013. As seen in the inset shown along with voltage oscillograms, the voltage drop is instantaneous in E 7018 and E 6013 while it is gradual in E 6010. Further, current variation is more in E 6010 than in the E 7018 and E 6013 (see insets in **Fig. 4.16**, **Fig. 4.17 and Fig. 4.18**). From these figures it can be seen that in case of E 6013 for every voltage drop there is corresponding increase in current. This was not observed in E 7018 and E 6010 electrodes. It can be clearly seen that the peak to peak variation in current for E 6013 is around 6A whereas in E 6010 and E 7018 it is around 5 A and 2 A respectively.

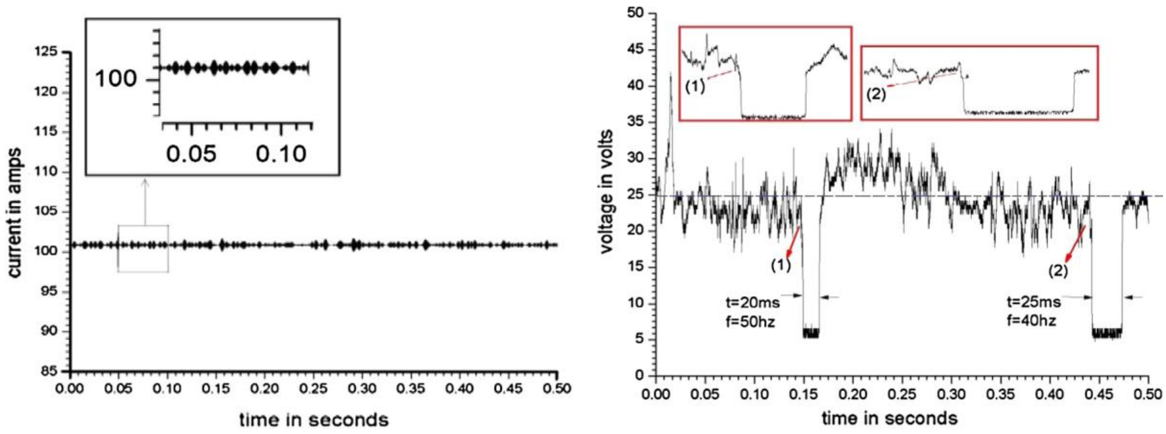


(a) Current



(b) Voltage

Fig. 4.16: Voltage and current signature pattern using E 6010 electrode and inverter power supply.



(a) Current **(b) Voltage**

Fig. 4.17: Voltage and current signature pattern using E 7018 electrode and inverter power supply.

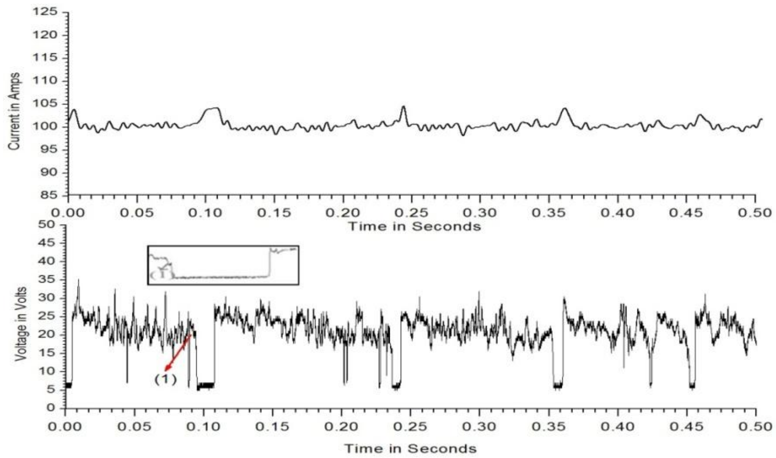
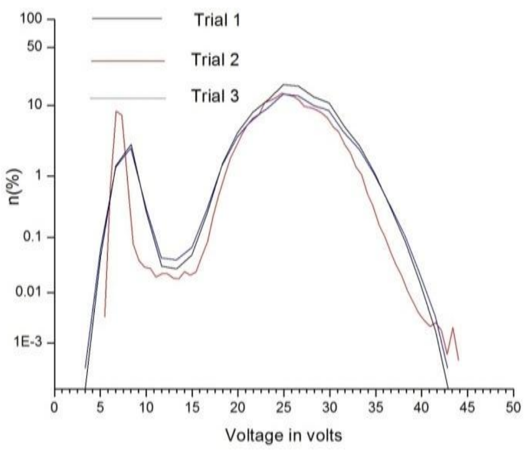
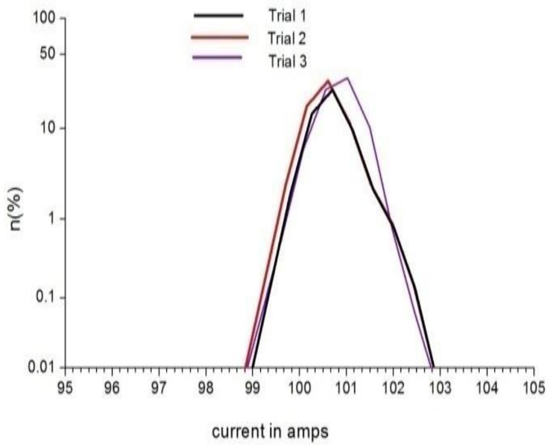


Fig. 4.18: Voltage and current signature pattern using E 6013 electrode and inverter power supply.

The PDD curves for the voltage data in **Fig. 4.19** for welds of E 7018 (though this is similar to what is already reported earlier in **Fig. 3.8** of **Chapter 3,** this is included here; for the sake of comparison with PDDs obtained for welds of different electrodes) in **Fig. 4.20** for welds of E 6013 electrode shows two distinct peaks, one at the lower voltage and the other at the voltage close to that displayed by the volt meter in the power source. The lower voltage peak is fairly sharp and other one is very broad; distributed over wide range of voltages. The low voltage peak observed in these PDDs can be explained based on the metal transfer that take place for E 7018 and E 6013 electrode during welding. In SMA welding carried out using E 7018 and E 6013, short circuit is the major mode of metal transfer [**1**] and the same can be seen in the image of metal transfer obtained using E 7018 and E 6013 electrodes and high speed camera setup in **Fig 4.21**. From this figure we can see that molten metal droplet formed initially at the tip of the electrode grows into a large drop, reducing the arc gap and often, metal transfer occur due to the short circuiting that takes place between the molten base metal and the drop at the tip of the electrode. As soon as short circuiting occurs there will be surge in current leading to a mild explosion at the electrode tip separating molten droplet from the electrode. Short circuit persists only for a few milliseconds; but occurs over and over again several times in a second resulting in metal transfer from electrode to the weld metal. Although in E 7018 and E 6013 majority of metal transfer will occur by the means of short circuit metal transfer, the droplet size in case of E 6013 was found to be larger than E 7018 (**Fig. 4.21 (a,b)**) which is in agreement with earlier reported by Haiyun et. al. [**1**]. A schematic of how variation in arc gap in these electrodes takes place during short circuit transfer is shown in **Fig. 4.22**.

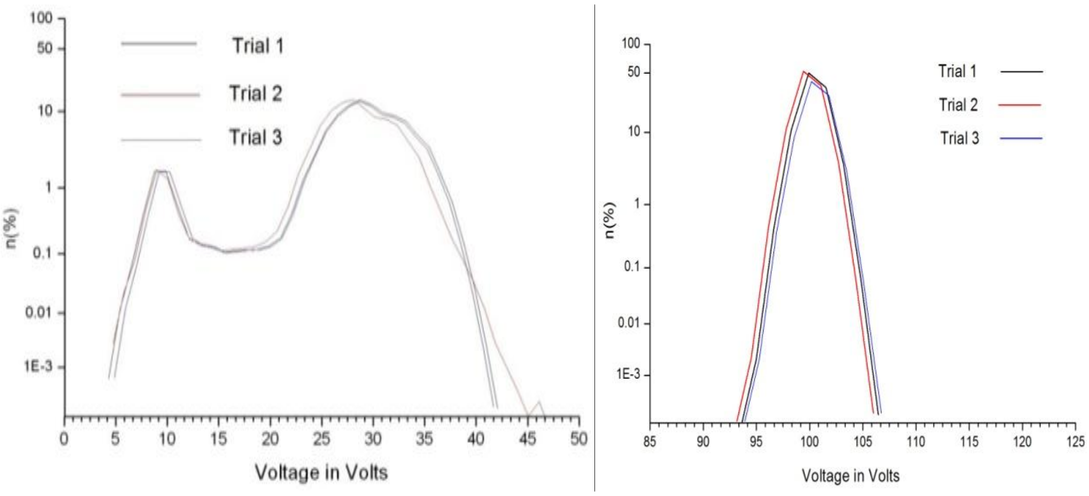


(a) Voltage



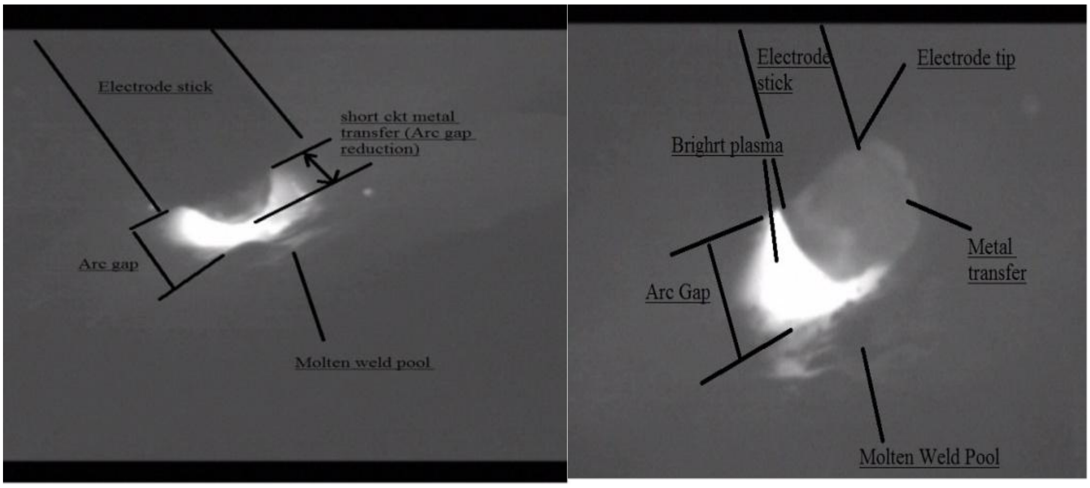
(b) Current

Fig. 4.19: PDD analysis of voltage and current for E 7018 electrode and inverter power supply.



(a) Voltage **(b) Current**

Fig. 4.20: PDD analysis of voltage and current for E 6013 electrode using inverter power supply.



(a) Short circuit transfer in E 7018 electrode **(b) Short circuit transfer in E 6013 electrode**

Fig. 4.21: Short circuit image seen with high speed camera.

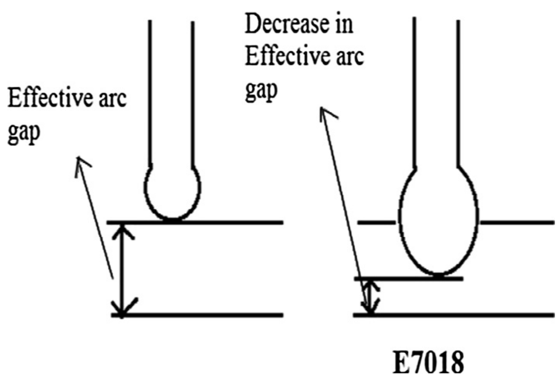
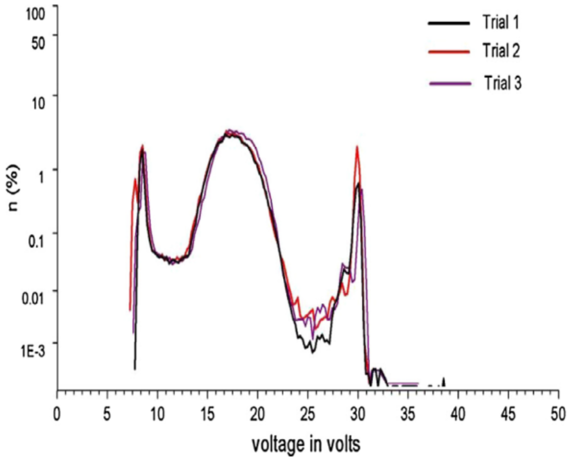
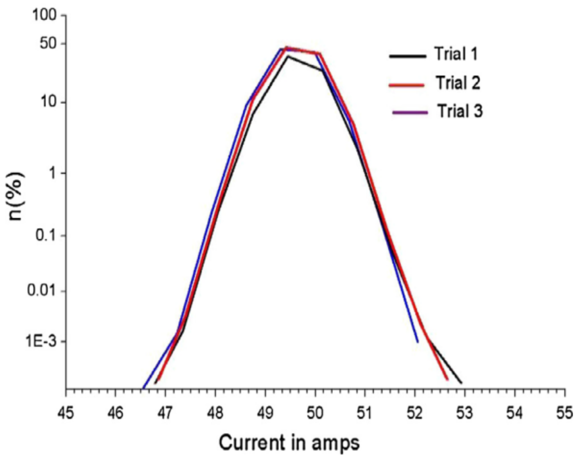


Fig. 4.22: Schematic of short circuit metal transfer in E 7018 and E 6013 electrodes.

A comparison of the voltage PDD obtained in **Fig 4.23 (a)**; using E 6010 electrode to that of PDD with that shown for E 7018 and E 6013 (in **Fig. 4.19(a)** and **Fig. 4.20(a))** reveals that there is additional peak at high voltage end of the PDD of the E 6010 electrode. This indicates there is increase in the arc gap resulting in an increase in arc voltage from the steady state value during welding. This difference observed in the PDDs for E 6010 with that of E 7018 and E 6013 electrode can be explained based on the basis of differences in the metal transfer of these electrodes during welding. As already explained, in E 7018 and E 6013 electrodes the principle mode of metal transfer is short circuit. In the case of E 6010 both short circuit and explosives/spray metal transfer has been reported [**1,3**]. This is confirmed from the high speed images of metal transfer across the arc during welding using E 6010 electrode (**Fig. 4.24**). **Fig. 4.24 (a)** shows the short circuit metal transfer that occurs in E 6010 electrodes and **Fig. 4.24 (b)** is the explosive/spray transfer that take place in the same electrodes. It should be noted that explosive/spray mode of transfer was not observed during welding using E 7018 or E 6013 electrodes. The explosive transfers occur because of high hydrogen and oxygen content in the arc atmosphere. A major source of hydrogen in the weld is the welding consumable. The flux coating in the consumables as well as the environment and manner of the filler metal storage can affect hydrogen levels in the consumable and resultant weld metal. The hydrogen produced in the arc atmosphere mixes with the molten metal resulting in effervescence consisting of molten metal and hydrogen gas. As the gas pressure increases in the effervescence, bursting of the bubbles occurs this in turn leads to mild explosion at the electrode tip and separation of the molten metal from the electrode to the weld pool. This mode of metal transfer can result in an increase in arc gap and this explains the peak observed in the voltage PDD of E 6010. The schematic of this phenomenon is shown in **Fig. 4.24(c)**.

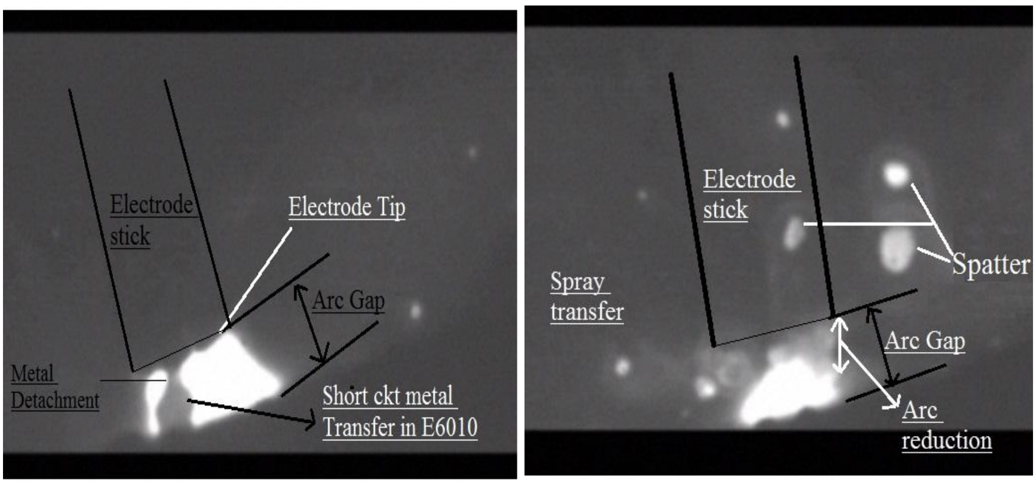


(a) Voltage

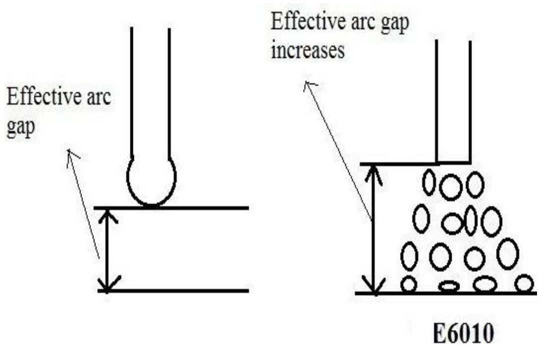


(b) Current

Fig. 4.23: Voltage and current PDD for E 6010 electrode using inverter power supply.



(a) Short circuit and (b) Spray mode of metal transfer image obtained using high speed camera



(b) Schematic of short circuit and spray mode of metal transfer

Fig. 4.24: Mode of metal transfer in E 6010 electrode.

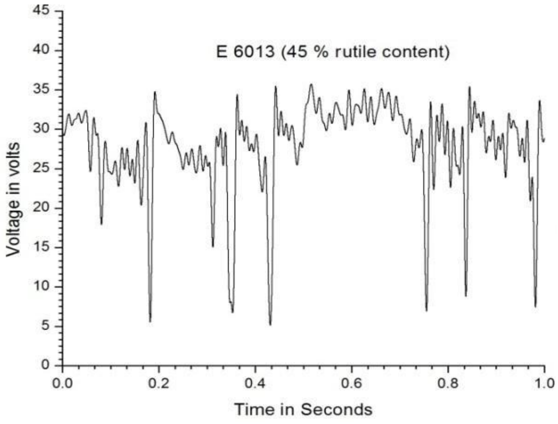
Comparison between current PDDs for E 7018 (**Fig. 4.19(b)**), E 6013 (**Fig. 4.20(b)**) and E 6010 (**Fig. 4.23)** indicates that current variation is more in E 6013, which is agreement with larger variation in current observed in the oscillogram of E 6013 than in that of E 7018 and E 6010.

Thus it is clear that data acquired using DSO is able to bring out clearly the differences in the arc characteristics of electrodes with different flux coatings. These differences are in agreement with the differences in the arc atmosphere while using these electrodes. Hydrogen is the main gas in the arc produced by cellulose electrode while carbon dioxide is the main gas in the arc atmosphere of the basic coated electrodes. As the ionization potential of hydrogen atom is high, arc force of hydrogen arc is high and this can promote spray transfer. Similarly, from studies on GMAW, it is known that in the arc atmosphere consisting predominantly CO_2 gas, short circuit transfer occurs easily and spray transfer seldom happens **[5]**.

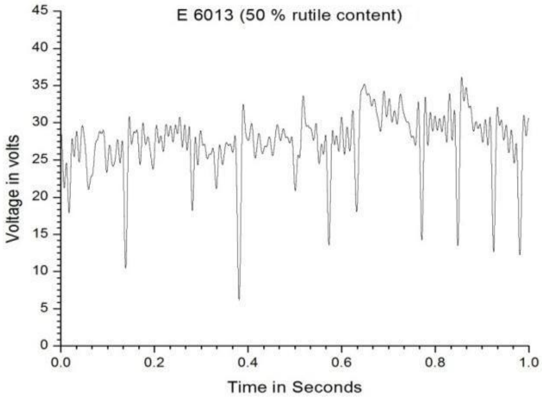
4.3.3 Variation in arc characteristics with flux composition

Fig. 4.25 shows the time domain analysis of E 6013 electrode. From this figure it can be seen that, when the rutile content in E 6013 electrode was 45 -50% (**Fig. 4.25 (a,b)**) frequent voltage dips on account of short circuit metal transfer was noticeable. As soon as the rutile content in E6013 increase to 55% (**Fig. 4.25(c)**), frequency of these voltage dips reduced to a greater extent, this infarct means reduction in short circuit mode of metal transfer.

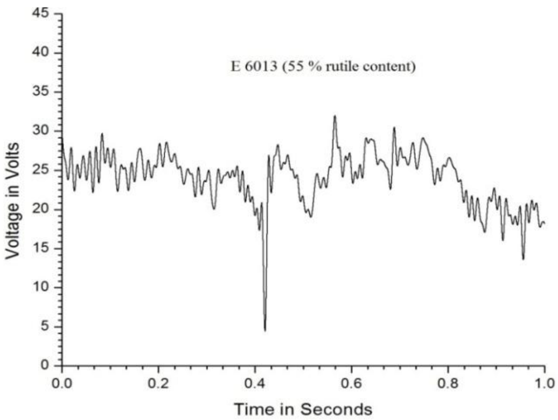
The results just presented using time domain is reflected in PDD analysis as well. **Fig. 4.26** shows the PDD analysis of E 6013 electrode with varying rutile content as specified in **Table 4.2**. From this figure we can see that for PDDs of E6013 electrodes with 45% and 50% rutile content, first peak, which corresponds to short circuit metal transfer is clear; but as the rutile content in is increased to 55%, first peak in voltage PDD is reduced. This reduction corresponds to reduction of short circuit metal transfer in this electrode.



(a) E 6013 with 45% rutile content



(b) E 6013 with 50% rutile content



(c) E 6013 with 55% rutile content

Fig. 4.25: Time domain analysis of E 6013 electrode with different rutile compositions.

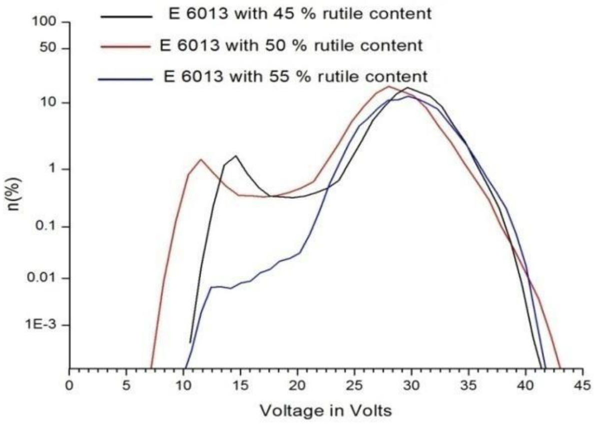
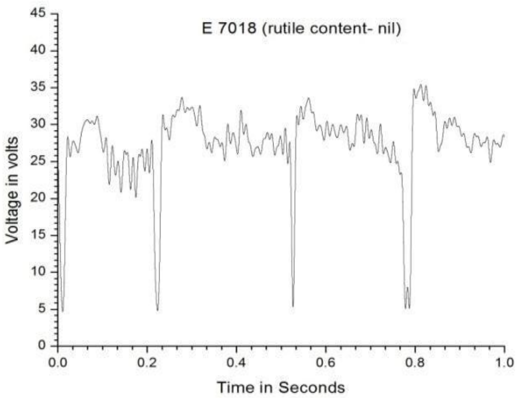


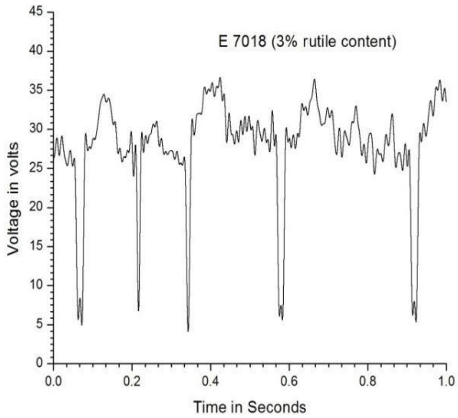
Fig. 4.26: PDD analysis of E 6013 electrode with varying rutile content.

In contrast to this, the time domain analysis of E 7018 electrodes with varying rutile content shown in **Fig.4.27** reveals that addition of rutile content up to 7% in the flux coating of the electrode has little effect of the metal transfer behavior. This means that in basic type of electrodes (i.e E 7018) major mode of metal transfer remains as short circuit mode irrespective of the different wt.% of rutile present in the flux coating.

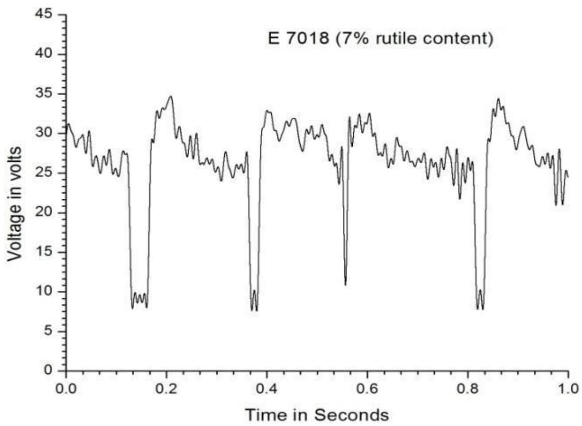
The facts just presented with time domain analysis of E 7018 are in correlation with that of its PDD analysis in **Fig. 4.28**. From this figure it can be seen that although there is slight difference in their voltage PDD first peak in these electrodes are predominately high, this means majority of metal transfer in these electrodes, irrespective of extent of rutile content, are in the form of short circuit.



(a) E 7018 with nil rutile content



(b) E 7018 with 3% rutile content



(c) E 7018 with 7% rutile content

Fig. 4.27: Time domain analysis of E 7018 electrode with different rutile compositions.

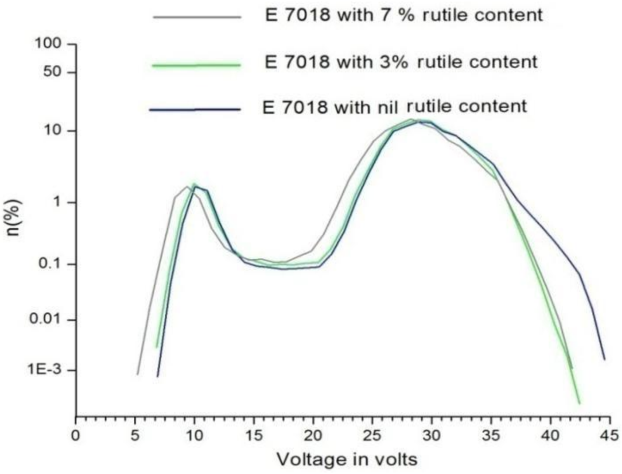


Fig. 4.28: PDD analysis of E 7018 electrode with varying rutile content.

4.3.4 Effect of baking of electrode

It is known that E7018 is used only after baking to remove the moisture content in the flux coating. It is expected that arc characteristics of the unbaked electrode to be different from that of the baked one. The data acquisition and analysis procedure developed is able to reveal this difference. **Fig. 4.29** shows the current and voltage oscillograms for the weld produced by unbaked E 7018 electrode; which is similar to those shown in **Fig. 4.17** except that steady state values of voltage and current are high. This was also in agreement with higher voltage and current values shown by the voltmeter and ammeter in the power source. However, voltage and current PDD generated for the unbaked electrode is shown along with those for baked electrode in **Fig. 4.30** and this shows a shift in both current and voltage PDDs for unbaked electrodes to higher values, though pattern of PDDs are similar to those of the baked electrode. Comparison of the PDDs for voltage of baked and unbaked electrode reveals that second peak in the PDD for unbaked electrodes is higher than that for the baked electrode. Thus, it is possible to find out whether an electrode is baked or not by analyzing the voltage and current signals [**6**].

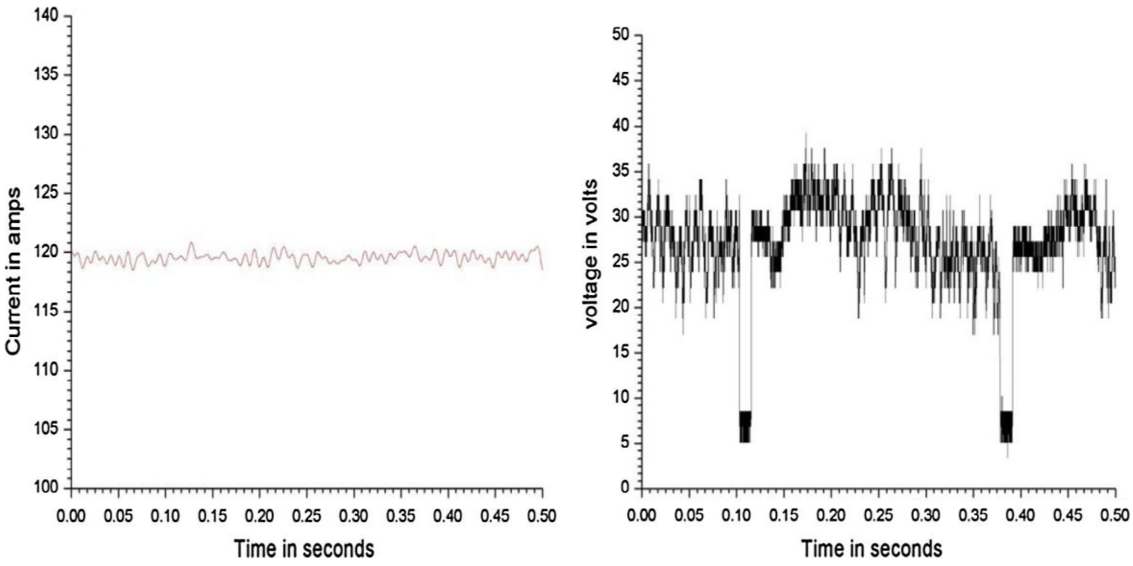
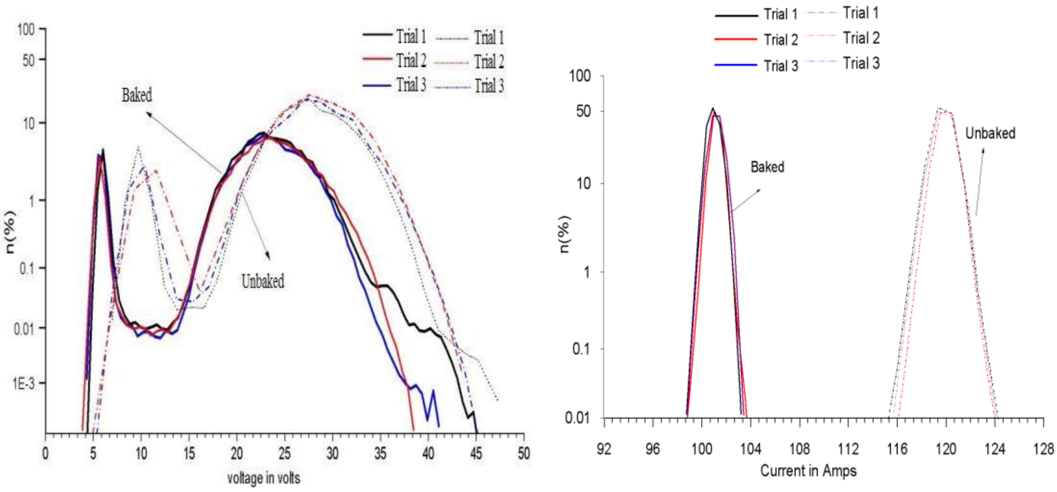


Fig. 4.29: Voltage and current oscillogram obtained during welding using unbaked E 7018 electrode.



(a) Voltage PDD **(b) Current PDD**

Fig. 4.30: PDD analysis of voltage and current characteristic behavior of unbaked and baked electrode.

The observed effect of non-baking on the performance of the electrode can be explained as follows. While making the weld bead for the same current set for the baked electrode arc was not stable, accordingly welder has increased the current for arc stability. This has led to a shift of the PDD for both voltage and current towards higher values. In the absence of baking electrode coating will have high moisture content, which would produce hydrogen in the arc atmosphere. As the ionization potential of hydrogen is higher than the other gases present in the electric arc is stable at high arc voltages. That is why; high voltage and current are required while using electrodes without baking. Similarity of both voltage and current PDDs for both the electrodes indicates that there is no change in the performance of electrodes, for example metal transfer, because of high moisture content.

4.4 Evaluation of GMAW process by varying composition of shielding gases

4.4.1 Experimental setup

In GMAW process, in addition to wire electrode, shielding gas employed to protect the arc is also consumable and composition of the shielding gas has a significant influence on the arc characteristic and modes of metal transfer in this welding process. In order to demonstrate that the proposed procedure is also capable of differentiating the effect of shielding gas in GMAW process, bead on plate welds are made with 100% Ar, 100% CO_2 and gas mixture of 80% Ar and 20% CO_2 using AWS ER 70S2 wires (1.2 mm dia.) on carbon steel plates. For each shielding gas, welds were made at three different currents as given in **Table 4.3** to obtain different modes of metal transfer during welding. It may be noted that GMAW of steel is not generally carried out with 100% Ar gas; but welds with 100% Ar is included in the present study to obtain three widely different combination of shielding gases. All the welds were made using the same machine (inverter) and the same welder. As in the case of SMAW process, voltage and current data were acquired at a sampling rate of 100,000 samples/s for duration of 20 seconds and welds for a given shielding gas and current level was repeated thrice. Data was subsequently filtered and analyzed.

Table 4.3 Various Gas Compositions and corresponding current value

Gas Composition	Set Current (In Amperes, A)	Wire speed (Inches Per Minute, IPM)
80 % Ar and 20 % CO_2	(a) 170 A	170
	(b) 200 A	200
	(c) 300 A	300
100 % Ar	(a) 190 A	190
	(b) 220 A	220
	(c) 240 A	240
100 % CO_2	(a) 150 A	150
	(b) 205 A	205
	(c) 220A	220

4.4.2 Analysis of voltage and current variations in GMAW process

Fig. 4.31 Shows data acquired at various current values from a GMAW process using ER70S wire for shielding gas of composition 80 % Ar + 20 % CO_2. From **Fig. 4.31(a)** (current 170 A and voltage 22 V), large number of sudden dip in the voltage oscillograms can be observed. This sharp reduction in voltage is because of short circuit transfer happening in actual welding process. Now as the current increased from 170 A to 200 A, at ~29 V, frequency of the voltage dips and corresponding current surge decreases drastically (**Fig. 4.31 (b)**) and the duration of each surge is also reduced, which indicates the mode of metal transfer is globular mode **[5]** and changing towards spray transfer. At 300 A and 35 V in **Fig. 4.31(c)** it can be noticed that voltage oscillogram is almost flat, and no visible reduction in voltage waveform from the steady state value has been noticed which actually corresponds to complete domination of spray transfer at this current to voltage combination. The welding current of 300A is considerably above the transition current of 255A reported for spray transfer to occur for this gas mixture and 1.2 mm diameter of electrode wire used in this study. Current variation obtained in this study is also similar to those reported in **[7]**.

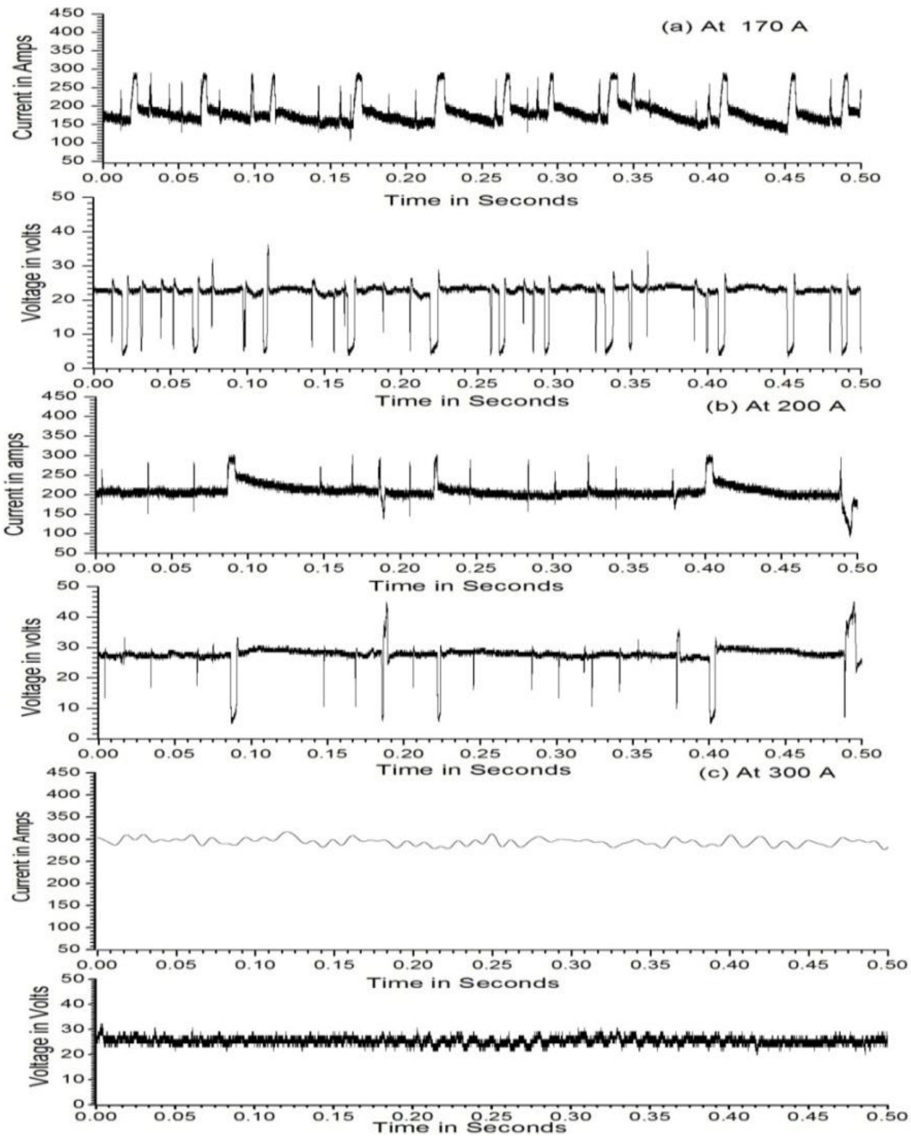


Fig. 4.31: Voltage and current oscillogram of GMAW process with 80 % Ar and 20 % CO_2.

Fig. 4.32 represents the PDD plot obtained for GMAW welding process when a gas composition of 80 % Ar and 20 % CO_2 was used, we can see from this voltage PDD that when initial current of 170 A was used, first peak of this PDD, is actually an indicative of short circuit transfer. This is in agreement of the conclusion that has been drawn from the analysis of time domain oscillogram from **Fig. 4.31(a)**. One of the consequences of short circuit transfer mode of metal transfer is the wide spatter of molten droplets which occur when molten weld metal is detached from the wire because of a mild explosion that occur during metal transfer due to surge in current resulting from globular transfer **[5]**. Accordingly, more spatters can be easily seen near the weld when short circuit transfer is the dominant mode of metal transfer (**Fig. 4.32(a)**). As current increases from 170 A to 200 A, there is transition and first peak of voltage PDD decreases. There is a corresponding decrease in the spatter observed. As current further increases to 300 A, first peak of voltage PDD in **Fig. 4.32(c)**, totally disappeared indicating that spray mode of metal transfer is occurring now with almost no spatter as revealed from the bead appearance.

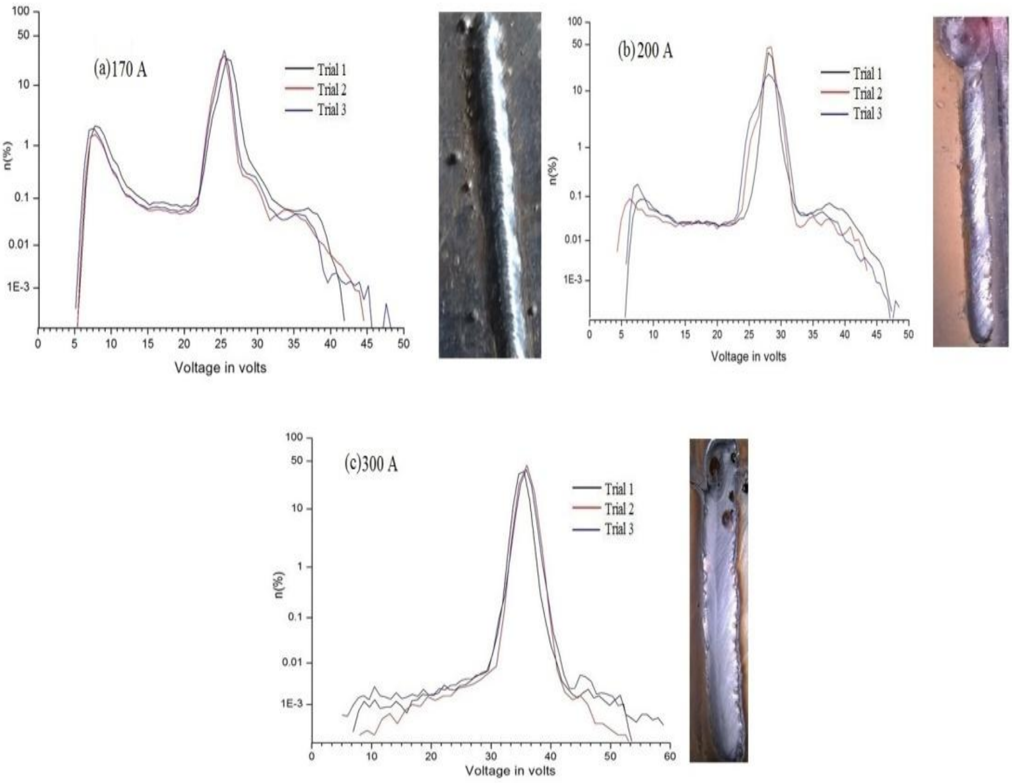
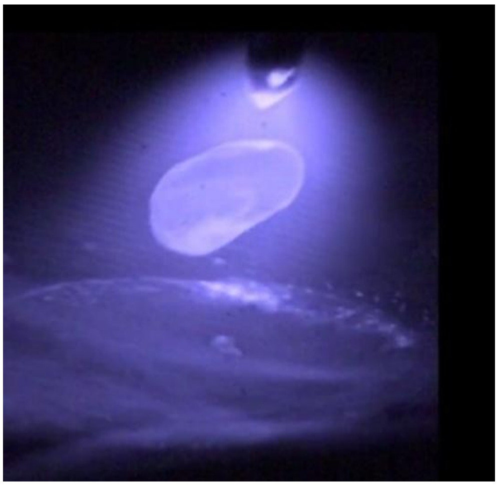
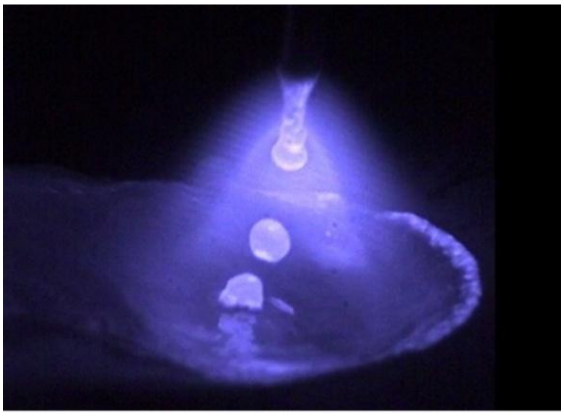


Fig. 4.32: Voltage, current PDD and corresponding bead Image of GMAW process for different values of current for a combination of 80 % Ar and 20 % CO_2.

Results presented here is in agreement with those reported in literature on modes of metal transfer in GMAW using 85%Ar+15%CO_2 shielding gas [**8**]. Here, using high speed imaging of the welding process, authors have shown how metal transfer changes from short circuit to globular and to spray transfer with increase in volte. These images are reproduced in **Fig. 4.33**.



(a) Short Circuit metal transfer (20 V) **(b) Globular metal transfer (33 V)**



(c) Spray metal transfer (36 V)

Fig.4.33 High speed camera image of various modes of metal transfer in GMAW process using 85 % Ar and 15 %CO_2 [8].

Fig. 4.34 shows the voltage and current oscillograms from GMAW process for three different levels of current when 100 % CO_2 is used as the shielding gas. It is clear that irrespective of the current and voltage employed for welding, frequent voltage drop with corresponding surge in current can be seen which indicate that in spite of increase in current and voltage, mode of metal transfer does not change to spray transfer. This is in agreement with the fact that for 100% CO_2 or even for gas mixtures with more than 20% CO_2 shielding gases, it is difficult to have spray transfer **[7]**. It is also known that with 100 % CO_2 short circuit transfer is common when welding is carried out at low current and this metal transfer is accompanied by a surge in current and a corresponding dip in voltage as obtained in the present study (**Fig. 4.34(a))**. However, at high current levels of 205 (**Fig. 4.34(b)**) and 220 A (**Fig. 4.34(c)**) mode of transfer appears to be predominantly globular.

PDD analysis of voltage data shown in **Fig. 4.35** is in accordance with the oscillograms it can be seen that in all the three cases of operation (i.e at 150 A, 205 A, and 250 A), there is clear peak at the low voltage which is indicative of short circuit or globular transfer. Increasing the current is only increasing the fluctuation in voltage at high values which only adds to welder's discomfort **[5]**.

Figures 4.36 and **4.37** show the oscillograms and corresponding voltage PDD for welds made with 100% Ar shielding gas at three different current levels. A comparison of these figures with those obtained for the 80 % Ar and 20% CO_2 gas mixtures (**Fig. 4.31** and **Fig. 4.32**), indicates that there are short circuit transfers at low currents and sprays transfer above transition currents and transition from globular to spray transfer at the intermediate current. A careful examination of these figures further reveals that frequency of voltage dips due to short circuit or globular transfer in 100% Ar is less when compared with 80% Ar and 20% CO_2 combination. This is due to its poor surface tension property of molten steel in Ar gas atmosphere which in turn affects the fluidity of the molten metal and the bead appearance. It may be noted that 100% Ar is seldom used as shielding gas for welding steels as it gives an unsatisfactory penetration profile; but this is included in the present study to demonstrate how changes in arc characteristics due to changes in shielding gas composition can be studied by data acquisition using DSO and subsequent analysis of the data.

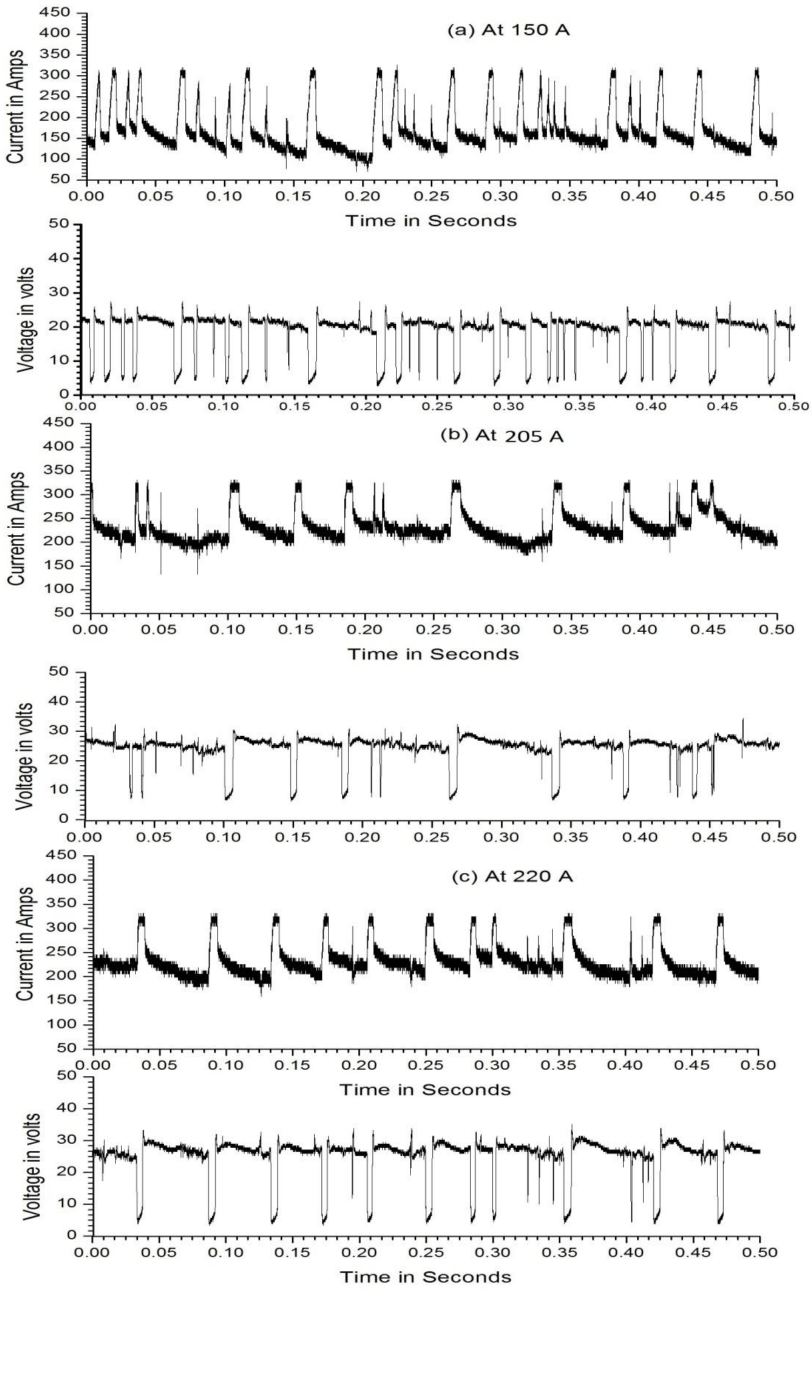


Fig. 4.34: Voltage and current oscillogram of GMAW process with 100% CO_2.

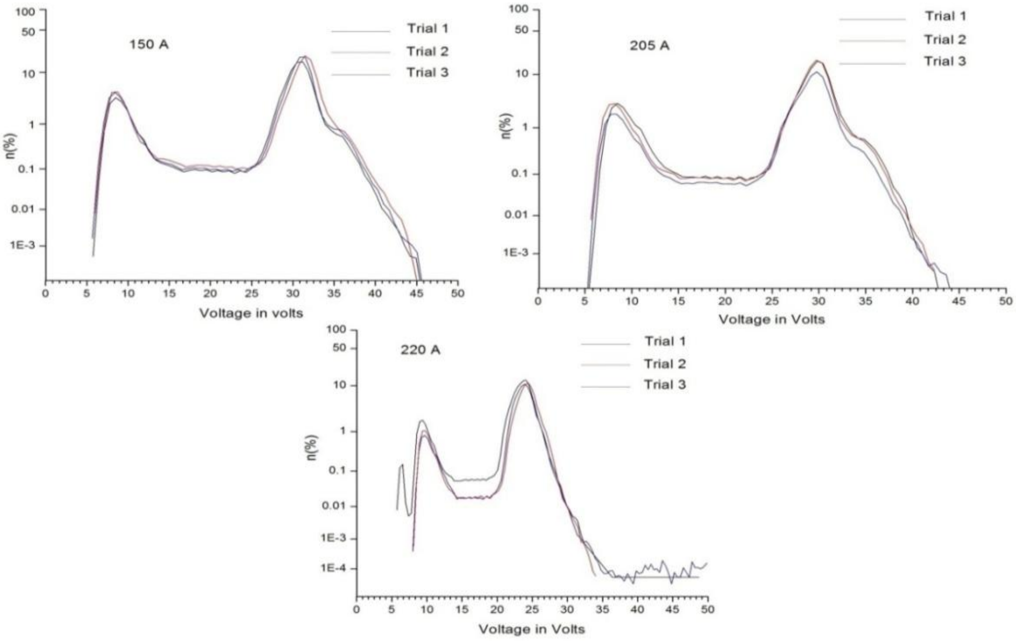


Fig. 4.35: Voltage and current PDD of GMAW process with 100 %CO_2.

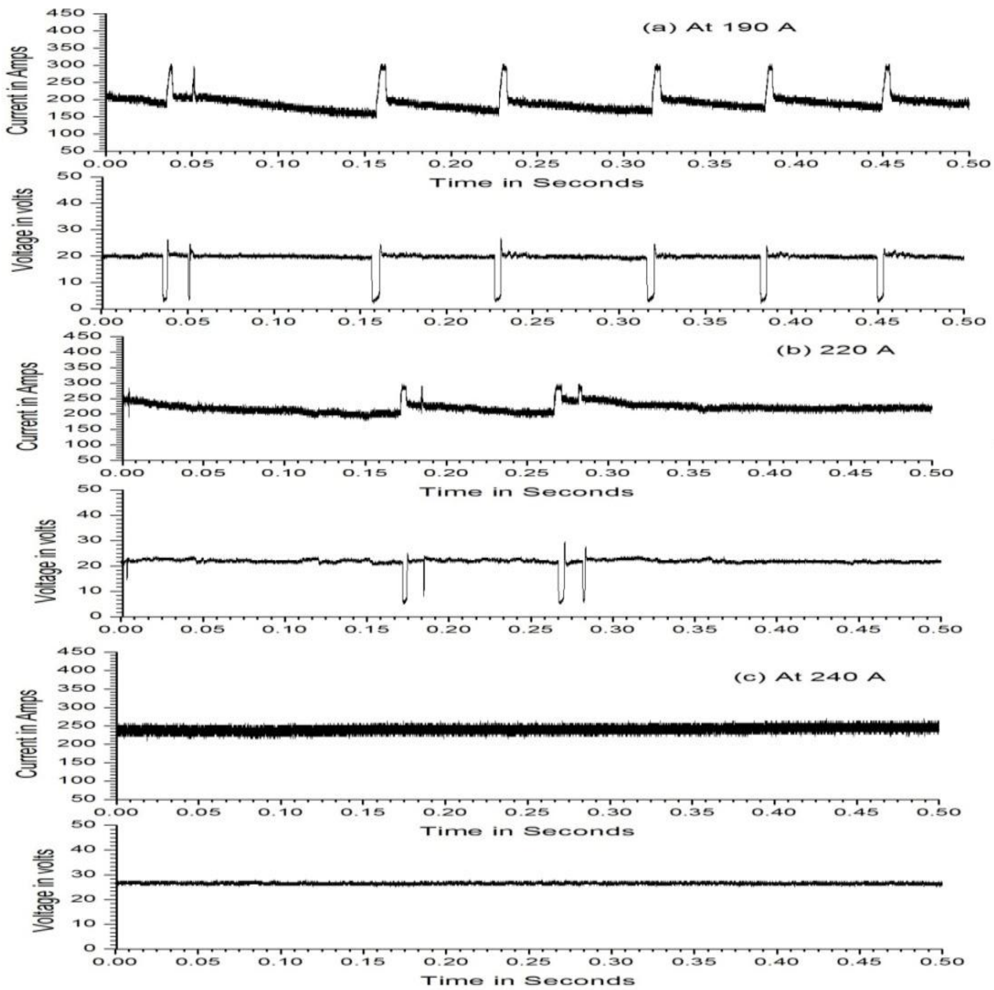


Fig. 4.36: Voltage and current oscillogram of GMAW process with 100% Ar.

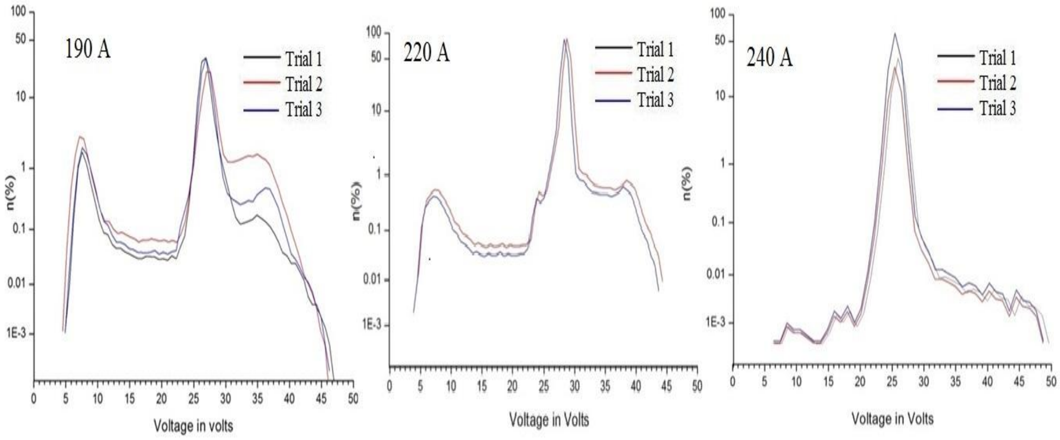


Fig. 4.37: Voltage and current PDD of GMAW process with 100% Ar.

From the above results, it is clear that using high speed data acquisition using DSO and subsequent statistical analysis of data, it is possible to differentiate between various modes of metal transfer that occur in GMAW process with change in shielding gas and welding current. Hence, this procedure can be used to study role of shielding gas composition on arc characteristics and for a given gas composition, the current and voltage values above which transition occurs to spray mode of transfer.

Summary

Online monitoring of the Arc welding process can be done to evaluate various welding parameters (welding skill, performance of power sources, quality of welding consumables, role of shielding gases etc.) using a commercially available, general purpose DSO.

Probability density distributions (PDD) which are generated using the welding data acquired at a very high sampling rate can differentiate between the skills levels of different welders. Voltage PDD of trainee welder gradually changes towards that of an experienced welder as the learning progress. From the shape of the voltage PDDs, using same type of machine and welding consumable, it is possible to rank the skill levels of a group of welders. Reasonably good correlation was obtained in grading the skill of the welders using PDD and SOM technique and grading obtained by the techniques currently employed.

Voltage PDD of one type of electrode is distinctly different from another. Hence, voltage PDDs can be used to differentiate between the welding consumables. It is possible to compare the performance of same type of electrode with minor changes in flux composition from the differences in the PDDs generated from the voltage signals acquired during welding with these electrodes.

Using appropriate statistical analysis of the data it is possible to differentiate between performance of different arc welding power sources; even the performance of the same type of power sources but from manufacturers can be easily differentiated. Similarly, role of shielding gas composition on different modes of metal transfer can be studied by analyzing the data acquired by high speed data acquisition using DSO. Thus, it is comprehensively shown that high speed data acquisition using a DSO and the analysis of the acquired data can be used to study various aspects of arc welding like, assessing the skill level of welders, performance of the welding power sources, differences in the arc behavior of different electrodes and effect of shielding gas composition and metal transfer behavior in GMAW process.

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5

Development of PSoC-5 based Weld Pattern Analyzer (WPA)

In **chapter 4**, it was demonstrated that that data acquisition and analysis procedure can be used to study the arc welding processes for various welding related applications. For all the applications mentioned in **chapter 4** data was acquired using a DSO. But, this system has certain limitations as well. A DSO is perfectly suited in a laboratory environment for the research and development purpose but when it come to the field application an extremely rugged system capable of withstanding the high voltage, current and frequency fluctuations over a long period of time is required. Additionally, DSO is general purpose equipment designed to acquire, display and record signal from any transducer and hence it has many additional features hence not suitable for integrating with a welding equipment for regular data acquisition in work shop. Further, cost of DSO is high compared to a welding machine and hence using DSO in a workshop environment is not economical. Finally, sufficient expertise, which is much different from that of handling welding equipment, is required to use DSO and this is seldom available in a welding shop.

So considering all these aspects, we attempted to design and develop our own data acquisition system (DAS) which should be cost effective, simple to use, suitable for a workshop environment and if possible, can be integrated with welding power source so that welding data can be acquired as and when required with minimum set up time. Such a DAS should meet the following requirements.

1. Throughput of the system should be reasonably high so that the system can acquire all the possible variations happening in physical process.
2. System should be a rugged one capable of working in a welding environment.
3. Should withstand high voltage, current and frequency fluctuations happening in a welding environment over a long period of time.
4. Should have an interactive human machine interface.
5. It should be possible to control the data export rate to an external computer for further processing.
6. Should have the simplest of design and controlling features, so that, the same can be operated by a welder or a welding supervisor.
7. Should be cost effective, extremely portable and can be integrated to the welding machine.

Considering the above mentioned objectives, data acquisition system for welding related application with inbuilt software package was designed using Programmable System on Chip (PSoC) based Platform. Subsequently a Human Machine Interface (HMI) was developed for an interactive layout and to process the voltage and current signals acquired using PSoC. This system was successfully used to acquire welding data and to carry out the subsequent time domain and statistical analysis of the weld data. It is shown that results are comparable with those obtained using DSO and the analysator Hannover **[1]**. Then, it was used to analyze skill levels of welders and effect of flux composition on arc characteristics. Results obtained matched well with those obtained using DSO and thus it is demonstrated that, this system can be used as an alternative to DSO for online data acquisition during welding and subsequent analysis of arc welding processes. Detailed description of how the design evolution of PSoC based system took place and how the system thus designed was used for welding related applications are described in this chapter.

5.1 Why PSoC?

PSoC system was chosen because SoC (System on Chip) is a technique where all the component of electronic circuitry can be designed in single IC and because of this, whole electronic circuitry can be minimized. Even noise immunity can be improved, which is one of the most important aspects in a welding environment. A SoC has one microcontroller or microprocessor or a Digital signal Processor core. It also has other blocks like, Read Only Memory (ROM), Random Access Memory (RAM), and Flash Memory etc. It can have Universal Serial Bus (USB), Universal Asynchronous Receiver/Transmitter (UART), a Serial Programming Interface (SPI), and an Ethernet Port. Hence, SoC provides a perfect platform to design any welding specific embedded design that needs to be in a single board. There are various members in PSoC family; a brief description about their types and specifications is given in **Table 5.1**

5.2 PSoC based Data Acquisition System (DAS) design

PSoC based system designed to acquire the welding data has the functions of data acquisition and also the capability to transmit the acquired signal through the RS232 interface of the board to external computer for post processing. Hence, to do all these activities the PSoC has a main code to process all the external user interactions. This main code activates the proper layer with the global resources defined. **Fig. 5.1** shows how main code is used for different system functioning **[2]**. The functional description of these functions is explained below.

Table 5.1 PSoC types and specifications

PSoC 1	**PSoC 3**	**PSoC 5**
Performance optimized 8-bit MCU	Performance optimized single cycle 8-bit 8051 core	High Performance 32-bit ARM Cortex-M3
Up to 24 MHz, 4MIPS, Flash 4 KB to 32 KB, SRAM 256 bytes-2KB, Operation 1.7V-2.5V	Up to 67-MHz, 33-MIPS, Flash 8 KB to 64 KB, SRAM 3 KB to 8 KB, Operation 0.5-5.5V	Up to 67-MHz, 84-MIPS, Flash 32 KB to 256 KB, SRAM 16 KB to 64 KB, Operation 2.7 to 5.5V
1 Delta-Sigma ADC (6-14 bit), 131 Ksps @ 8-bit , Up to two DACs (6-8-bit)	1 Delta-Sigma ADC (8-20-bit), 192 Ksps @ 12-bit , Up to four DACs (8-bit)	1 Delta-Sigma ADC (8-20-bit), 2 SAR ADCs (12-bit) 192 Ksps @ 12-bit: 1 Msps , Up to four DACs (8-bit)
Active: 2ma, Sleep: 3 micro amperes, FS USB 2.0, I^2C, SPI, UART	Active: 1.2mA, Sleep 1 micro ampere, Hibernate: 200 nano Amperes , FS USB 2.0, I^2C, SPI, UART, CAN, LIN, I^2S	Active: 2mA, Sleep 2 micro ampere, Hibernate: 300 nano Amperes , FS USB 2.0, I^2C, SPI, UART, CAN, LIN, I^2S
Requires ICE Cube and Flex Pods	On-chip JTAG, Debug and Trace; SWD, SWV	On-chip JTAG, Debug and Trace; SWD, SWV
Up to 64 I/O	Up to 72 I/O	Up to 72 I/O

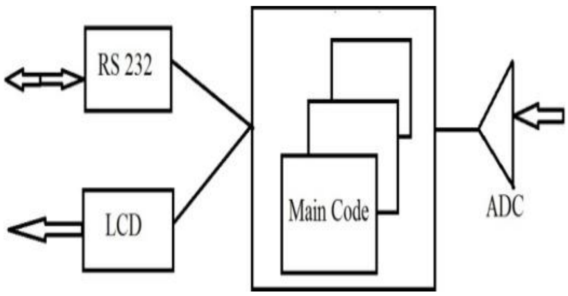


Fig. 5.1: Main code functioning in PSoC design.

First, the communication between the user and the system is made through the RS232 interface in the board. In order to achieve that, the UART user module is used in the PSoC. It is responsible for transmitting the signal information gathered by the PSoC to the RS232 and then allowing the user to send the proper command for switching between the system functions.

The LCD shows information about the active function and the set parameters. Depending on the function it also shows information about the signal that is being acquired.

The ADCs are the one of the most important aspect to design an effective data acquisition. This part is composed of several ADCs types (Delta sigma, Successive Approximation Register (SAR), integrating type etc.) and configurations in order to compare their results and to study the main aspects of signal acquiring. Depending on ADC types, resolution and sample rates can be selected.

The main code makes it possible to switch between various functions like accessing UART, memory etc. It depends on the RS232 communication. When a command is received from the user, the code goes to the function called, sets the parameters desired, or loads the proper layer. It is also responsible for transmitting the signal information through the RS232. All functions of the system are provided by the PSoC, through different user modules loaded. Global resources for this design include the clocks and the reference voltages [**2**].

5.2.1 PSoC-3 based data acquisition system design.

From the **Table 5.1** the detailed specifications of PSoC family members can be seen. Based on these, a PSoC-3 (CY8C3866AX) with the main code was initially chosen for development of DAS because it has one delta-sigma ADC which could sample the incoming signals at the rate of 192 ksps. In addition to various commonly used LEDs and switches other commonly used components on the motherboard for this design was:-

1. Voltage –Current (Analog) Input for input weld data
2. JTAG Programming for firmware programming.
3. LCD for continuous display.
4. USB communication for serial data transmission.
5. Power Supply module

These schematic of these components and the mother board of PSoC-3 based design are shown in **Fig. 5.2** and **Fig. 5.3** respectively.

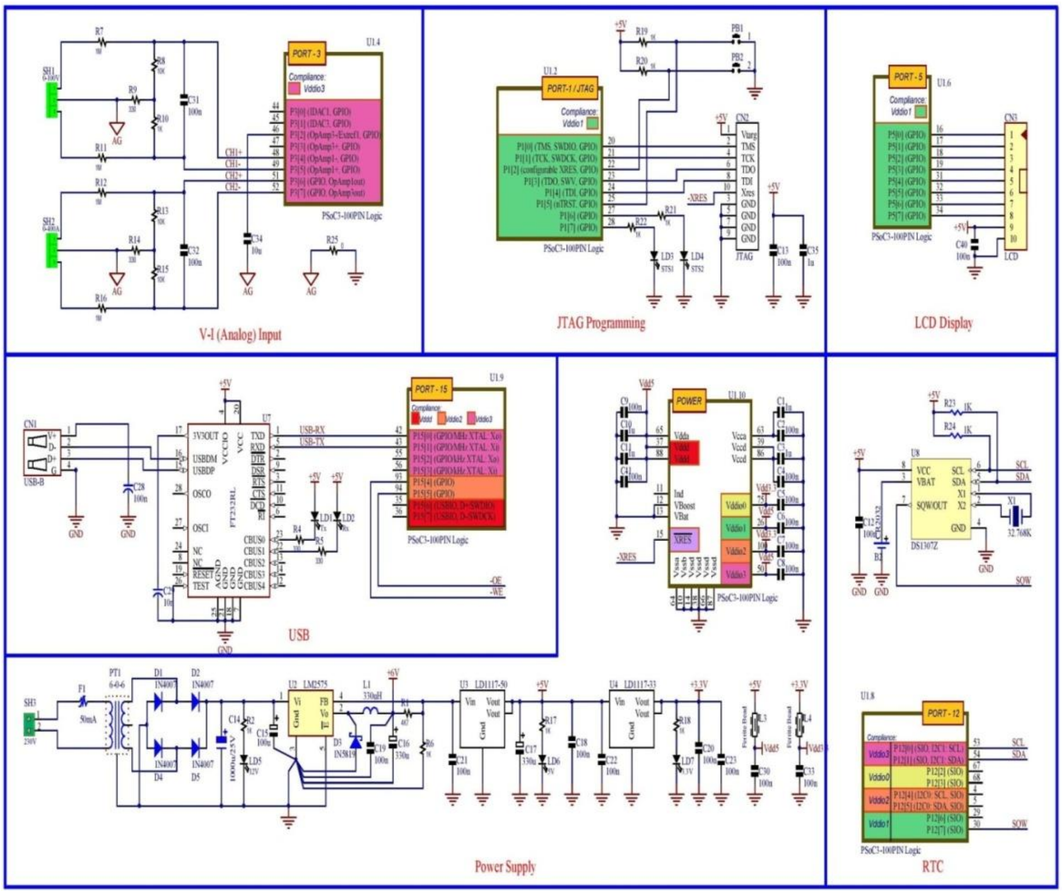


Fig. 5.2: Various components on PSoC-3 design mother board [3].

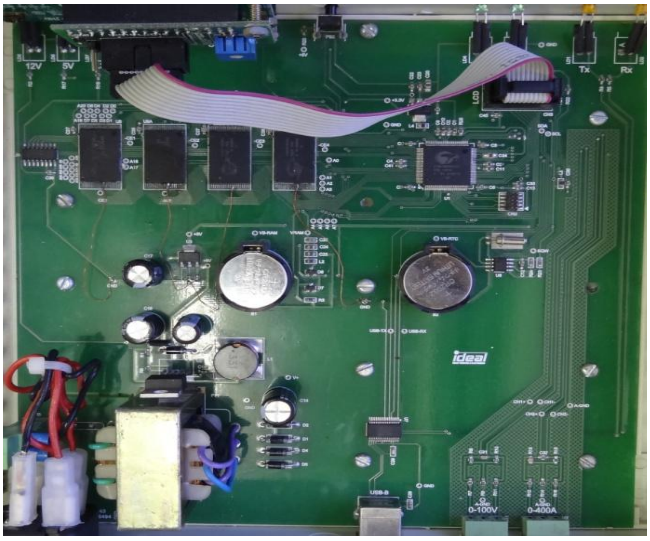


Fig. 5.3: Mother board of PSoC-3 design.

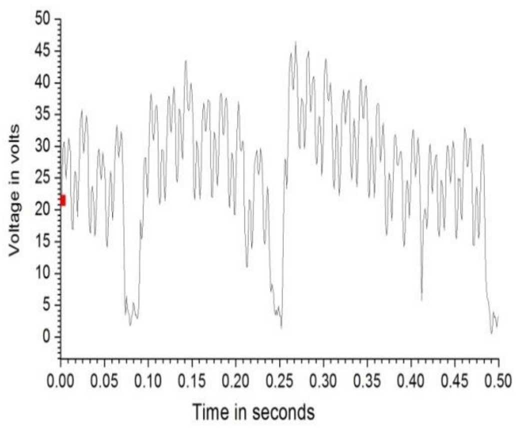
Although PSoC-3 based system could acquire the welding data and export it to an external computer, it could do it only at maximum rate of 20,000 samples/s, much lower than 100,000 samples/s desired for our study and 192,000 samples/s as per the PSoC-3 specification. The results and possible reasons for the low sampling rate achieved are discussed below.

5.2.1.1 Data acquisition using PSoC-3 based design

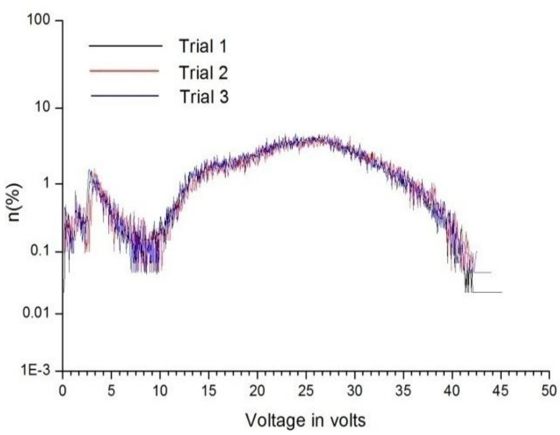
For weld data acquisition using systems developed using PSoCs, bead on plate welds using E7018 electrodes (3.15 mm) and inverter power source were made. Welding current was set at 100A and voltage employed was 25V. The instantaneous values of voltage and current data were acquired using PSoC-3 based DAS for duration of 20s while making bead-on-plate welds on carbon steel plates using E 7018 electrodes (3.15 mm dia.) and an inverter power source. The current set for this experiment was 100A and the displayed voltage was 25V. Data thus obtained was subsequently filtered and used for plotting PDD curve to analyze the quality of the data obtained from these hard wares. PDD obtained from the DSO data was used as a standard PDD for all the comparison purpose.

Although both voltage and current data was acquired using this hardware, only voltage data was used to evaluate the quality of the data thus acquired. **Fig. 5.4** shows the time domain and PDD analysis of the voltage signals acquired by PSoC-3 design. In PSoC-3 based design, Because of low data acquisition rate (20,000 samples/s), quantum of data acquired was less and hence, many of the events happening in the real process were not recorded properly. This is reflected in time domain graph of the voltage data obtained with PSoC-3 based design in **Fig. 5.4(a)**. From this figure we can see that small variations in the voltages happening in the actual welding process are effectively ignored as welding voltages is freely jumping from one value (skipping various events in between) to other without showing many of the data points for a particular instance of voltage value.

This, in turn, is reflected in the PDD analysis of the voltage data acquired using PSoc-3 based design (**Fig. 5.4(b)**); from this figure it is clear that the PDD thus obtained is distinctly different from those obtained with DSO in previous chapters. Voltage PDD (**Fig. 5.4(b)**) showed random fluctuations, these variations in a PDD should be smooth and continuous over entire range of voltage values.



(a)Time domain analysis



(b) PDD analysis

Fig. 5.4: Time domain and PDD analysis of the voltage data acquired using PSoC-3 design.

From the above discussion it is clear that the quality and quantum of data acquired using PSoC-3 design will not be the true representative of the actual welding process and hence, cannot be used for evaluation purpose.

The throughput limitation in PSoC-3 design was taking place because of various reasons, first of all as already mentioned for a high speed data acquisition system choice of ADC is an extremely important factor. In PSoC-3 based design, we have used Delta Sigma ADC, which cannot sample the incoming signal at a very fast rate. Secondly, in this design single ADC was used for both Voltage and Current Conversion, so that same ADC was utilized on time sharing basis (by the use of multiplexer) for converting analog data into digital data (**Fig. 5.5**). Consequently, speed of conversion was getting affected. Lastly, in PSoC 3 design, to address different memory locations (for storing the data into DAS memory) software counter with increment at every iteration was used and because of this time taken for the acquisition was more and throughput was less.

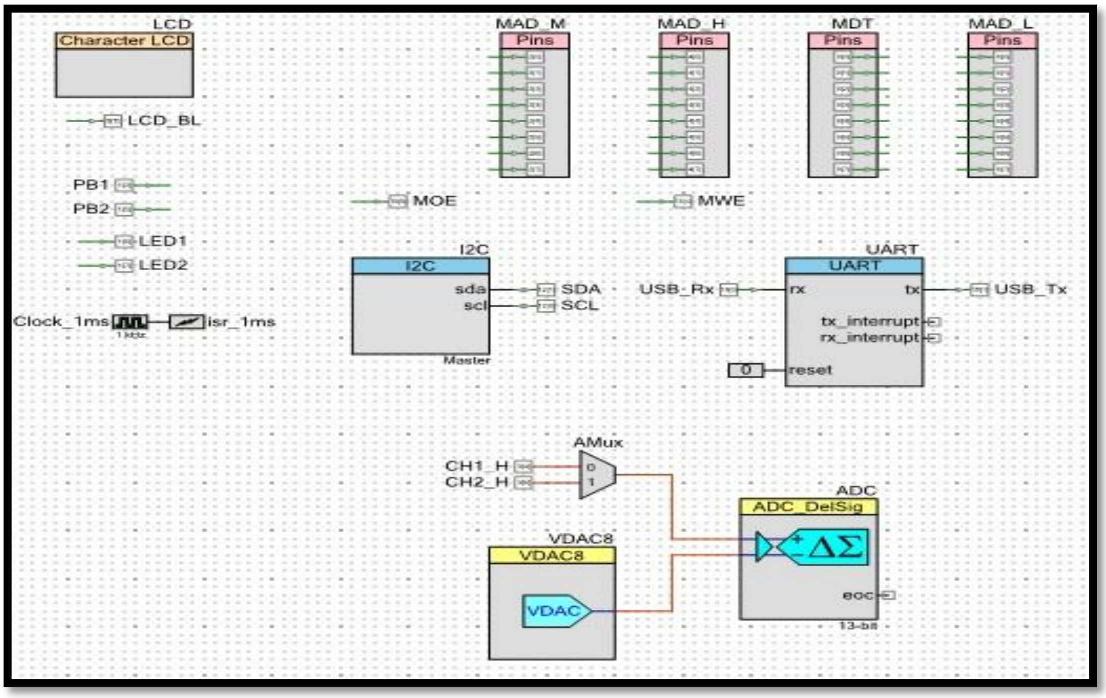


Fig. 5.5: Top schematic of PSoC-3 based design.

5.2.2 Design evolution of DAS from PSoC-3 to PSoC-5 based design

To achieve higher sampling rate (fast data throughput) PSoC-3 based design was modified to PSoC-5 (CY8C5868AX) based design. **Fig.5.6** shows the motherboard of PSoC-5 based design.

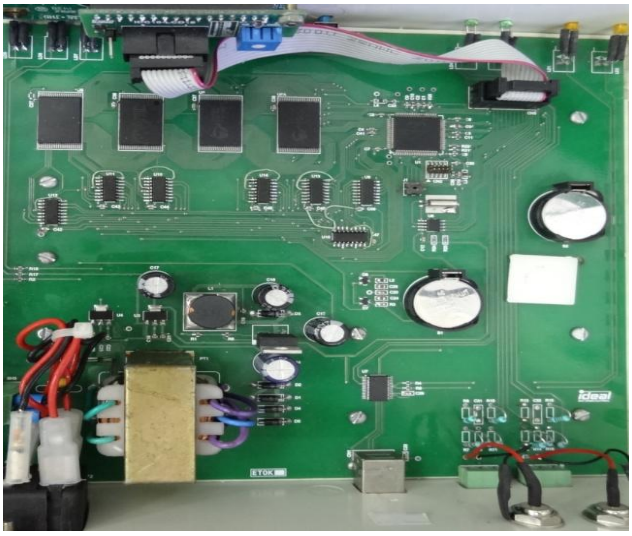


Fig. 5.6: Mother board of PSoC-5 design.

PSoC-5 based platform uses Successive Approximation (SAR) type ADC (**Fig. 5.7**), which has a much faster sampling rate in comparison to Delta Sigma ADC used in PSoC-3 design. Secondly, in PSoC-5 based design two separate ADCs were used for both voltage and current data (**Fig. 5.7**), so that the time dependency on one ADC was shared between two, consequently, execution time reduced. Lastly, to enhance the data acquisition rate further, data storing scheme in PSoC-5 based design were modified by modifying the addressing scheme to access the address of different memory locations. In PSoC 5, hardware counter with auto increment addressing scheme was implemented to address consecutive memory location; this is shown in **Fig. 5.8.** From this figure we can see that 74HC193 4-bit U/D counter were used in PSoC-5 design to locate various memory locations, in PSoC-3 based design there were no such arrangements. PSoC-5 based design thus developed was named as Weld Pattern Analyzer (WPA).

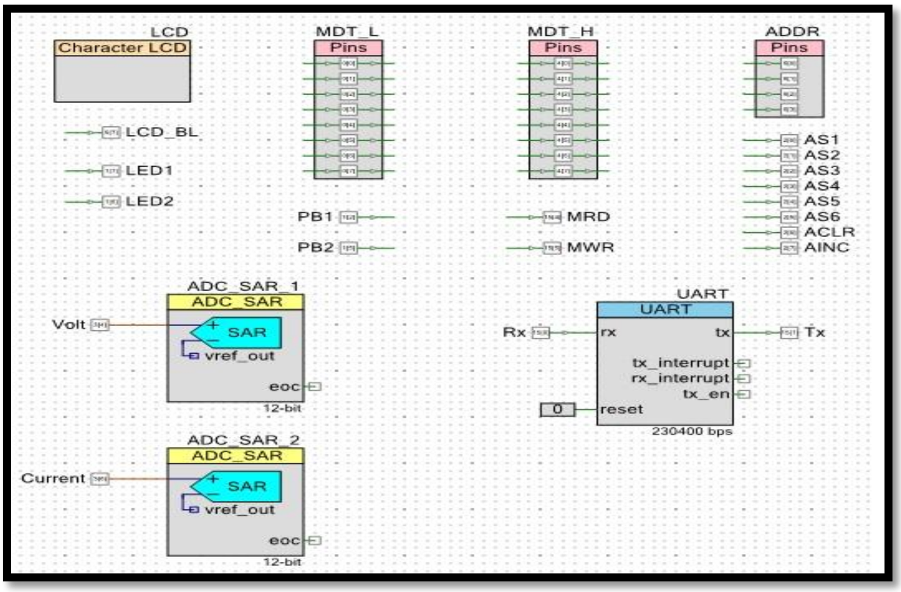


Fig.5.7: Top schematic of PSoC-5 based design.

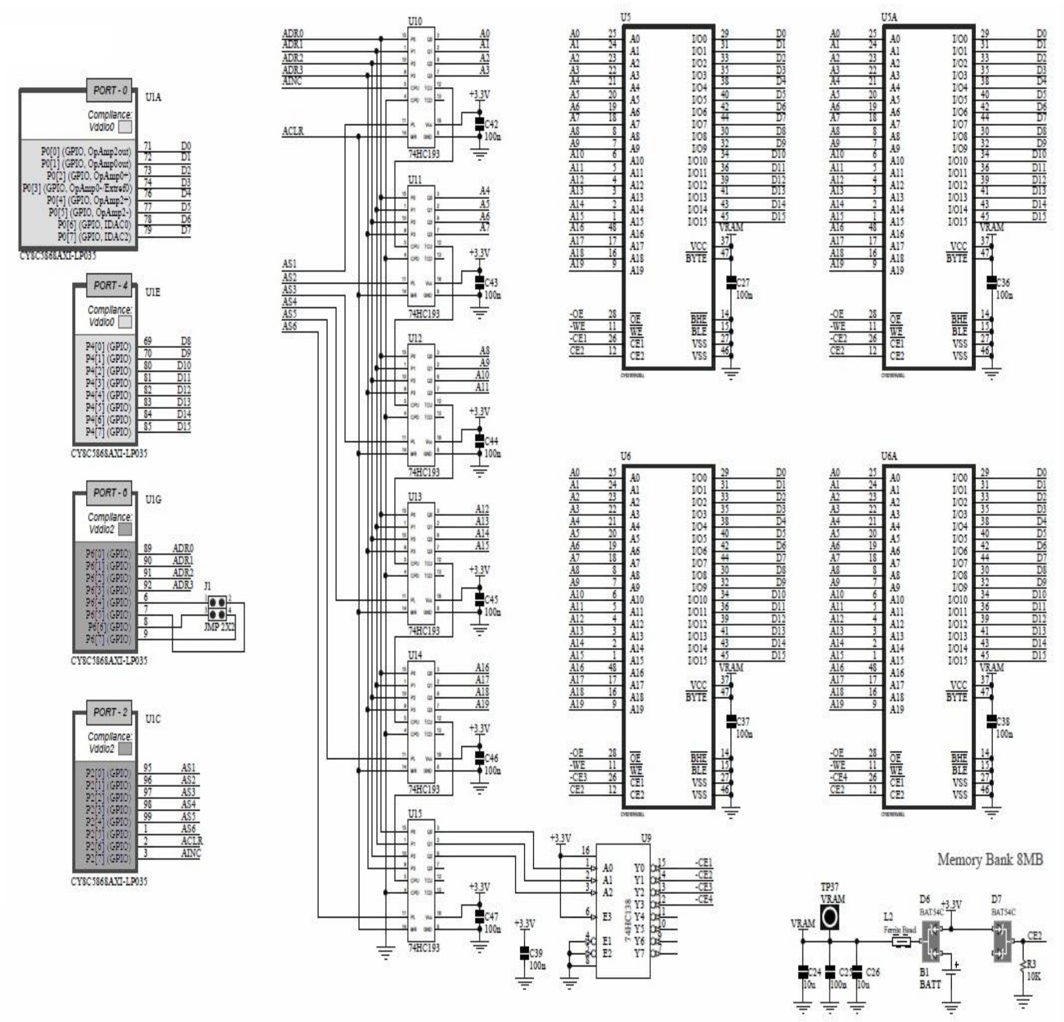


Fig. 5.8: Memory addressing arrangement in PSoC-5 based design.

5.2.3 PSoC-5 (WPA) programming

PSoC Creator 3.3 Integrated Development Environment (IDE) **[3-4]** was used for programming the device. The IDE consist of a C compiler which was used for programming purpose. C language codes for the hardware thus written are given in the **Appendix B**. In-circuit emulator and a development board was used for testing the functionality of the hardware. **Fig. 5.7** shows the top schematic of PSoC-5 (WPA) firmware.

5.2.4 Operation of WPA (PSoC-5 based design)

In PSoC-5 based design (Weld Pattern Analyzer) combination of hardware and software was implemented in such a way that as soon as sensing element senses voltage and current signals they have to be amplified and conditioned. Then digitization and sampling of the input signal were obtained so that the resultant data can be stored in consecutive memory location with the help of hardware counter. The stored data is then transferred to the external computer for post processing using WPA software and hardware combinations. A schematic of WPA operation is shown in **Fig. 5.9**.

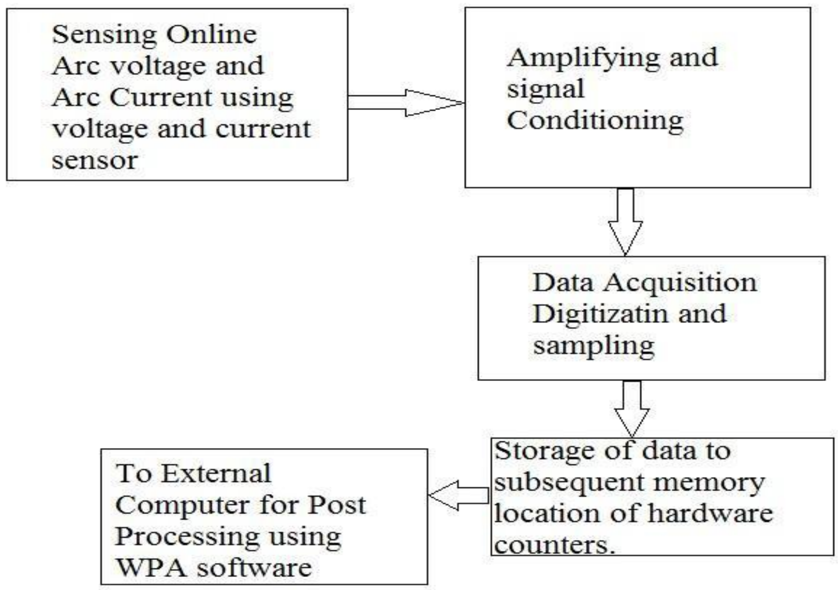


Fig. 5.9: Working schematic of WPA (PSoC-5 design).

Fig. 5.10 shows front and rear view of PSoC-5 based design (WPA), this consists of: -

a) Front End

1. Status LEDs – shows the type of operation being carried out (i.e. transmission/reception)

2. Test LEDs- for testing the device operation.

3. Key 1- used to initiate the data acquisition.

4. Key 2- used for data transmission to external computer.

5. LCD- used for displaying recorded voltage, current and status of the device.

b) Back End

1. Serial Port Connection- for connecting serial cable to serially transfer the acquired data to the external computer.

2. BNC Connection- facilitates the BNC type connection for voltage and current sensors.

3. Two wire connections- provide the facility to connect two wire type voltage and current sensors

Fig. 5.11 shows the work flow diagram of WPA. Once the power is switched on, the firmware installed in WPA initiates the communication process with voltage and current sensors. If WPA senses the readings, it will start loging the raw data to consecutive memory location and will wait till the acquisition of voltage and current signals gets over. After this WPA will transfer these data to external computer via serial communication port. If readings are not obtained, then the equipment should be checked for proper connections and in case the readings are not corect then the sensors should be calibrated properly.

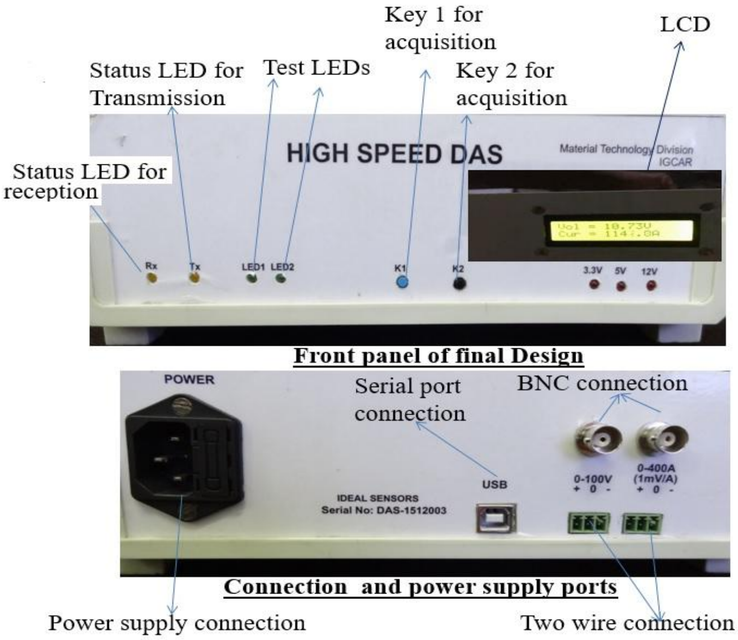


Fig. 5.10: Top and rear view WPA.

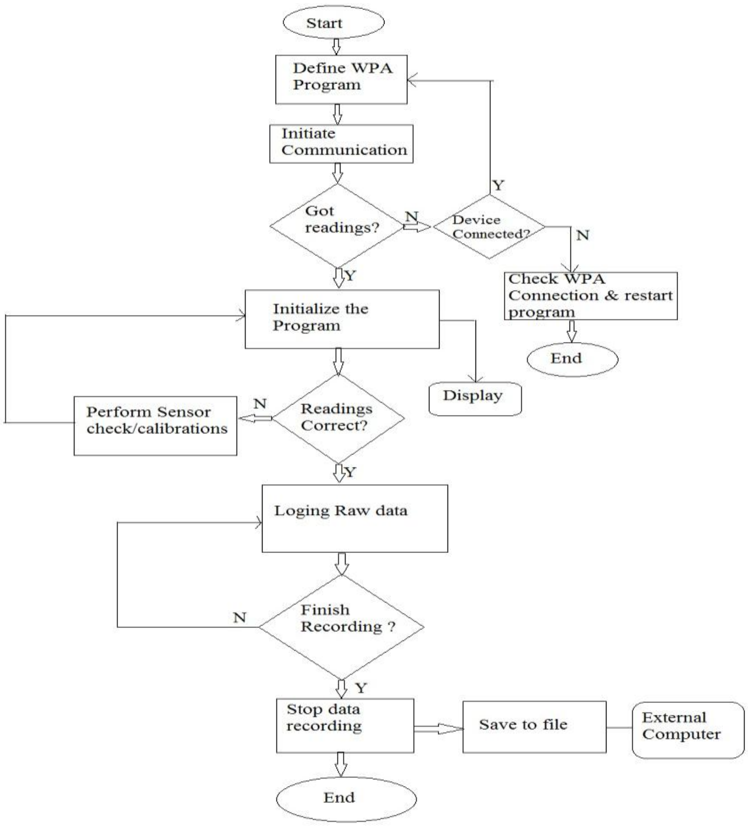


Fig. 5.11: Working flow diagram of WPA.

Data thus collected from the WPA was used to visualize the welding signal both in online and offline mode. In online mode the random fluctations in data were seen at the time of welding and in offline mode these variations were stored in computer hard disk for further processing. How this was done is described in next sections.

5.2.4.1 Online (Real-Time) visualization/analysis of weld data

To visualize the welding data on real time, lab-view based interface was designed; this is shown in **Fig. 5.12**. The interface designed with lab-view provided the flexibility to see real time voltage and current signal. Front panel of this interface consists of COM port selection tab (so that proper COM port can be selected), baud rate tab, debug tab (to show any error message) and data array (to show the array of data that has been acquired) tab can also be seen in this figure.

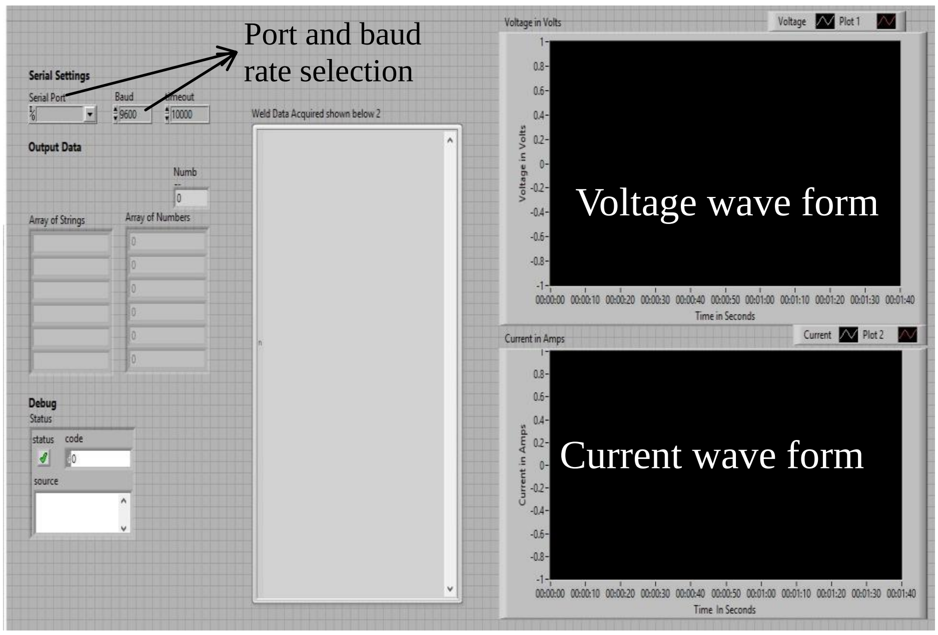


Fig. 5.12: Real time visualization/analysis of current and voltage signal with lab view.

Lab view Interface is slower in response consequently; HyperTerminal interface of the windows was also used to record the data and to store the same in desired memory location of an external computer (**Fig. 5.13**).

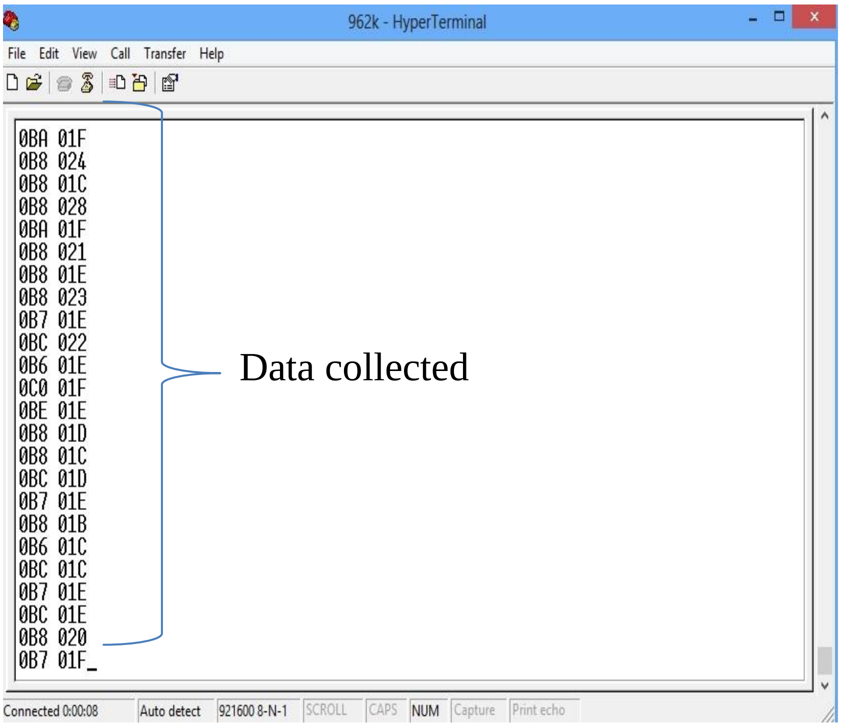


Fig. 5.13: Real time data collection with hyper terminal.

5.2.4.2 Offline analysis of welding data

Fig. 5.14 shows the flow diagram of the analysis performed by Weld Pattern Analyzer (WPA) in Offline mode. In Offline mode WPA provides an Interface window to the user which allows the user to select desired option from a list of popup menu. This Mode consists of three major sections namely Interface Windows, file loading and analysis section and lastly the printing and saving of final result.

This interface was designed using MATLAB 2009, and the code used for this designing are presented in **Appendix C**.

Interface window

Interface window has three major dialogue boxes namely file loading and analysis selection menu, exit menu and print menu.

File loading and analysis selection menu

This is used to load the *.CSV file for further analysis. Any number of voltage and current data file can be selected for the analysis. Depending on the requirement of the user, duration of weld data to be analyzed can also be modified. Various parameters of welding can be studied under this menu, different pop menu provided under Interface Window (**Fig. 5.15**) are shown in **Fig. 5.16**.

Exit: Exit from the Interface window and

Print/save: results obtained from various Popup Menu can be viewed /stored in hard drive location and can be printed as a hardcopy for having a record.

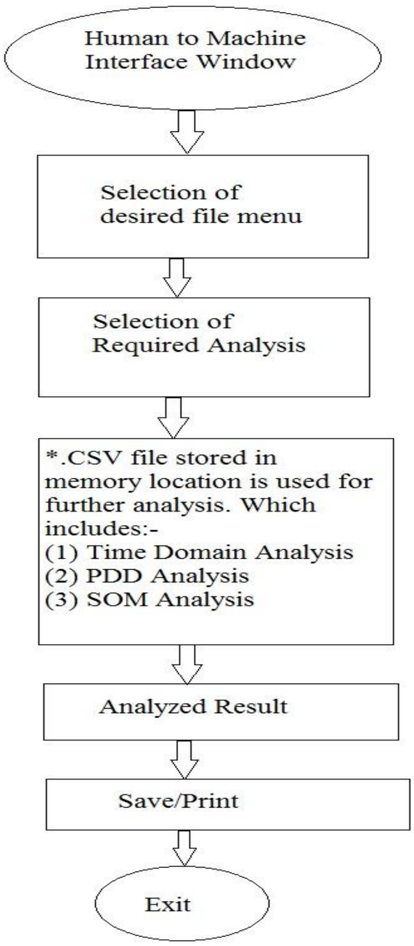


Fig. 5.14: Flow diagram of interface window for analyzing acquired data.

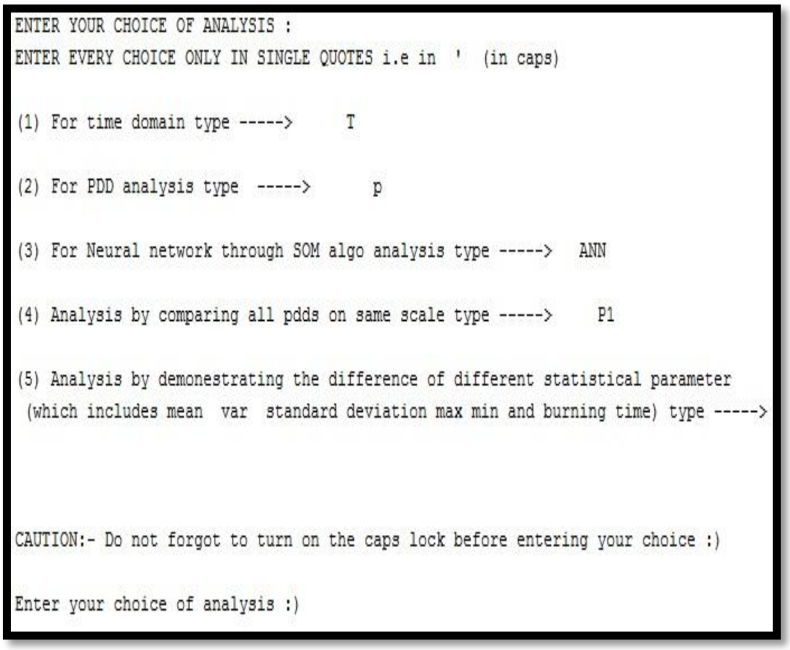
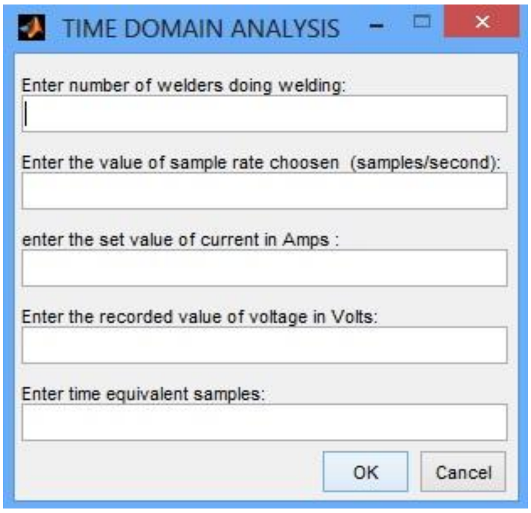
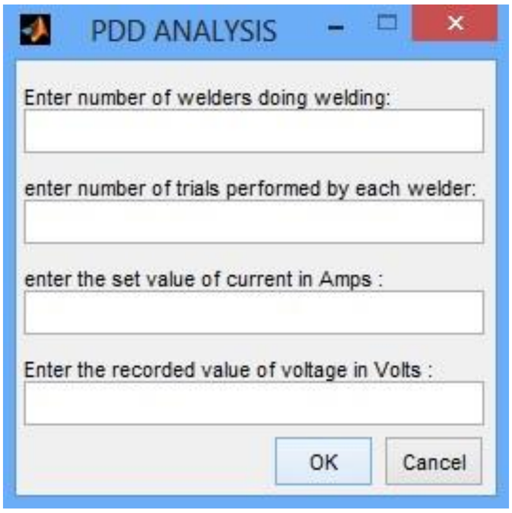
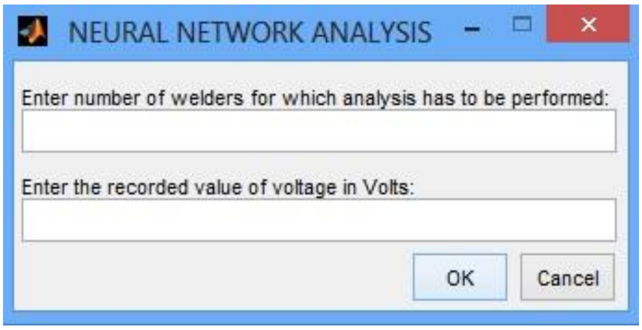


Fig. 5.15: Overall interface window.





(a) Time domain analysis **(b) PDD analysis**

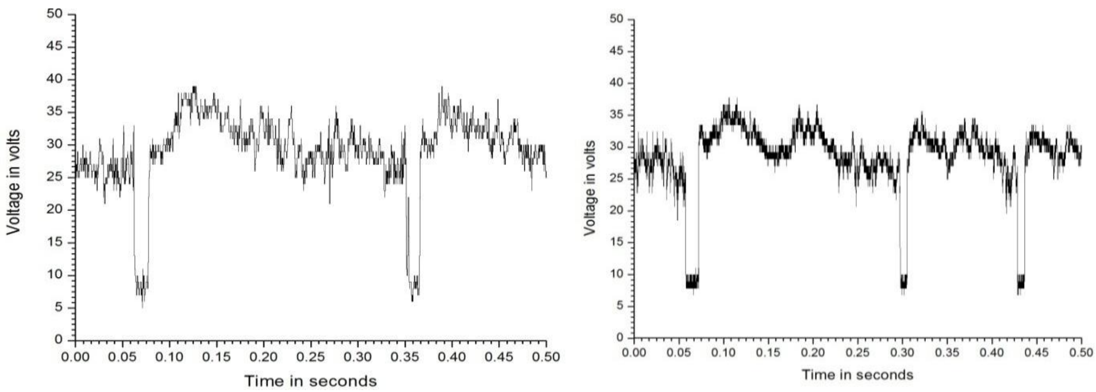


(c) ANN (SOM) analysis

Fig. 5.16: Various pop-up menu provided under interface window for WPA.

5.3 Data acquisition using PSoC-5 based design

Fig. 5.17(a) shows the time domain analysis of voltage data acquired at the rate of 100,000 samples/s with PSoC-5 based design (WPA). The experimental details are exactly same as those given in this chapter for the data acquisition using PSoC-3 based system in **section 5.2.1.1.** Due to increase in the data acquisition rate quantum of data acquired increased significantly and this is reflected in its time domain analysis. From this figure we can see that more number of data points is now present to represent the physical variations of the process. A comparison of time domain analysis obtained using PSoC-5 data with that of DSO data in **Fig. 5.17(b)** shows a good correlation between them.

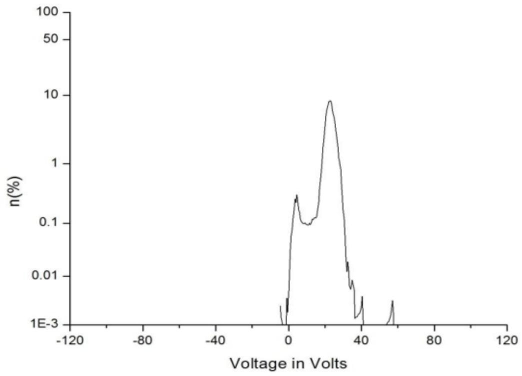


(a)Time domain analysis with PSoC-5 based design **(b)Time domain analysis with DSO**

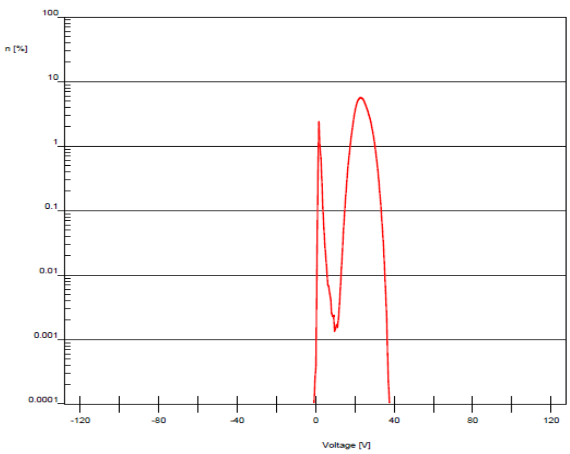
Fig. 5.17: Time domain analysis of the voltage data acquired using PSoC-5 (WPA) and DSO.

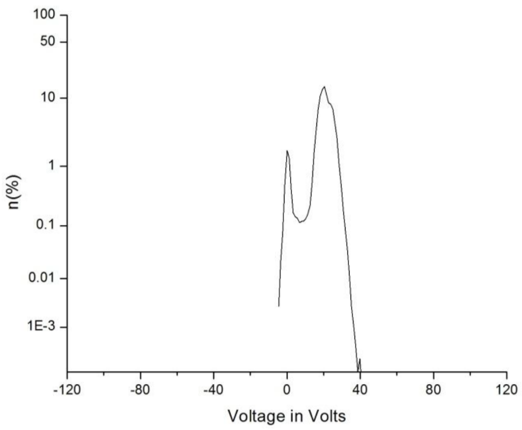
Fig. 5.18(a) shows the PDD analysis of the voltage data obtained using PSoC-5 based design, due to the increase in data through put rate PDD thus obtained improved significantly; smoothness in the PDD can be seen from this figure. Further, data acquired using PSoC-5 based design was found to be consistent and repeatable for different trials. To have a more clear understanding, PDD analysis of the voltage data obtained using PSoC-5 based design was compared with the PDD of the voltage data acquired using DSO and those acquired using Analysator Hanover **[1]** which is shown in **Fig. 5.18(a,b,c).** These data were acquired simultaneously using WPA, DSO and analysator Hanover for a welding made using E 7018 electrodes and an inverter power source. Very good correlation between these PDDs can be seen from this figure. Here, it should be noted that the voltage PDD generated by Analysator **[1]** is presented over a large range varying from -120 V to 120 V and hence, for the comparison purpose the range of the voltage PDDs obtained with DSO and WPA (PSoC-5 design) are also modified to match this.

Having demonstrated that the quality of data acquired by PSoC-5 based design (WPA) is comparable to those acquired using DSO and Analysator Hanover, WPA was used for studying the arc welding process, as done using DSO and presented in Chapter 4.



(a) Voltage PDD with PSoC-5 based design





(b)Voltage PDD with Analysator [1] (c) Voltage PDD with DSO

Fig. 5.18: PDD analysis of the voltage data acquired using PSoC-5 (WPA), Analysator and DSO.

5.4 Applications of WPA for evaluation of arc welding process

Suitability of WPA to study arc welding process was demonstrated by using this to assess the skill level of welders and to study the variation of arc characteristics of E 7018 and E 6013 electrodes with change in flux composition. In both the cases, PDDs obtained using WPA were compared with those obtained using DSO and it is demonstrated that WPA can indeed be used for these applications.

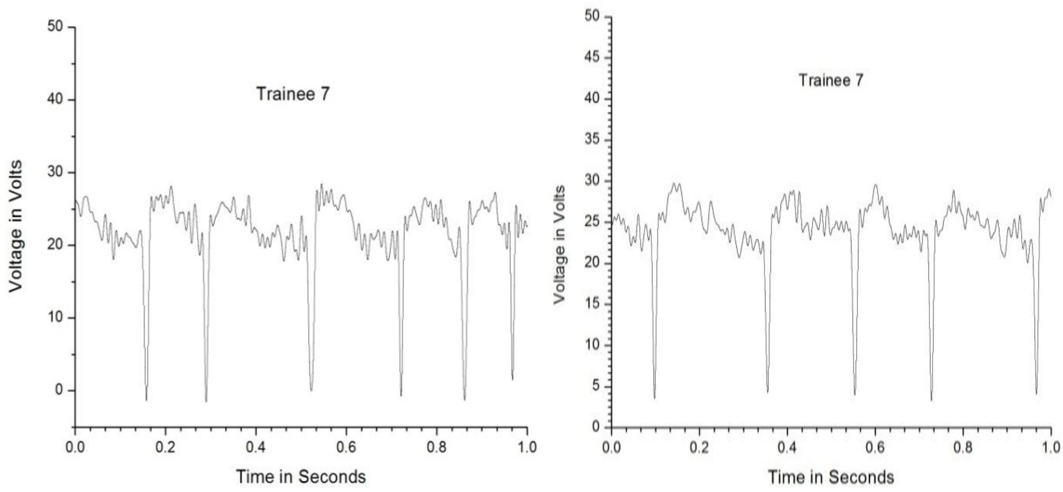
5.4.1 Evaluation of welding skill

5.4.1.1Experimental details

For demonstrating that PSoC-5 based design can be used to evaluate the skill level of various trainee welders using the procedure developed in **chapter 4**, data was acquired from a batch of trainee welders who have completed the welder training from a training institute. Bead-on-plate welds were made by these welders on a carbon steel plate using E7018 electrodes and an inverter power source. Set current and voltage displayed was 100A and 25V respectively. Instantaneous value of voltage and current data were acquired at the rate of 100,000 samples/s for the duration of 20s. Data thus acquired was filtered using low pass filter and subjected to post processing using statistical (PDD) analysis. Skill of the welders was also assessed independently from the dimensional measurements of the bead-on-plate weld and examination of the bead profile.

5.4.1.2 Time domain and PDD analysis

Time domain and PDD analysis of voltage data acquired using WPA and DSO of a trainee welder in a skill training institute is shown in **Fig. 5.19** and **Fig. 5.20**. Unlike the time-domain graph obtained of the PSoC-3 design (Fig 5.4b), the time-domain graph of WPA matches well with oscillogram of the DSO. PDDs for WPA and DSO are also similar; though there are some minor differences. In PDD of WPA, the range of voltage recorded is wider than that recorded using DSO. However, the two peak behavior is clearly seen in PDD of WPA though the peak corresponding to short circuit is relatively small.



(a)Time domain analysis with PSoC-5 (WPA) **(b)Time domain analysis with DSO**

Fig. 5.19: Time domain analysis of the voltage data acquireed using PSoC-5 (WPA) and DSO.

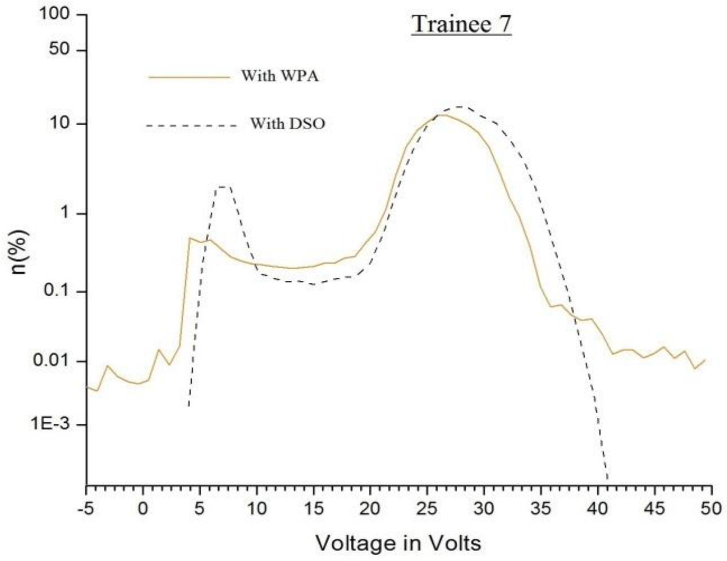


Fig. 5.20: PDDs obtained with the data acquired by DSO and WPA for one typical trainee welder.

Fig. 5.21 shows PDD generated using the data acquired using WPA for the eight welders passing out from a training institute. PDD generated for the data acquired for an experienced welder is also shown. Using the criteria of separation of the two peaks (as discussed in **Chapter 4**), the skill levels of welders are ranked in the figure.

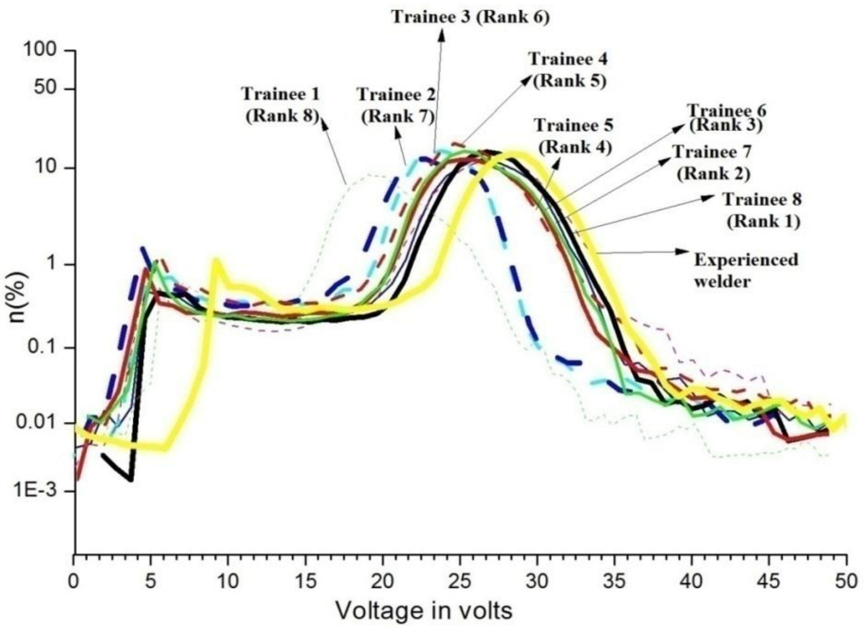


Fig. 5.21: PDD analysis of various welders' data from the skill training institute.

Fig. 5.22 shows one of the typical weld beads made by each welder. From the comparison of ranking given in **Fig. 5.22** and appearance of the weld bead made by the welder, one can conclude that ranking is in line with the appearance of the weld bead. The weld bead by Trainee 1 is not uniform in its width and is not straight and this welder is ranked 8^{th} based on the shape of the PDD. In contrast, the weld bead made by Trainee 8 is straight and uniform in its width throughout the length and from the shape of PDD, this welder is ranked as most skilled. Ranking of other welders also matches with the appearance of the weld bead produced by them. Hence, it is demonstrated that data acquisition using WPA and its subsequent analysis can be used to evaluate the skill level of welders as it was done using the data acquired using DSO.

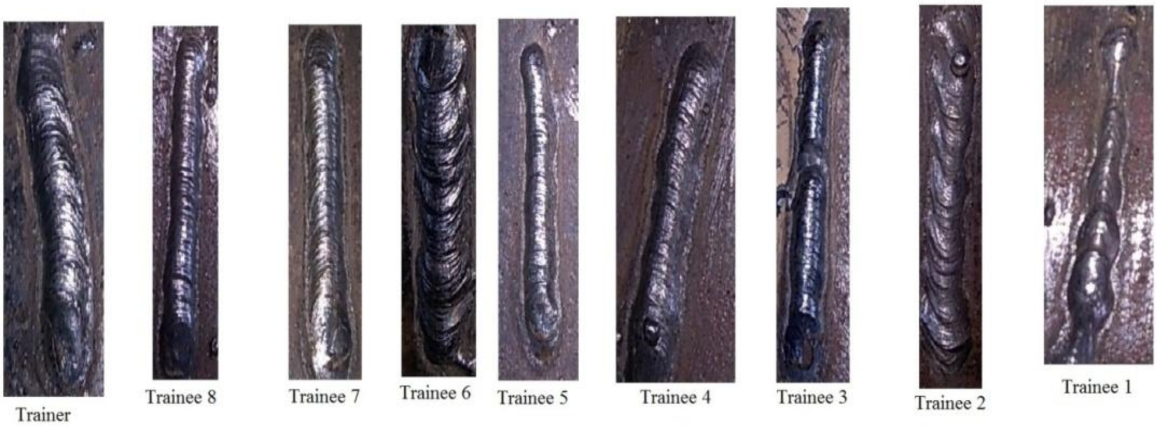


Fig. 5.22: Bead images of various trainee welders from the skill training institute.

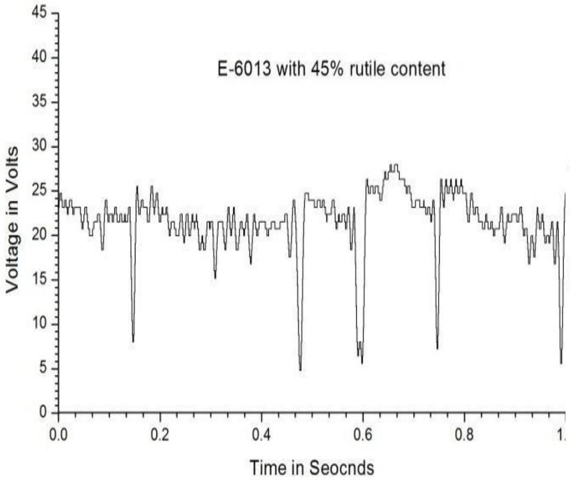
5.4.2 Evaluation of welding consumables

5.4.2.1 Experimental setup

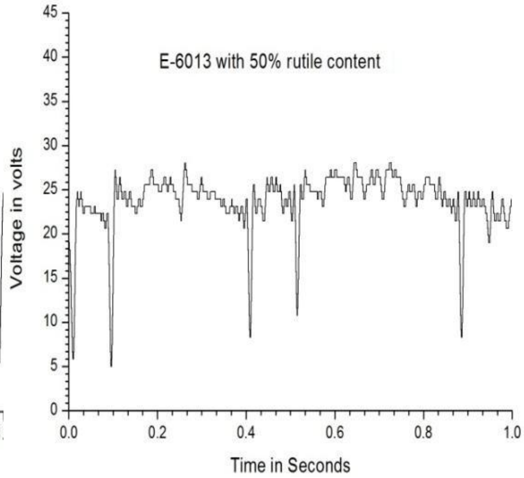
For demonstrating that WPA can also be used to evaluate various welding consumables, data was acquired using WPA along with those acquired using DSO for bead-on-plate welds made using E 7018 electrodes and E 6013 electrodes varying in their rutile content. The experimental details are exactly same as those given in **section 4.3.3** of **Chapter 4.**

5.4.2.2 Effect of variations in flux compositions.

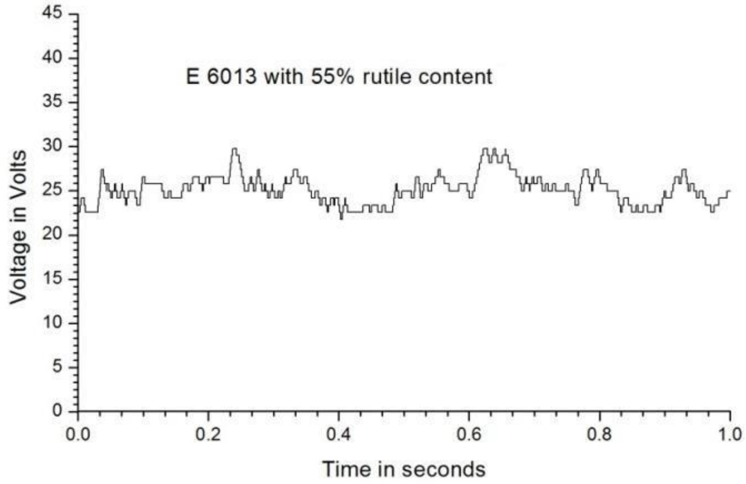
Time domain and PDD analysis of voltage data acquired using WPA for E 6013 electrodes varying in their rutile content is shown in **Fig. 5.23 (a,b,c)** and **Fig. 5.24** respectively. Both are similar to those obtained for data acquired using DSO for the same electrodes and shown in **Fig. 4.25**: and **Fig. 4.26** respectively in **chapter 4**. Decrease in the occurrence of short circuit transfer for electrodes with 55% rutile content is observed in the data acquired both by DSO and WPA.



(a) E 6013 with 45% rutile content



(b) E 6013 with 50% rutile content



(c) E 6013 with 55% rutile content

Fig. 5.23: Time domain analysis of E 6013 electrodes.

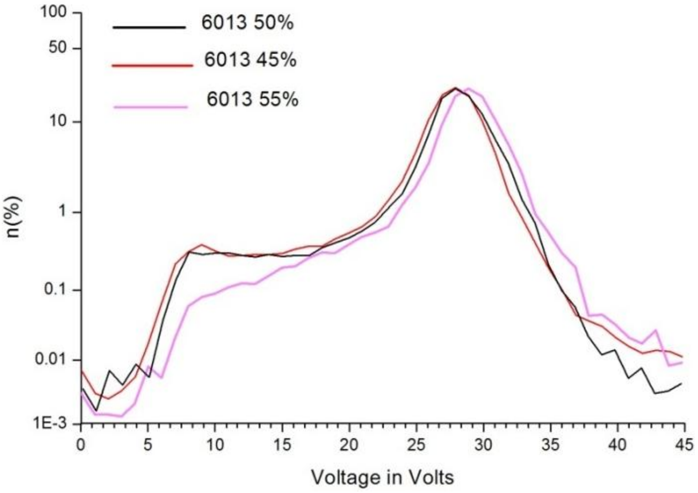
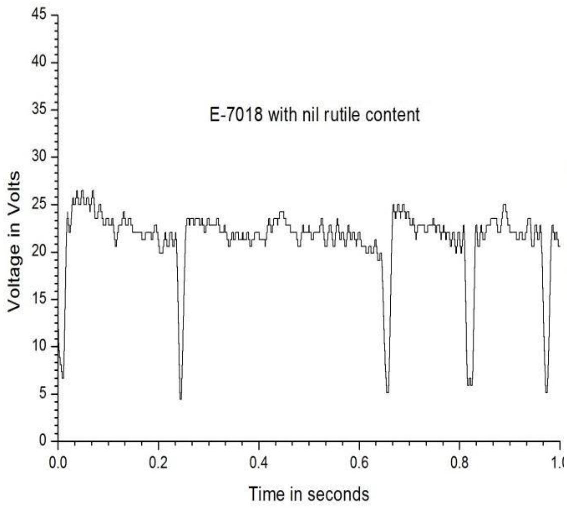
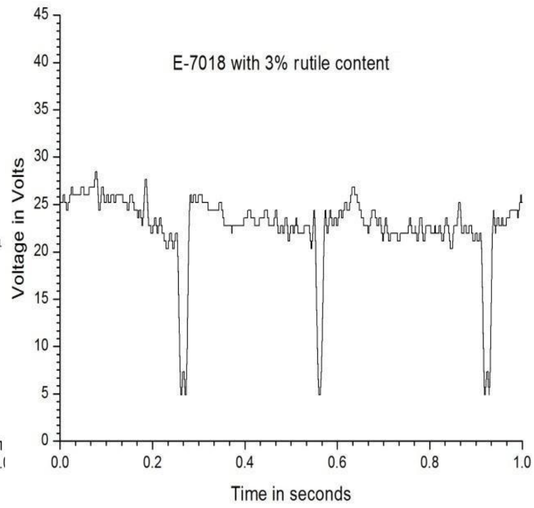


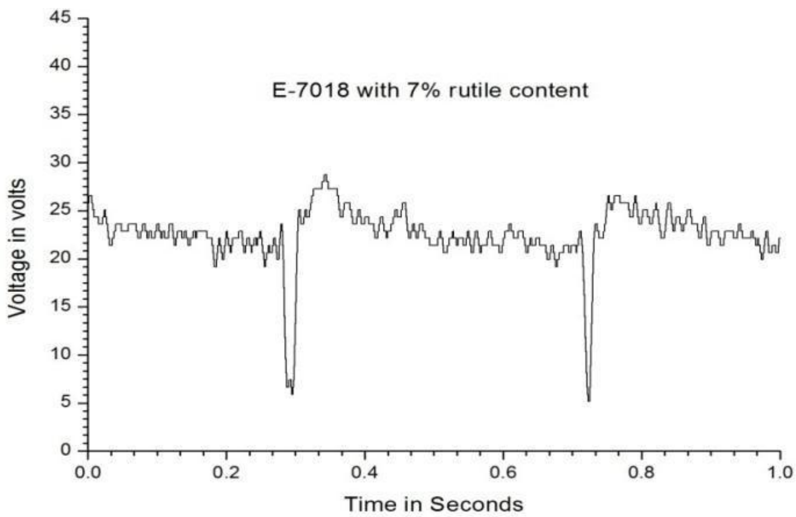
Fig. 5.24: PDD analysis of E 6013 electrode with varying rutile content.

Time domain and PDD analysis of E7018 electrodes with different levels of rutile contents shown in **Fig. 5.25** and **Fig. 5.26** respectively also reveals the similar results as it was obtained for data acquired using DSO and shown in **chapter 4**. In this case, increasing rutile from 0- 7wt.% did not show any significant change either in time domain analysis or in PDD indicating effect of rutile content in the range studied on mode of metal transfer in E 7018 electrode is negligible.





(a) E 7018 with rutile content- nil **(b) E 7018 with 3% rutile content**



(c) E 7018 with 7% rutile content

Fig. 5.25: Time domain analysis of E 7018 electrode with different rutile content.

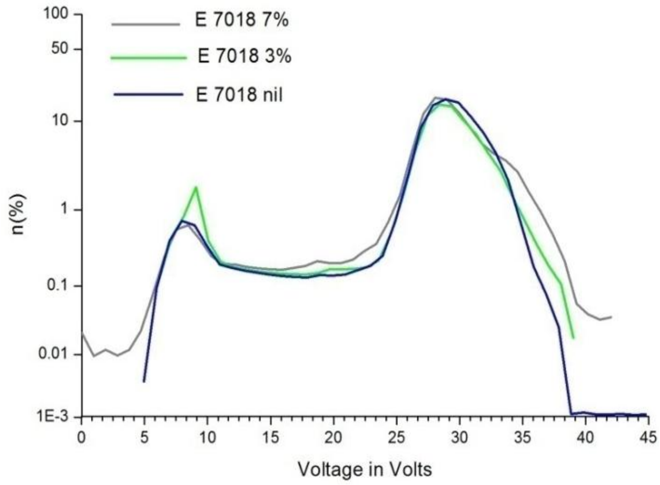


Fig. 5.26: PDD analysis of E 7018 electrode with varying rutile content.

From the above illustrations it can be said that WPA more or less meets most of the requirement that were listed in the introduction of this chapter for an effective data acquisition system that can replace DSO. Speed of data acquisition, volume and accuracy of data acquired are comparable to that of any standalone data acquisition system developed for this purpose.

Usage of SoC in WPA makes it an excellent noise immune system. Consequently, WPA thus developed can manage electrostatic and electromagnetic noises present in a welding environment. By numerous trials and analysis, it has been proved that WPA can withstand high current and voltage fluctuations arising due to arc variations in a welding process. Ruggedness and durability of WPA has also been proven by its continuous usage to monitor the arc welding process. Unlike DSO this system has very fewer controlling parameters and extremely user friendly interface. Consequently, a less skilled person can also operate it with ease. Additionally, due to the usage of simple yet interactive HMI using Lab-view, hyper terminal and mat-lab software WPA has an option to vary the data export rate to the external storage. Further, WPA provides an arrangement that gives continuous power backup to the memory blocks of WPA hardware. This means that, even in the case of main power outage the data stored in WPA memory will not get erased. Finally, compared to DSO or any other commercial available weld monitoring systems, WPA developed in this work is an extremely cost effective tool.

The Weld Pattern Analyzer and the procedure are so simple and cost effective that they can be incorporated into welding power sources for the purpose of on-line data acquisition and subsequent analysis. For example, it is already shown how the PDD of a welding data of a trainee welder gets modified (**chapter 4**) as the training progresses. Making use of this information an intelligent system with a feedback control can be incorporated in the welding power source that is employed for welder training, so that at the time of welding itself the welders gets a feedback from the system to adjust or to maintain a proper arc gap. If this can be done, self-learning of welding skill will be possible in a short span of time.

WPA system can be further improved to store extremely large amount of data from multiple trials into its memory. Such a system can store data from different trials continuously and process them together subsequently. This would be useful in evaluating performance of different power sources or consumables and assessing skill levels of a large number of welders in one go.

Summary

In this chapter development of a Weld Pattern Analyzer (WPA) which is based on PSoC-5 platform, has been described Evolution of this system originally from PSoC-3 system to the present PSoC-5 system is also given. Human Machine Interface for WPA was developed to visualize the voltage and current signals. Application of WPA for assessing skill levels of welders and studying the effect of flux composition on arc characteristics of welding consumables were demonstrated. One to one correspondence of these results with those obtained with similar studies carried out using DSO proves that WPA can be used as a cost effective and user friendly alternative to DSO for the purpose of weld data acquisition and analysis.

Reference

1. D. Rehfeldt, M. Rehfeldt., Computer-aided quality assurance (CAQ) of Al-MIG-welding with analysator hanover, in *Proceedings International Forum on Automobile Welding*, *Mechanical Engineering Press*, Beijing, 2003.

2. Fernando Manzano Rubio., M.Tech Thesis on Programmable-System-on-Chip based data acquisition for educational purposes, Universitat politecnica de catalunya, Spain, April 2012.

3. Web: **http://www.cypress.com/**

4. Web: http://www.cypress.com/products/32-bit-arm-cortex-m3-psoc-5lp

6

Conclusion, contributions and scope for future research

6.1 Conclusion

In this work, a Weld Monitoring system with a commercially available general purpose DSO for data acquisition and suitable voltage and current sensors is developed for on-line data acquisition and subsequent analysis to study arc welding processes. It is shown that Speed of data acquisition, volume and accuracy of data acquired using DSO are comparable to that of any standalone data acquisition system developed for this purpose. Using rigorous analysis, it was then shown that FFT low pass filter is appropriate to filter out the noise present in the weld data. Further, to acquire all the possible variations taking place in actual welding process rate of data acquisition was optimized and it is proposed that 100,000 samples/s is suffice for reliable acquisition of welding data.

Analysis of welding data thus acquired for duration of 20 seconds has shown that online monitoring of the welder’s skill using a commercially available DSO is possible. Probability density distributions (PDDs) which are generated using the welding data acquired is able to differentiate between the skill levels of different welders. Voltage PDD of trainee welder changes continuously to be similar to that of an experienced welder as the learning progresses. From the shape of the voltage PDDs, generated using same type of machine and welding consumable, it is possible to rank the skill levels of different welders in a group. Ranking thus obtained matched fairly well with the ranking of the welders made using the current practice of visual examination of the welds.

Voltage PDD of one type of electrode has been distinctly different from another. Hence, voltage PDDs generated from data acquired during welding with different electrodes are used to differentiate electrodes as cellulose, rutile and basic types etc. It is also possible to identify the effect of variation in the composition in the same type of flux on the arc characteristics of the welds produced. This aspect could be exploited to grade different consumables of the same type from different manufacturers or different batches of same manufacturer. Analysis of weld data gathered with the help of DSO has also been used to grade different welding power sources.

Subsequently the DSO in the weld monitoring system has been replaced using a Programmable System on Chip (PSoC) based Data Acquisition System. User friendly Human Machine Interface (HMI) using MATLAB and LABVIEW software have also been developed for this system. Results obtained using this system, named as Weld Pattern Analyzer (WPA) matched well with those obtained using DSO. The developed system in this thesis work is very economic, rugged, compact and portable compared to DSO and can even be integrated with a welding power source for continuous monitoring of the welding process.

6.2 Contributions

Major contribution of this research work are listed below.

1. Development of Weld Pattern Analyzer (WPA), a dedicated, affordable and innovative tool that can be used for a comprehensive analysis of the welding.

2. Development of a novel, innovative and simple yet robust inferential technique for grading/Evaluating/analyzing welding parameters.
3. Using the technique suggested in this work, one can evaluate the skill of the welders as soon as welder makes a weld bead, without any need to time consuming measurements of the dimensions of the weld bead. Further, progress of learning of a trainee welder can be monitored almost continuously from PDD or SOM analysis of the voltage signal acquired. One can also use PDD or SOM analysis for screening out unskilled welders from skilled during recruitment drives of large number of welders.
4. Various parameters have been found that can be used to evaluate the performance of same/different type of power sources supplied by same/different manufacturers. Additionally, with the help of proposed technique it should be possible to monitor the performance of the power source over a period of time.
5. Proposed technique can be used to evaluate/differentiate different welding consumables and welding processes as well.
6. An interfacing software package was developed for weld pattern analysis.
7. This facility provides feasibility for online monitoring and diagnosis of Arc welding.
8. WPA can be used as an excellent cross verification tool to assess quality of Arc welding process.

6.3 Scope for future research work

1. In this work main focus was on the quality evaluation of SMAW and GMAW welding process. Other arc welding processes like TIG and Submerged Arc

Welding are not covered. Study can be extended to these welding processes and a Welding pattern analyzer (WPA) which can be used for all the arc welding processes can be developed.

2. PDDs generated from WPA are slightly different from those generated using DSO data and Analysator Hannover. This could be attributed to A/D card used in WPA. However, a systematic study can be undertaken to improve the WPA further to minimize this difference.
3. WPA can be integrated as a part of the welding power source with proper output devices to transfer the acquired data for on line monitoring or storage and post processing. In this way welding data for each and every welding carried out using this machine can be made available as and when required.
4. One of the potential applications WPA is to detect a weld defect as soon as it happens from the variation in the electrical signals. This has not been attempted in the present work and is proposed for future.
5. WPA can be used to assess the environmental hazards associated with arc welding processes. Signatures for undesirable metal fumes and gases present in the arc atmosphere in the electrical signals can be used to assess the health hazards to welding personal.
6. A system can be developed to incorporate with WPA to transmit the welding data using Wireless – Fidelity [Wi-Fi] / Internet to a remote location for post processing or to seek the expert opinion about the process behavior.

APPENDIX

A

SOM Algorithm

Overall SOM algorithm is shown below: -

1) Training

- Select output layer network topology

 a) Initialize current neighborhood distance, D (0), to a positive value

 b) Initialize weights from inputs to outputs to small random values.

 Let t = 1

- While computational bounds are not exceeded do

 a) Select an input sample i_l

 b) Compute the square of the Euclidean distance of i_l from weight vectors (w_j) associated with each output node: -

$$\sum_{k=1}^{n} \left(i_{l,k} - w_{j,k}(t)\right)^2$$

 c) Select output node *j** that has weight vector with minimum value from step b) *d)* Update weights to all nodes within a topological distance given by D (t) from j^*, using the weight update rule:

$W_j(t+1) = w_j(t) + \eta(t)(i_l - w(t))$

e) Increment t

- End while

Learning rate decreases with time: $0 < \eta(t) \leq \eta(t-1) \leq 1$

2) *Testing*: Use weights from training

B

Keil-c Programming Code for Weld Pattern Analyzer

```
#include <project.h>

#define SAMPLE_SIZE     0x1E8480

void SRAM_AddressReset(void)
{
    ACLR_Write(1);
    ACLR_Write(1);
    ACLR_Write(0);
    ACLR_Write(0);
}

void SRAM_AddressInc(void)
{
    AINC_Write(1);
    AINC_Write(0);
    AINC_Write(1);
}

void SRAM_AStrobeA0(void)
{
    AS1_Write(0);
    AS1_Write(1);
}

void SRAM_AStrobeA4(void)
{
    AS2_Write(0);
    AS2_Write(1);
}

void SRAM_AStrobeA8(void)
{
    AS3_Write(0);
    AS3_Write(1);
}

void SRAM_AStrobeA12(void)
{
    AS4_Write(0);
    AS4_Write(1);
}
```

```
void SRAM_AStrobeA16(void)
{
    AS5_Write(0);
    AS5_Write(1);
}

void SRAM_AStrobeA20(void)
{
    AS6_Write(0);
    AS6_Write(1);
}

unsigned int SRAM_RD(void)
{   unsigned int Dat;

    MRD_Write(0);
    Dat = MDT_H_Read();
    Dat <<= 8;
    Dat |= MDT_L_Read();
    MRD_Write(1);
    return Dat;
}

void SRAM_WR(void)
{
    MWR_Write(0);
    MWR_Write(1);
}

void BackLightON(void)
{
    LCD_BL_Write(1);
}

void BackLightOFF(void)
{
    LCD_BL_Write(0);
}

void SRAM_AddressWrite(unsigned long Addr)
{
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA0();
    Addr >>= 4;
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA4();
    Addr >>= 4;
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA8();
    Addr >>= 4;
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA12();
    Addr >>= 4;
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA16();
    Addr >>= 4;
    ADDR_Write(Addr & 0x0000000f);
    SRAM_AStrobeA20();
```

```
    Addr >>= 4;
}

void SRAM_ModeRead(void)
{
    MDT_L_SetDriveMode(PIN_DM_RES_UP);
    MDT_L_Write(0xff);
    MDT_H_SetDriveMode(PIN_DM_RES_UP);
    MDT_H_Write(0xff);
}

void SRAM_ModeWrite(void)
{
    MDT_L_SetDriveMode(PIN_DM_STRONG);
    MDT_L_Write(0x00);
    MDT_H_SetDriveMode(PIN_DM_STRONG);
    MDT_H_Write(0x00);
}

void Test_SRAM_AddressReg(void)
{
    SRAM_AddressReset();
    SRAM_AddressWrite(0x00ee);
    SRAM_AddressInc();
    SRAM_AddressInc();
    SRAM_AddressInc();
    SRAM_AddressWrite(0x0000ff);
    SRAM_AddressInc();
    SRAM_AddressReset();
    SRAM_AddressInc();
    SRAM_AddressWrite(0x00ff00);
    SRAM_AddressWrite(0xffff00);
    SRAM_AddressWrite(0xffffff);
    SRAM_AddressInc();
    SRAM_AddressReset();
}

void Test_ADC_Display(void)
{   unsigned int AdcV, AdcC;
    unsigned long Dly;

    LCD_Position(0, 0);
    LCD_PrintString("                ");
    LCD_Position(1, 0);
    LCD_PrintString("                ");
    ADC_SAR_1_StartConvert();
    ADC_SAR_2_StartConvert();
    while(1)
    {
        ADC_SAR_1_IsEndConversion(ADC_SAR_1_WAIT_FOR_RESULT);
        AdcV = ADC_SAR_1_GetResult16();
        ADC_SAR_2_IsEndConversion(ADC_SAR_2_WAIT_FOR_RESULT);
        AdcC = ADC_SAR_2_GetResult16();
        LCD_Position(0, 0);
        LCD_PrintString("                ");
        LCD_Position(0, 0);
        LCD_PrintNumber(AdcV);
        LCD_Position(1, 0);
        LCD_PrintString("                ");
```

```
        LCD_Position(1, 0);
        LCD_PrintNumber(AdcC);
        Dly = 200000;
        while(Dly--);
    }
}

void Adc_2SRAM(void)
{   unsigned int AdcV, AdcC;
    unsigned long Addr;

    Addr = 0;
    ADC_SAR_1_StartConvert();
    ADC_SAR_2_StartConvert();
    SRAM_AddressReset();
    SRAM_ModeWrite();
    while (Addr < SAMPLE_SIZE)
    {   ADC_SAR_1_IsEndConversion(ADC_SAR_1_WAIT_FOR_RESULT);
        AdcV = ADC_SAR_1_GetResult16();
        ADC_SAR_2_IsEndConversion(ADC_SAR_2_WAIT_FOR_RESULT);
        AdcC = ADC_SAR_2_GetResult16();
        MDT_L_Write(AdcV & 0xff);
        AdcV >>= 8;
        MDT_H_Write(AdcV & 0x0f);
        SRAM_WR();
        Addr++;
        SRAM_AddressInc();
        MDT_L_Write(AdcC & 0xff);
        AdcC >>= 8;
        MDT_H_Write(AdcC & 0x0f);
        SRAM_WR();
        Addr++;
        SRAM_AddressInc();
    }
    ADC_SAR_1_StopConvert();
    ADC_SAR_2_StopConvert();
}

void SRAM_2USB(void)
{   unsigned char Msd, Mid, Lsd;
    unsigned int Dat;
    unsigned long Addr;

    SRAM_AddressReset();
    SRAM_ModeRead();
    Addr = 0;
    while(Addr < SAMPLE_SIZE)
    {   Dat = SRAM_RD();
        Lsd = Dat & 0x000f;
        Lsd += ((Lsd < 10) ? '0' : '7');
        Dat >>= 4;
        Mid = Dat & 0x000f;
        Mid += ((Mid < 10) ? '0' : '7');
        Dat >>= 4;
        Msd = Dat & 0x000f;
        Msd += ((Msd < 10) ? '0' : '7');
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
        UART_PutChar(Msd);
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
```

```
        UART_PutChar(Mid);
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
        UART_PutChar(Lsd);
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
        UART_PutChar(' ');
        SRAM_AddressInc();
        Dat = SRAM_RD();
        Lsd = Dat & 0x000f;
        Lsd += ((Lsd < 10) ? '0' : '7');
        Dat >>= 4;
        Mid = Dat & 0x000f;
        Mid += ((Mid < 10) ? '0' : '7');
        Dat >>= 4;
        Msd = Dat & 0x000f;
        Msd += ((Msd < 10) ? '0' : '7');
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
        UART_PutChar(Msd);
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
        UART_PutChar(Mid);
        while (UART_ReadTxStatus() & UART_TX_STS_FIFO_FULL);
//        UART_PutChar(Lsd);
        UART_PutCRLF(Lsd);
        SRAM_AddressInc();
        Addr++;
        Addr++;
    }
}


void Test_SRAM_Data(void)
{
    unsigned long Address;

    SRAM_AddressReset();
    SRAM_ModeWrite();
    Address = 0;
    while (Address < 0x400000)
    {   MDT_L_Write(0xee);
        MDT_H_Write(0xee);
        SRAM_WR();
        SRAM_AddressInc();
        Address++;
    }
    SRAM_AddressReset();
    SRAM_ModeRead();
    Address = 0;
}

unsigned char Cmd_Wait(void)
{
    while((PB1_Read()==1) && (PB2_Read()==1));
    if(PB1_Read()==0)
        return 1;
    else
        return 2;
}

void Init(void)
{
```

```
    AS1_SetDriveMode(PIN_DM_STRONG);            // Set drive mode for
Memory Address regs
    AS2_SetDriveMode(PIN_DM_STRONG);
    AS3_SetDriveMode(PIN_DM_STRONG);
    AS4_SetDriveMode(PIN_DM_STRONG);
    AS5_SetDriveMode(PIN_DM_STRONG);
    AS6_SetDriveMode(PIN_DM_STRONG);
    AINC_SetDriveMode(PIN_DM_STRONG);
    ACLR_SetDriveMode(PIN_DM_STRONG);
    ADDR_SetDriveMode(PIN_DM_STRONG);
    MRD_SetDriveMode(PIN_DM_STRONG);
    MWR_SetDriveMode(PIN_DM_STRONG);

    LCD_BL_SetDriveMode(PIN_DM_STRONG);
    LED1_SetDriveMode(PIN_DM_STRONG);
    LED2_SetDriveMode(PIN_DM_STRONG);

    PB1_SetDriveMode(PIN_DM_DIG_HIZ);
    PB1_Write(1);
    PB2_SetDriveMode(PIN_DM_DIG_HIZ);
    PB2_Write(1);

    ADC_SAR_1_Start();
    ADC_SAR_1_SetPower(ADC_SAR_1__HIGHPOWER);
    ADC_SAR_1_SetResolution(ADC_SAR_1__BITS_12);
    ADC_SAR_2_Start();
    ADC_SAR_2_SetPower(ADC_SAR_2__HIGHPOWER);
    ADC_SAR_2_SetResolution(ADC_SAR_2__BITS_12);

    UART_Start();
    LCD_Start();
    SRAM_AddressReset();
//    LED1_Write(1);
//    LED2_Write(1);
    BackLightON();
    LCD_PrintString("WELCOME TO");
    LCD_Position(1, 0);
    LCD_PrintString("WELD DAS");
    CyGlobalIntEnable; /* Enable global interrupts. */
}

int main()
{
    Init();
    CyGlobalIntEnable;
//    Test_SRAM_AddressReg();
    Test_SRAM_Data();
 //   Test_ADC_Display();
//    Adc_2SRAM();
//    LED1_Write(1);
    for(;;)
    {   LCD_Position(0, 0);
        LCD_PrintString("Press Key...    ");
        LCD_Position(1, 0);
        LCD_PrintString("K1-ACQ  K2-TX   ");
        if(Cmd_Wait() == 1)
        {   LCD_Position(0, 0);
            LCD_PrintString("Acquiring Input  ");
            LCD_Position(1, 0);
```

```
            LCD_PrintString("Please Wait .... ");
            Adc_2SRAM();
        }
        else
        {   LCD_Position(0, 0);
            LCD_PrintString("Transfer Data    ");
            LCD_Position(1, 0);
            LCD_PrintString("Please Wait .... ");
            SRAM_2USB();
        }
    }
}

/* [] END OF FILE */
```

C

User Interface Code Using Mat-lab

```
clc;
clear all;
fprintf('ENTER YOUR CHOICE OF ANALYSIS : \n')
fprintf('ENTER EVERY CHOICE ONLY IN SINGLE QUOTES i.e in  ''  (in
caps) \n')
fprintf('\n')
fprintf('(1) For time domain type ----->      T   \n')
fprintf('\n')
fprintf('(2) For PDD analysis type  ----->       p \n')
fprintf('\n')
fprintf('(3) For Neural network through SOM algo analysis type ----->
ANN   \n ')
fprintf('\n')
fprintf('(4) Analysis by comparing all pdds on same scale type ----->
P1   \n ')
fprintf('\n')
fprintf('(5) Analysis by demonstrating the difference of different
statistical parameter   \n ')
fprintf('(which includes mean  var  standard deviation max min and
burning time) type ----->        N \n')
fprintf('\n')
fprintf('\n')
fprintf('\n')
fprintf('CAUTION:- Do not forgot to turn on the caps lock before
entering your choice :)  \n ')
fprintf('\n')

 Enter=input('Enter your choice of analysis :)  ');

switch(Enter)
     case 'T'

 prompt={'Enter number of welders doing welding:','Enter the value of
sample rate choosen  (samples/second):','enter the set value of
current in Amps :','Enter the recorded value of voltage in
Volts:','Enter time equivalent samples:'};
title='TIME DOMAIN ANALYSIS';
answer=inputdlg(prompt,title);
N = str2num(answer{1});
sr = str2num(answer{2});
s = str2num(answer{3});
s1 = str2num(answer{4});
l = str2num(answer{5});
d = fdesign.lowpass('Fp,Fst,Ap,Ast',0.0000001,0.005,1,60);
```

```
Hd = design(d,'equiripple');
 n=1;
 fprintf('CAUTION:- Now do not forgot to turn off caps lock before
entering your choice :)  \n ')
 fprintf('\n')

for e= 1:N
  fprintf('Enter the path of welding current data for welder
number: %d\n',e)

    a=input('Name of the current data file for the above mentioned
welder (in single qoutes i.e in '') =');      % for ex.
'D:\Users\vikas\Documents\MATLAB\New folder (2)\sbb2.dat'
% Import the file
DELIMITER = ',';
HEADERLINES = 4;
newData1 = importdata(a, DELIMITER, HEADERLINES);

% Create new variables in the base workspace from those fields.
vars1 = fieldnames(newData1);
for i = 1:length(vars1)
    assignin('base', vars1{i}, newData1.(vars1{i}));
end

newData1
cmod=data;

c=(cmod);

%c=dlmread(a,'\t', 2, 0);      %  weld data in csv format obtained
after filtering

c2=c(:,1);

c3=c2(1:l);
B{n}=c3;
n=n+1;
end
for x1=1:N
    B2=B{x1};
     B1=B2(1:l);


y4=filter(Hd,B{x1});
%  y = filter(Hd,c3);
%  y1=filter(Hd,c2);

figure(x1)
lencurrent=length(y4);
mn=mean(y4);
yfilter=(y4./(mn/s));
r10=1:1:lencurrent;
unf=(B1./(mn/s));
subplot(2,1,1)
% comet((r10/sr),unf)
plot((r10/sr),unf)
  axis([0 l/sr s/2 2*s])
```

```
  set(gca,'YTick',[s/2 (s/2 +20) (s/2+40) s (s+20) (s+40) (s+60)
(s+70) 2*s])
Title('CURRENT OSCILLOGRAM (with noise)')
xlabel('Time in Seconds --> ')
ylabel('Current in Amps --> ')
subplot(2,1,2)
% comet((r10/sr),yfilter)
plot((r10/sr),yfilter)

Title('CURRENT OSCILLOGRAM (without noise)')
xlabel('Time in Seconds --> ')
ylabel('Current in Amps --> ')
axis([0 l/sr s/2 (s+40)])
%   set(gca,'YTick',[s/2 (s/2 +20) (s/2+40) s (s+20) (s+40)]  )

end
m=1;

for i=1:N
  DELIMITER2 = ',';
HEADERLINES2 = 4;
   fprintf('Enter the path of welding voltage for welder
number: %d\n',i)
a1=input('Name of the voltage data file for the above mentioned
welder (in single qoutes i.e in '') =');      % for ex.
'D:\Users\vikas\Documents\MATLAB\New folder (2)\sbb2.dat'

% Import the file
newData12 = importdata(a1, DELIMITER2, HEADERLINES2);

% Create new variables in the base workspace from those fields.
vars3 = fieldnames(newData12);
for j = 1:length(vars3)
    assignin('base', vars3{j}, newData12.(vars3{j}));
end

newData12

cv=data;

cv1=cv(:,1);




  A{m}=cv1;

m=m+1;
end
for x=1:N
 A2=A{x};
 A1=A2(1:l);
y4=filter(Hd,A{x});

m1=mean(y4);
m01=mean(A{x});
```

```
 figure(x)



lencurrent11=length(A1);
r1011=1:1:lencurrent11;

subplot(3,1,3)
plot((r1011/sr),((-A1./(m01/(s1))+2*s1)))

% axis([0 l/sr -10 3*s1])
%
 set(gca,'YTick',[0 20 30 40 60 80 110] )
%  axis([0 l/sr 0 (s1+80)])

Title('VOLTAGE OSCILLOGRAM ')
xlabel('Time in Seconds --> ')
ylabel('Voltage in Volts --> ')



lencurrent1=length(y4);
r101=1:1:lencurrent1;
subplot(4,1,4)
plot((r101/sr),((-y4./(m1/(s1))+2*s1)))

axis([0 l/sr -10 3*s1])
%
%  set(gca,'YTick',[0 20 30 35 40] )

Title('VOLTAGE OSCILLOGRAM(without noise)')
xlabel('Time in Seconds --> ')
ylabel('Voltage in Volts --> ')

end

     case 'P'
clc;
clear all;


prompt={'Enter number of welders doing welding:','enter number of
trials performed by each welder:','enter the set value of current in
Amps :','Enter the recorded value of voltage in Volts :'};
title='PDD ANALYSIS';
answer=inputdlg(prompt,title);
N = str2num(answer{1});
K = str2num(answer{2});
s = str2num(answer{3});
s1=str2num(answer{3});
g=1;
uc=1;
 fprintf('CAUTION:- Now do not forgot to turn off caps lock before
entering your choice :)  \n ')
 fprintf('\n')
```

```
for vc= 1:N
    for vc1 =1:K
DELIMITER1c = ',';
HEADERLINES1c = 4;

fprintf('Enter the path of welding current for welder
number: %d\n',vc)
    fprintf('and provide his trial no: %d\n',vc1)

t2c=input('Name of the current data file for which wlder no. and his
trial no. are mentioned above(enter in single qoutes i.e in '')
=');      % for ex.   'D:\Users\vikas\Documents\MATLAB\New folder
(2)\sbb2.dat'
% Import the file
newData11c = importdata(t2c, DELIMITER1c, HEADERLINES1c);

% Create new variables in the base workspace from those fields.
vars2c = fieldnames(newData11c);
for j = 1:length(vars2c)
    assignin('base', vars2c{j}, newData11c.(vars2c{j}));
end

newData11c
tc=data;

t0c=tc(:,1);
Cuc{uc}=t0c;

tbl1c = tabulate(Cuc{uc});
uc=uc+1;
P = {'k','b','r','g','y',[.5 .6 .7],[.8 .2 .6]} % Cell array of
colros.


 hold

figure(vc)
%  plot(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),
'color',P{i},'marker','o')


% b1c=tbl1c(:,1)./(mean(tbl1c(:,1))/s);
 subplot(2,1,1)
plot(tbl1c(:,1)./(mean(tbl1c(:,1))/s),(tbl1c(:,3)),'color',P{vc1},'ma
rker','*')
set(gca, 'YScale', 'log')
set(gca,'YTick',[0.00000 0.001 0.01 5 50 ] )

hold off


Title('CURRENT PDD')
xlabel('Current in Amps --> ')
ylabel('n(%)---> ')

%%%%%%
```

```
    end
end
for v=1:N

 for i= 1:K
DELIMITER2v2 = ',';
HEADERLINES2v2 = 4;
fprintf('Enter the path of welding voltage for welder number: %d\n',v)
    fprintf('and provide his trial no: %d\n',i)
a1v2=input('Name of the voltage data file for which wlder no. and his
trial no. are mentioned above(enter in single qoutes i.e in '')
=');      % for ex.   'D:\Users\vikas\Documents\MATLAB\New folder
(2)\sbb2.dat'

% Import the file
newData12v2 = importdata(a1v2, DELIMITER2v2, HEADERLINES2v2);

% Create new variables in the base workspace from those fields.
vars3v2 = fieldnames(newData12v2);
for j = 1:length(vars3v2)
    assignin('base', vars3v2{j}, newData12v2.(vars3v2{j}));
end

newData12v2

cvv2=data;

cv1v2=cvv2(:,1);
 C{g}=cv1v2;


tbl21v2 = tabulate(C{g});
 g=g+1;

 len21v2=length(tbl21v2);
r21v2=1:1:len21v2;

% for i=1:n
%
% plot('color',rand(1,3));
%
% end
P = {'k','b','r','g','y',[.5 .6 .7],[.8 .2 .6]} % Cell array of
colros.
% x = 0:.01:1;

 hold

figure(v)
 subplot(2,1,2)
 plot(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),
'color',P{i},'marker','o')
  set(gca, 'YScale', 'log')
set(gca,'YTick',[0.00000 0.001 0.01 5 50  ] )
hold off
```

```
%Title('VOLTAGE PDD')
xlabel('Voltage in Volts --> ')
ylabel('n(%)---> ')

 end

end

    case 'ANN'


clc;
clear all;
 prompt={'Enter number of welders for which analysis has to be 
performed:','Enter the recorded value of voltage in Volts:'};
title='NEURAL NETWORK ANALYSIS';
answer=inputdlg(prompt,title);
N1 = str2num(answer{1});
s1 = str2num(answer{2});

g=1;
 fprintf('CAUTION:- Now do not forgot to turn off caps lock before 
entering your choice :)  \n ')
 fprintf('\n')
for v=1:N1

%  for i= 1:K
DELIMITER2v2 = ',';
HEADERLINES2v2 = 4;
fprintf('Enter the path of welding voltage for welder number: %d\n',v)

a1v2=input('Name of the voltage data file for the above mentioned 
welder (in single qoutes i.e in '') =');      % for ex. 
'D:\Users\vikas\Documents\MATLAB\New folder (2)\sbb2.dat'

% Import the file
newData12v2 = importdata(a1v2, DELIMITER2v2, HEADERLINES2v2);

% Create new variables in the base workspace from those fields.
vars3v2 = fieldnames(newData12v2);
for j = 1:length(vars3v2)
    assignin('base', vars3v2{j}, newData12v2.(vars3v2{j}));
end

newData12v2

cvv2=data;

cv1v2=cvv2(:,1);
 C{g}=cv1v2;
m2=mean(C{g});
X = transpose(C{g}./(m2/s1));

X=X(1:500);
iter=1;
%// toal number of nodes
```

```
totalW = 50;
%//initialization of weights
w =transpose( rand(500, 1));
%// the initial learning rate
eta0 = 0.1;
%// the current learning rate (updated every epoch)
etaN = eta0;
%// the constant for calculating learning rate
tau2 = 500;

%//map index
[I,J] = ind2sub([10, 10], 1:50);

  %// time costant for decay of learning rate
alpha = 0.5;
%// the size of neighbor
sig0 = 200;

sigN = sig0;
%// tau 1 for updateing sigma
tau1 = 500/log(sigN);
side=2;
p=[side side];
q=side^2;
minmax=[];

[l,N]=size(X);
for i=1:l
minmax=[minmax; min(X(i,:)) max(X(i,:))];
end
%Defining and training the SOM
net=newsom(minmax,p,'gridtop', 'mandist');
net.trainParam.epochs=iter;
net.trainParam.show=50;
net = train(net,X);

    for j=1:N
        x = X(:,j);
        x1=transpose(w(:,j));
        dist = sum( sqrt((x1 - repmat(x,1,totalW)).^2),1);

        %// find the winner
        [v1 ind] = min(dist);

        %// the 2-D index
        ri = [I(ind), J(ind)];

        %// distance between this node and the winner node.
        dist = 1/(sqrt(2*pi)*sigN).*exp( sum(( ([I( : ), J( : )] -
repmat(ri, totalW,1)) .^2) ,2)/(-2*sigN)) * etaN;

        %// updating weights
        for rr = 1:50
            w(:,rr) = w(:,rr) + dist(rr).*( x - w(:,rr));

        end
    end
```

```
    %// update learning rate
    etaN = eta0 * exp(-i/tau2);
    %// update sigma
    %sigN = sigN/2;
    sigN = sig0*exp(-i/tau1);

  g=g+1;
  S{v}=v1;
%   A{}=S{v};
%   sort(A)


end

Str = sprintf('%s,', S{:});
D = sscanf(Str, '%g,');
[dummy, ranking] = sort(abs(s1-D));
sortedC = S(ranking);
clc;
fprintf('Deviation from the recorded value is  : ')
sort(abs(s1-D))
fprintf('SINCE, STABLE HAND LEADS TO STABLE ARC GAP WHICH INTURN
LEADS TO GOOD WELD;  \n\n')
fprintf(' Hence RANKING of welders in increasing order  are \n' )
fprintf('  \n' )
 fprintf('CAUTION:- Now do not forgot to turn off caps lock before
entering your choice :)  \n ')
 fprintf('\n')
for v2=1:N1

 fprintf(' WELDER : %d' ,v2')
 fprintf('  has a ranking of  ')
 ranking (v2)


end
fprintf('  among all welders  \n')

    case 'P1'
   clc;
clear all;

 prompt={'Enter number of welders doing welding:','Enter the recorded
value of voltage in Volts:'};
title='PDD ANALYSIS OF ALL ON THE SAME SCALE';
answer=inputdlg(prompt,title);
N = str2num(answer{1});
s1 = str2num(answer{2});

g=1;

for v=1:N

 DELIMITER2v2 = ',';
HEADERLINES2v2 = 4;
```

```
fprintf('Enter the path of welding voltage for welder number: %d\n',v)
    fprintf(' provide any of his trial :\n')
a1v2=input('File name of the voltage data for the above mentioned
welder (in single qoutes i.e in '')  = ');      % for ex.
'D:\Users\vikas\Documents\MATLAB\New folder (2)\sbb2.dat'

% Import the file
newData12v2 = importdata(a1v2, DELIMITER2v2, HEADERLINES2v2);

% Create new variables in the base workspace from those fields.
vars3v2 = fieldnames(newData12v2);
for j = 1:length(vars3v2)
    assignin('base', vars3v2{j}, newData12v2.(vars3v2{j}));
end

newData12v2

cvv2=data;

cv1v2=cvv2(:,1);
 C{g}=cv1v2;


tbl21v2 = tabulate(C{g});
 g=g+1;


     len21v2=length(tbl21v2);
r21v2=1:1:len21v2;

% for i=1:n
%
% plot('color',rand(1,3));
%
% end
P = {'k','b','r','g','y','m','c',[.5 .6 .7],[.8 .2 .6]} % Cell array
of colros.
% x = 0:.01:1;

 hold

  plot(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),
'color',P{v},'marker','o')

hold off
 set(gca, 'YScale', 'log')
set(gca,'YTick',[0.00000 0.001 0.01 1 2 3 5 7 10 20 50 ] )
% gtext('welder 1')
% annotation('textbox', [0.2,0.4,0.1,0.1],...
%            'String', 'welder v');
% str1 = '\leftarrow welder ','v';
% text(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),str1)

%     title('VOLTAGE PDD ');
%     [welder-1 black, 2 blue, 3 red, 4 green ,5 yellow, 6 magenta, 7
cyan color]
```

```
    xlabel('Voltage in Volts --> ')
ylabel('n(%)---> ')


end
%  plot(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),
'color',P{v},'marker','o')
%  str1 = '\leftarrow welder ';
%  text(r21v2./(mean(r21v2)/s1),(tbl21v2(:,3)),str1)
case 'N'
clc;
clear all;

 prompt={'Enter the no of welders doing welding  :','Enter sampling
rate :'};
title='NORMALIZATION ANALYSIS';
answer=inputdlg(prompt,title);
N1 = str2num(answer{1});

sr = str2num(answer{2});
g=1;
i=0;
for v=1:N1
DELIMITER2v2 = ',';
HEADERLINES2v2 = 4;
fprintf('Enter the path of welding voltage for welder number: %d\n',v)

a1v2=input('Name of the voltage data file for the above mentioned
welder (in single qoutes i.e in '') =');      % for ex.
'D:\Users\vikas\Documents\MATLAB\New folder (2)\sbb2.dat'

% Import the file
newData12v2 = importdata(a1v2, DELIMITER2v2, HEADERLINES2v2);

% Create new variables in the base workspace from those fields.
vars3v2 = fieldnames(newData12v2);
for j = 1:length(vars3v2)
    assignin('base', vars3v2{j}, newData12v2.(vars3v2{j}));
end

newData12v2

cvv2=data;

y=cvv2(:,1);

 C{g}=y;

 g=g+1;
%  T =length(y);
% t1=T/40000;
m2=mean(y);
X = (y./(m2/25));
% for u=1:length(X)
% if X<30
```

```
% T=t/sr;
P = {'k','b','r','g','m','c','y',[.5 .6 .7],[.8 .2 .6]} % Cell array
of colros.

k=0.1;

z=[mean(X) var(X)  std(X) max(X) min(X) 0.2+k ];

i=i+1;

r=X./max(X);
R=0:0.2:max(r);
%u=1:1:z./(mean(z)/4)

% x = [100 200 400 1000 2000 5000 10000 20000 50000];
% y = rand(9,6); % Your y-axis data
 %s=z/(max(z));
hold
plot(z, R,'k','color',P{v},'marker','o');

hold off
grid on
 %set(gca,'XTick', [1 2 3 4 5 6])
% set(gca,'YTick', [0 0.2 0.4 0.6 0.8 1])
 xlabel('Array components ')
 ylabel('unitary amplitude ')
  title('Bubble represents resp. the MEAN  VAR  STANDARD DEVIATION
MAX MIN and BURNING TIME  [welder-1 black, 2 blue, 3 red, 4 green ,5
magenta, 6 cyan, 7 yellow color]');

end
  end
```