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Power Electronics for Resistance Spot Welding Equipment.

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ABSTRACT

Resistance spot welding is an inexpensive and efficient way of joining metals. It has extensive applications in household appliances and in automotive industries. The traditional approach in relation to spot welding machines is to use 50 Hz welding transformers. The drawback associated with these transformers is that they are both heavy and bulky. Moreover, the fusing requirements become larger due to increased welding power.

With the development of high power semiconductor switches and DC-DC converter topologies, it is now possible to develop inverter drive resistance spot welding equipment (RSE) which can be operated at frequencies higher than the 50Hz frequency. The advantage of using high frequencies is the reduction in the size of the transformer. Moreover, the fusing requirements are relaxed, as the power is shared between three phases.

In many industrial applications long welding arms are required between the transformer and the weld spot, which increases the inductance. The parasitic inductance in welding arms limits the maximum rate of change of the current. In order achieve a higher power the current has to be rectified. To rectify a current of the order of tenth of kA is challenging task and is one of the major sources of loss.

The full bridge converter topology is used for the inverter drive RSE. The power switches used in the converter are IGBT. In RSE, the DC link capacitors are used to store high energy. In the case of circuit failure, the stored energy can cause the IGBT device to rupture and in order to avoid this, a protection scheme is discussed in this work.

A controller circuit, using a DSPIC33FJ16GS502 controller, is developed in order to drive a high frequency full bridge converter, which can also be used to drive the IGBTs in the RSE.

The secondary side welding current is of the order of kilo amperes. A requirement for the welding control is that the current must be sensed precisely and in order to fulfill this, a Hall sensor system has been developed. This developed circuit is used in the feed-back control of the RSE. The presence of metallic objects and tools in the vicinity of the Hall sensor system can affect its precision. We have estimated the

exclusion distance for the metal objects from the sensor by means of a model developed in COMSOL Multiphysics software.

ACKNOWLEDGEMENTS

Sundsvall, March, 2012

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ABBREVIATIONS AND ACRONYMS

RSW	Resistance Spot Welding
AC	Alternating Current
DC	Direct Current
RSE	Resistance Spot Welding Equipment
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semi-conductor Field Effect Transistor
SCR	Silicon Controlled Rectifier
PCB	Printed Circuit Board
MHz	Mega Hertz
TVS	Transient Voltage Suppressor
kA	Kilo Amperes

LIST OF FIGURES

LIST OF TABLES

LIST OF PAPERS

This thesis is based on the following five papers, herein referred to by their Roman numerals:

Paper I **STUDY THE INFLUENCE OF THE ALIGNMENT AND NEARBY METALLIC OBJECTS ON THE HALL SENSOR SYSTEM FOR CURRENT MEASUREMENT IN RESISTANCE SPOT WELDING MACHINE**
Jawad Saleem, Abdul Majid, Kent Bertilsson and Linda Schuberg.
International Conference on Environment and Electrical Engineering 2011. Rome Italy 8th May to11th May 2011.

Paper II **A STUDY OF THE IGBT RUPTURE PHENOMENON IN MEDIUM FRECUENCY RESISTANCE SPOT WELDING MACHINE**
Jawad Saleem, Abdul Majid, Stefan Haller and Kent Bertilsson.
ACEMP International Aegean Conference on Electrical Machines and Power Electronics & Electromotion September 08-10, 2011 Turkey Istambul.

Paper III **HIGH FREQUENCY FULL BRIDGE CONVERTER USING MULTILAYER CORELESS PRINTED CIRCUIT BOARD STEP-UP POWER TRANSFORMER**
Jawad Saleem, Abdul Majid, Radhika Ambatipudi, Hari Babu Kotte and Kent Bertilsson.
20th European Conference on Circuit Theory and Design Linköping Sweden August 29- 31,2011.

Related papers not included in the thesis

Paper IV **HIGH FREQUENCY HALF-BRIDGE CONVERTER USING MULTILAYERED CORELESS PRINTED CIRCUIT BOARD STEP-DOWN POWER TRANSFORMER**
Abdul Majid, Hari Babu Kotte, Jawad Saleem, Radhika Ambatipudi and Kent Bertilsson.
8th Internal Conference on Power Electronics-ICPE 2011 at JejuSouth Korea May 28-June 03 2011.

THESIS OUTLINE

The thesis is organized as follows:

Chapter 1: This chapter provides a basic understanding and the different types of resistance welding processes. Single phase, three phase or inverter drive are being used in the spot welding process with their related advantages and disadvantages are discussed. In particular, a resistance spot welding process has been discussed in detail.

Chapter 2: This explains the different components involved in rectified resistance spot welding equipment (RSE). The RSE consists of a three phase input rectifier unit, inverter unit with IGBT's as switches, a medium frequency power transformer with output rectifier, control unit and driver circuit. All of these units are discussed in detail.

Chapter 3: This chapter explains the technique involved in measuring current from the secondary side of the inverter based RSE, and explains the influence of the alignment of the sensor and the presence of nearby objects on the sensor reading in the developed system.

1   INTRODUCTION

Welding is an economical and efficient means of joining metals permanently. Welding is often accomplished by melting the work piece and then adding the filler material. The joint is allowed to cool down, in order for it, to become a strong weld. Different energy sources including laser, electric arc, electron beam, electric current, etc, are used for this welding. Arc welding and oxy-fuel welding were the first processes to be developed followed by resistance welding. Different welding methods used commercially are described as follows.

- **Forge welding:** In this process, the metals to be welded are heated to a high temperature and then pressure is applied to make the welding joint. Forge welding is one of the simplest method by which, similar and dissimilar metals can be joined together.

- **Thermite welding:** In this process, two metals become bonded after being heated by a superheated metal that has experienced a chemical reaction. It is a chemical welding process involving the joining of two electrical conductors.

- **Gas welding:** In this process an oxy-fuel welding torch is used for heating the metal to form a welding joint. This welding is commonly called oxy acetylene welding.

- **Arc welding:** In this process heat is applied by means of an electric arc which is inserted between the parts to be joined together. During the welding process the electrode melts and fills the gap at the joint. AC and DC power units can be used to create an electric arc between the electrode and the base material.

- **Resistance welding:** In this process the parts to be welded are joined together by passing an electric current. Work-pieces are held together, under pressure, which is exerted by electrodes. The amount of heat delivered during spot welding is determined by the resistance between the electrodes and the amplitude and duration of the current.

1.1 RESISTANCE WELDING

Resistance spot welding process was invented in 1877 by Professor Elihu Thomson and has been extensively used since then in manufacturing industry, especially in the automobile and air craft industries [1],[2]. In the spot welding process, an electric current is passed through the parts being welded together, by using highly conductive electrodes. A pressure is exerted during the process so as to hold the parts to be welded. The weld is made by a combination of heat, pressure, and time. In order to make a good welding joint, sufficient heat must be produced at the surface of the metal plates which are to be joined together. Current, force and time must be properly related in order to obtain a good weld. The total heat energy dissipated during the weld process [3] is given by the following relationship.

$$Q = I^2 Rt \tag{1}$$

where I is welding current, R is resistance between the electrodes, t is the duration of the welding current and Q is total energy of the weld. The heat generated is directly proportional to the resistance offered at any point in the section being welded.

The resistance welding process can be classified into

- Projection welding
- Spot welding
- Seam welding
- Flash butt welding

1.1.1 Projection welding

It is a type of resistance welding process in which specially designed projections, shown in Figure 1 exist in one part. The simultaneous welding of several projections is possible during one weld. This projection, act as a current concentrator for the welding process and these projections are the high points during the welding cycle, that make the first contact. The main advantage of the resistance projection welding is the speed and versatility to be automated. With projection welding, several welds can be conducted simultaneously.
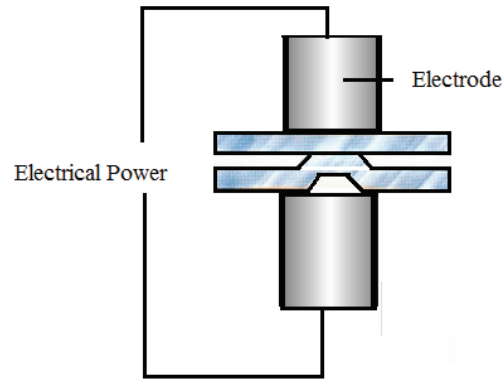
Figure 1 Projection Welding

1.1.2 Spot Welding

Spot welding process is a widely used process in both the automotive and other industries. The process utilizes a large amount of current within the range 1kA to 200kA. In RSW, a high welding current is passed from the welding electrodes.
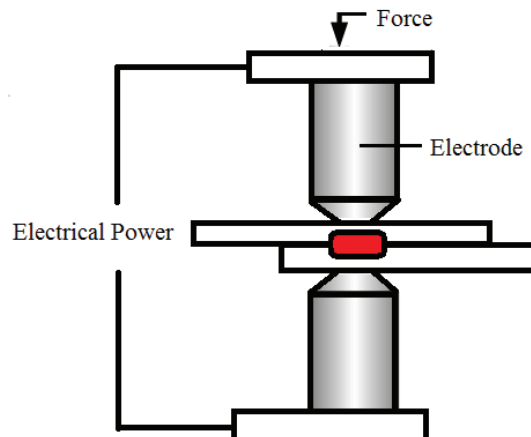
Figure 2 Spot Welding

The metal sheets to be joined together are placed in between the welding electrodes. Due to the resistance, offered at the junction of the work pieces,

heat is generated, which melts the metal at the interface thus forming a welding nugget as shown in Figure 2. Sufficient heat must be generated at the welding joint to raise the metal to the desired temperature. If the heat produced is less than this temperature then the result will be a low strength weld.

1.1.3 Seam Welding

In seam welding the electrodes which are used for the welding, are in the form of rollers as shown in Figure 3. The electrical current is passed through the roller shaped electrodes, which produce heat at the interface of the sheets to be joined. A seam welding process produces a series of nuggets at the interface of the work pieces.
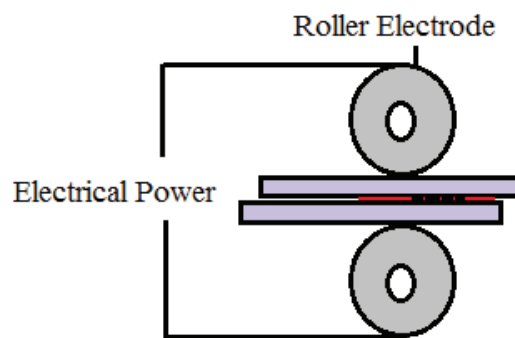
Figure 3 Seam Welding

1.1.4 Flash Welding

In flash / butt welding process, one work piece remains fixed at one end by mean of the stationary clamps and the other is movable. The arms are connected to the power supply unit. The movable component is brought closer to the fixed work piece and as these work pieces come closer to each other, a short circuit takes place, which leads to arcing or flashing as shown

in Figure 4. This flashing produces heat at the interface and brings the temperature to the forging temperature. At this point both the work pieces are forged together to form a welding joint.
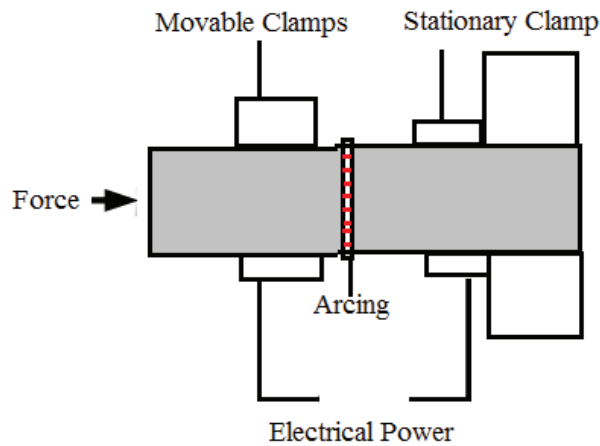
Figure 4 Flash Welding

1.2 RESISTANCE SPOT WELDING MACHINE

The basic structure of spot welding machine is shown in Figure 5 and Figure 6 [4]. Figure 5 shows the main part of the vertical spot welder. There is a controller unit controlling the regulation for the welding. The pressure cylinder, applies the required force to the electrodes to make the welding joint. There are water connections so as to provide cooling to the electrodes, transformer, rectifier and the switches. The adjustable electrodes are made of copper to ensure good conductivity. A two step foot pedal is used in this machine, in which the first step is to apply the pressure and the second is to start the welding. Figure 6 shows the different electrical/electronic components used in RSE. The major components are the power transformer, rectifier unit and capacitor bank. The transformer is used to produce low voltage high magnitude current. The rectifier unit rectifies the three phase input AC voltage to DC which is stored in the capacitor bank.

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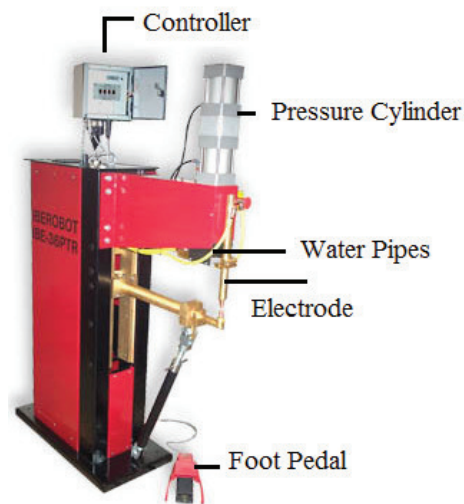
Figure 5 Spot Welding Machine [4] Figure 6 Electrical Components of RSW [4]
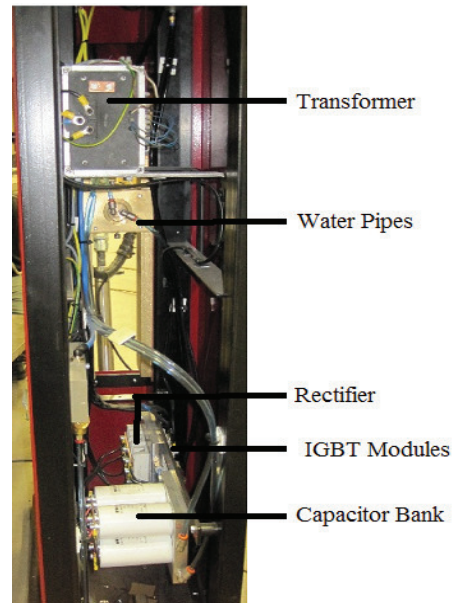
1.2.1 Electrical Configuration of the Machine

The performance of the spot welding machines is greatly affected by the type of electrical source used in the spot welding machine, for example, single phase, three phase or invert drive. The choice of the source depends on a number of factors such as the available primary current, the output current required, equipment size, weight and cost [5],[6]. The most commonly used power sources in spot welding machines are

- Single phase AC units.
- Single phase DC units.
- Secondary side rectified three phase DC units.
- Secondary side rectified inverter units.

Single phase AC spot welding machines are the simplest and are relatively, the least expensive. These machines consist mainly of a single phase transformer with a timer circuit. These machines are not very energy

efficient as the secondary side circuit suffers from substantial inductive losses.

Single phase DC unit spot welding machines are much more efficient than the single phase AC unit machines. The rectification of the secondary side current reduces the losses due to inductance. The rectifier adds a little weight to the machine, but this is compensated for by the good welding quality and the increased efficiency of the machine as compared to that of a single phase AC unit machine.

To obtain a better quality weld and to use better technology, the secondary side rectified three phase DC machines are used. These machines are capable of delivering a high current magnitude, which makes them suitable for welding thicker materials and aluminum alloys. However, they are quite bulky due the size and weight of the transformer and the additional diodes.

To increase the machine efficiency and power output, inverter based spot welding machines are becoming a good choice for welding [7]. The inverter based RSW machine usually consists of a three phase AC supply unit, a rectifier unit which rectifies the input voltage and stores energy in the capacitor bank as shown in Figure 7. After this, there is an inverter unit consisting of switches, which are operated at a medium frequency of 100-1000 Hz.
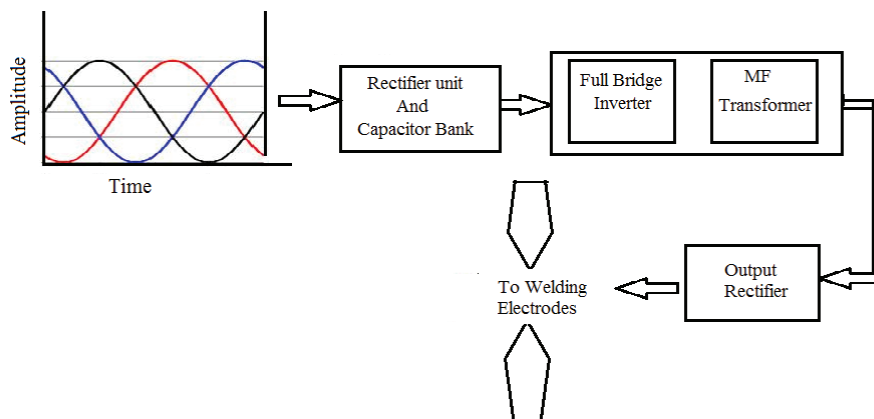
Figure 7 Inverter Supply RSE

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The invert circuit produces an output, which is delivered to a single phase transformer, which steps down the voltage and steps up the current. The transformer has two secondary windings and a full wave rectifier mounted on it. The rectified output is then delivered to the welding electrodes.

Single phase AC units are robust and less expensive. These units have only transformer and timer as main components and are suitable for low volume applications. There is less efficiency for such equipment because of the substantial inductive loss on the secondary side. Single phase DC units are more energy efficient than the single phase AC. The rectifier adds extra weight, but the increased efficiency enables the use of a lighter transformer.

The secondary rectified three phase DC units are efficient in comparison to single phase units. This equipment has the capability of delivering high welding currents. The inverter based secondary side rectified machines are energy efficient and compact, saving approximately 50% of the weight as compared to an AC unit of equivalent power rating [6].

1.3   THE WELDING PROCESS

The welding time cycle is a series of discrete time events as shown in Figure 8.

- **Squeeze time**: During the squeeze time, the welding electrodes are moved together and the force is applied from the pressure chamber. The pressure will force the work pieces together to build up the necessary resistance for the welding process. If there is less squeeze time, the welding current will start flowing before the work pieces are tightly joined together. This will cause overheating, spatter, electrode wear and, eventually, a defective weld.
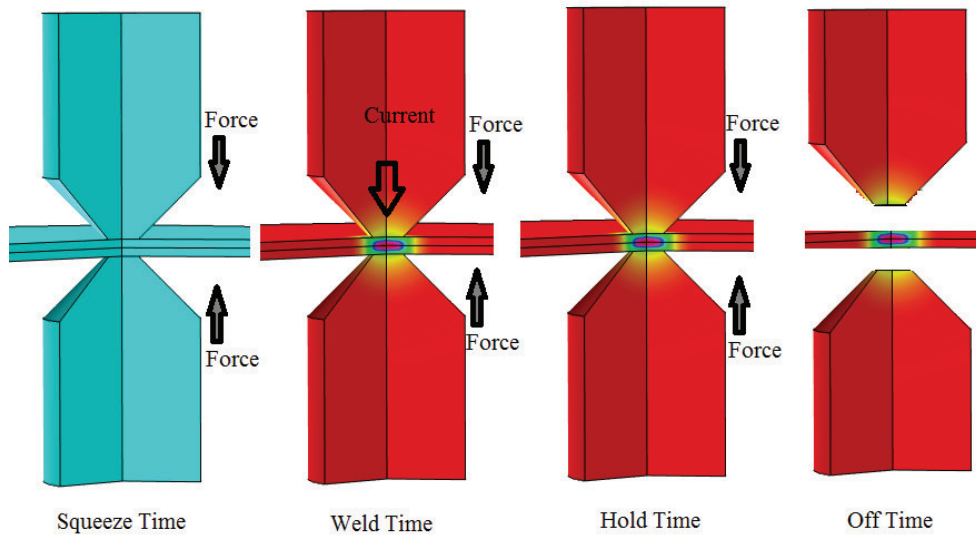
Figure 8 Sequence of Steps in Welding Cycle

- **Weld time**: The weld time is the time during which a set amount of current flows through the work pieces. If this time is large, expulsion will take place, which means that the molten metal is expelled from the welding nugget as a shower of sparks. On the other hand, if this time is less cold weld is obtained, or sometimes no welding nugget is formed.

- **Hold time**: This is the time after the application of the current, pressure is applied so that the work pieces are held tightly together to form a welding nugget.

- **Off time**: During this time the pressure is released and the electrodes are separated for the next spot weld.

1.3.1 Heat Generation in Spot Welding

In RSW, the resistance to the flow of current on the secondary side of the transformer is provided by the metal sheets, which are to be joined together. This will produce heat at the metal to metal interface thus forming a welding nugget. There are seven major points of resistance in the work region as shown in Figure 9. These are as follows:

1. The upper or moving electrode R1.
2. The region between the upper or moving electrode and the top work piece R2.
3. Top metal work piece R3.
4. The interface between the top and the bottom work pieces R4.
5. The bottom metal work piece R5.
6. The region between the lower electrode and the bottom work piece R6.
7. The lower or fixed electrode R7.
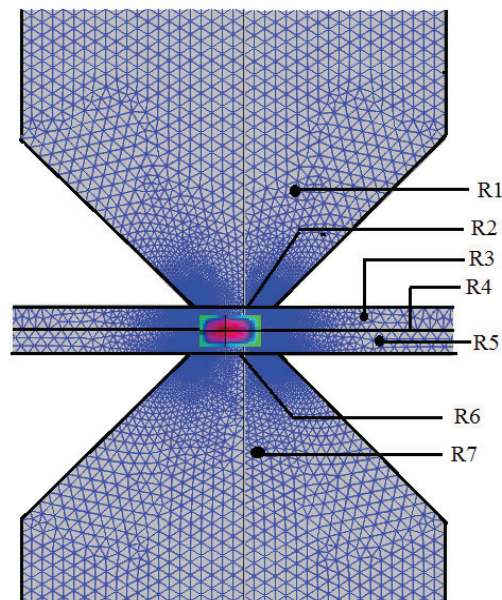
Figure 9 Resistance of Various Regions

The resistance in these regions is different and thus the heat produced in the region will be different as all the resistances are in series and each point of resistance will retard the current flow. The resistance is lowest in regions 1 and 7 because the electrodes are made of copper and tungsten alloys, which are good conductive materials.

The contact resistance in regions 2 and 6 is somewhat high and therefore the temperature during the welding process is also high. In the regions 3 and 5 contact resistance decreases because it lies in between the metal and thus metal continuity exists and the resistance is lower. In region 4, which is the interface of the two work pieces, has the maximum resistance and thus the highest temperature. Because of the high temperature in this region, the metal starts to melt and form the welding nugget.

In comparison with the various fusion welding methods, the following benefits are available for RSW [11].

- Heat energy is confined to a limited area which results in a minor deformation of the work piece.
- Welding times are shorter, usually under 1 second.
- The RSW method is energy efficient and is also environmentally friendly.
- No filler material is needed.
- The operation of the equipment is user friendly.

The disadvantages of other fusion welding processes are

- The size of the transformer becomes very bulky at high power levels.
- There is a practical limit of the current that can be taken from the grid due to the fusing requirements of the industry in which it will be used.

2 RECTIFIED RESISTANCE SPOT WELDING SYSTEM

Inverter type welding equipment with secondary side rectified, are becoming a good choice for spot welding. For a given application, an inverter type equipment can be made to be more compact and with a lower fusing requirement. These machines are capable of delivering a high magnitude electric current. Figure 10 shows a simple model of the inverter based spot welding equipment.
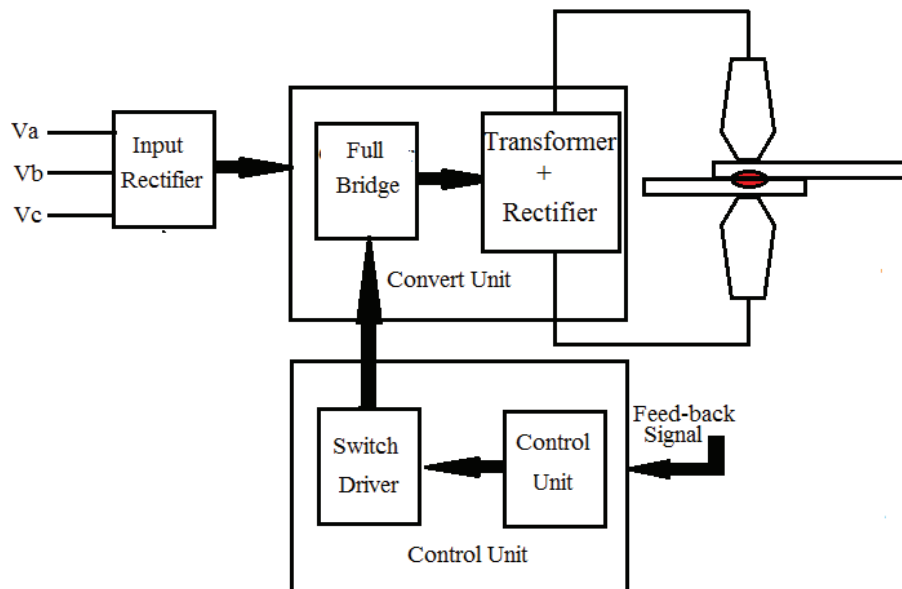
Figure 10 Inverter type spot welding basic circuit diagram

The RSE consists of following main parts

1. Three phase input rectifier unit.
2. Inverter unit.
3. Medium frequency power transformer.
4. Output rectifier unit and filter.
5. Control unit and Driver circuit.

2.1 RECTIFIER UNIT

The three-phase bridge rectifier circuit has three-legs, with each phase being connected to one of the three phase voltages as shown in Figure 11. The rectifier unit, at the input, is used to rectify the three phase AC voltage and to store the DC voltage in a capacitor bank.
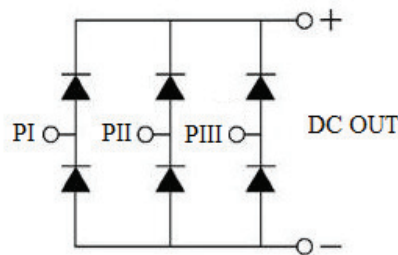
Figure 11 Three phase rectifier

2.2 INVERTER UNIT

The main function of this unit in the RSE is to produce a medium frequency AC signal, which is fed to a single phase transformer. It is important to decide proper inverter topology to be used in the converter base RSE. Important factors for the selection of the topology, given in [8] are:

- Input and output voltages(lower, higher or inverted, multiple outputs etc)
- Output power (some topologies are limited in power)
- Safety (Isolated / non isolated)
- Cost (related to number of power devices)

Three most common symmetrical types of converters are

- Push pull converter
- Half bridge converter
- Full bridge converter

To obtain a better understanding of the topology, both half bridge and full bridge converter circuit were implemented [9] and [10]. The controller

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circuit developed for these topologies can also be used in the driving circuitry for the RSE.

The push pull converter as shown in Figure 12 is the simplest type of converter, which is able to provide the bi-directional magnetic flux in the transformer core.
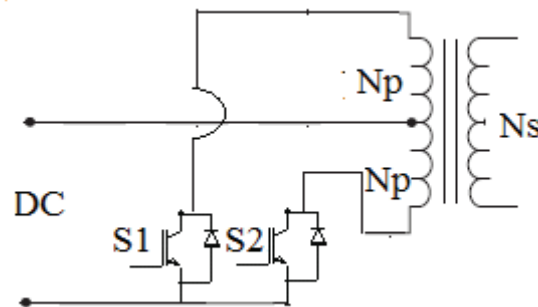
Figure 12 Push pull configuration

In this topology, there is an alternate turn ON for the two switches. The maximum power can be obtained if each switch is turned on for half of the period. A dead time always occurs between the end of the conduction of one switch and the turn-on time of the other, in order to avoid simultaneous conduction of the two switches. The switches are easy to drive since they are both referenced to the ground, however they must withstand twice the input supply voltage.

A half bridge converter as shown in Figure 13 is also capable of providing a bi-directional magnetic flux in the transformer. The capacitors are in series across the supply, to fix a mid-point so that the switches withstand only once the input voltage V_{in}. The dead time between the conduction of the two switches is mandatory in order to avoid a short circuit as shown in the Figure 14.
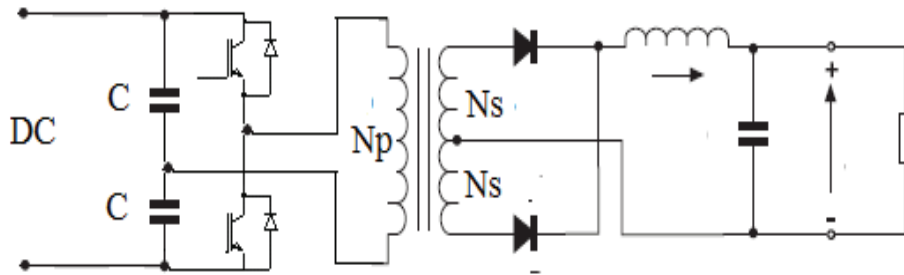
Figure 13 Half bridge Configuration
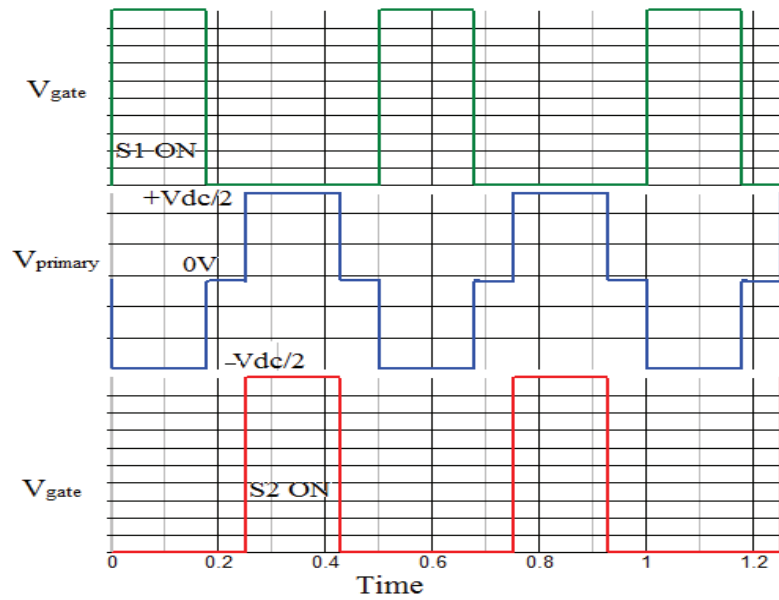
Figure 14 Wave form for the half bridge circuit

The transformer primary voltage is $+V_{dc}/2$ when the switch $S1$ is switched on, or it is $-V_{dc}/2$ when the switch $S2$ is switched on. The disadvantage is that the capacitors used to create the electrical center will be quite large and also expensive [11].

A full bridge converter circuit as shown in Figure 15 also provides a bi-directional flux in the transformer. The transformer's primary voltage is $+V_{dc}$ when the switches $S1$ and $S2$ are switched on, or is $-V_{dc}$ when switches $S2$, $S3$ are switched on.

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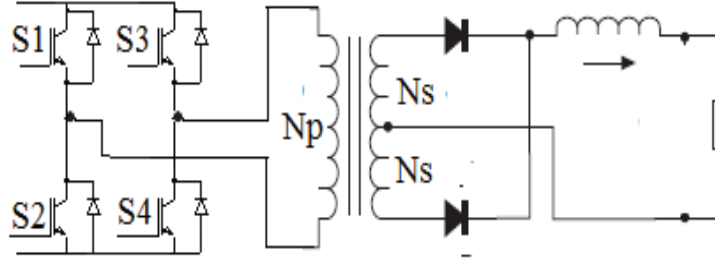
Figure 15 Full bridge configuration
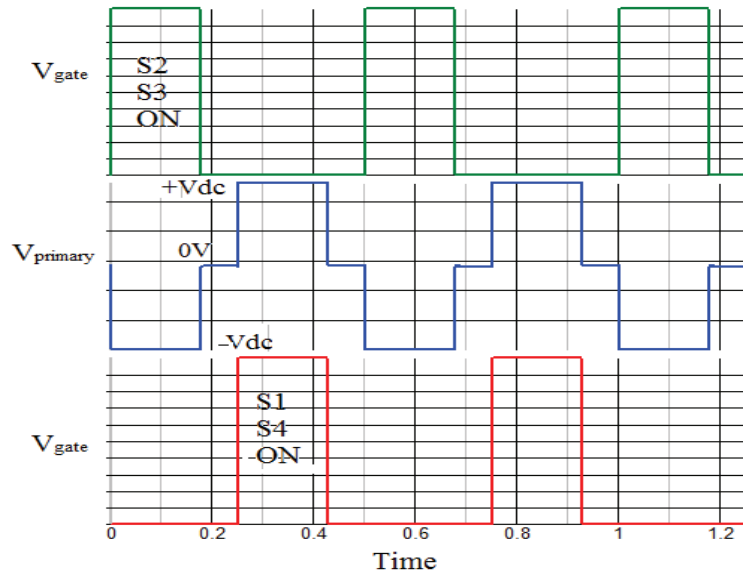
Figure 16 Wave form for the full bridge circuit

The transformer primary voltage is 0V when all four switches are off. To avoid a short circuit, and thus the breakdown of the switch, the turn on time of *S1* must not overlap with the turn on time for *S2*. The same condition applies to *S3* and *S4*.The full bridge circuit is used in high power applications [8]. The advantage of a full bridge over a half bridge is that, the voltage imposed across the primary is a square wave of $\pm V_{dc}$, instead of $\pm V_{dc}/2$ for the half bridge.

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In the full bridge, the transformer's primary turns must be twice those of the half bridge as the primary winding must sustain twice the voltage. The peak and RMS currents are half of the half bridge because, the transformer primary supports twice the voltage as compared to the half bridge. With twice the primary turns but half the RMS current, the size of the full-bridge transformer is identical to that of the half bridge at equal output powers [12].

2.3   SWITCHES FOR THE MEDIUM FREQUENCY RSE

Power electronics is the technology associated with efficient conversion and control of electric power by using power semiconductor devices. The goal is to control the flow of energy from the source to the load. The power semiconductor devices are used as switches. In the early fifties, Silicon controlled rectifiers were used as switches in the converter circuits. The Bipolar transistor in the sixties became a competitor for the SCR, as it had a blocking capability of a few hundred volts. The power MOSFET gained popularity at the end of the seventies [12], [13]. Its voltage drive capability, high gain, ease of paralleling, and its high operating frequency, up to MHz made it a good choice for the designer to use in a converter. The on state resistance Rds_{on} for the device is high, which leads to conduction losses. Therefore the MOSFETs are restricted to low voltage high frequency circuits. IGBT, which first came in end eighties, had the advantage of a low on state resistance and ease of control of a MOSFET. A summary of the capabilities of these devices in relation to their voltage/current ratings and their operating frequencies is shown in the Figure 17 [14]. The requirement for the switches [11] used in the converter are:

- Low voltage drop, when the switch is on in order to minimize the losses.
- High blocking voltage capability of the switch in the forward direction. This will reduce the need to daisy chain multiple switches.
- Positive temperature coefficient, paralleling of the device is possible.
- Low control voltage/current, to simplify the driving circuitry.

IGBTs are becoming a more popular choice for the designers in relation to converter based spot welding machine, because of the advantages, for being a high voltage switch and high frequency operation. A 1200 V and 145 Amp IGBT SKM 100GB128D by Semikron [15] were used in the RSE and are discussed in the thesis.
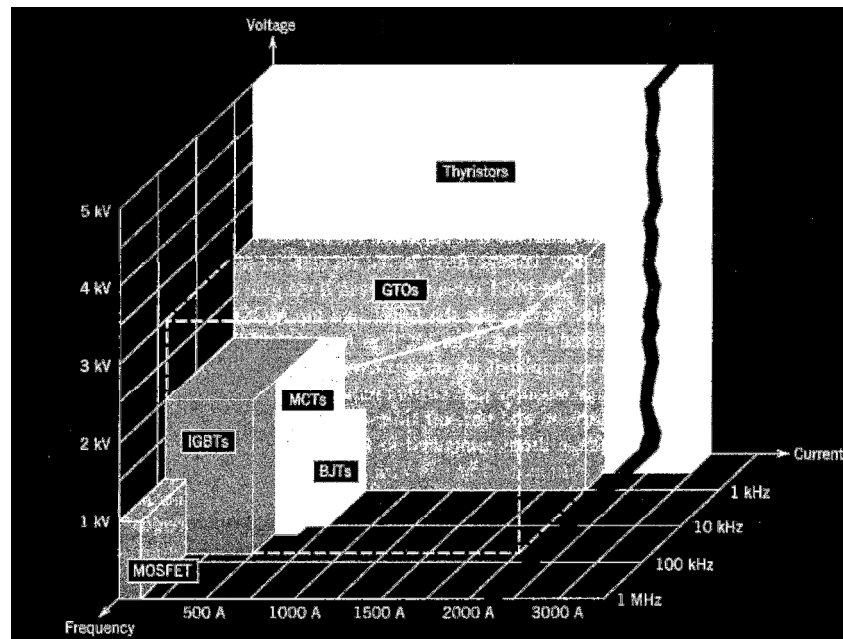
Figure 17 Summary of the power semi conductor device capabilities [14]

2.3.1 IGBT structure

The IGBT is a combination of a BJT and a MOSFET. IGBT is voltage-controlled device in a similar manner to that of a MOSFET. It has the advantages of a high-current handling capability of a bipolar, with the ease of control of a MOSFET. The structure of the IGBT is shown in the Figure 18. The structure of the IGBT is similar to that of MOSFET with an additional P+ layer. There is a similar insulated gate as in the MOS device, therefore, the principle of operation at the input is also the same, namely that when $V_{gs} > V_{th}$, the N channel is formed for the flow of electrons from N+ to N-. When V_{ds} is applied, holes from the P+ region move to N-. Some electrons recombine with the hole, and the remainder are collected at the source. Due to this P+ junction, the device can block a negative voltage. A power MOS had a built-in body diode, but the IGBT itself does not possess this, however, the module has a recovery diode matched to its switching requirements. The turn on of the IGBT is the same as that for the Power MOS. The rate at which the input capacitance C_{gs} (gate to source) is charged will determine the turn on. However, in turn off, there are majority carries from N- to P+ and also minority carries from P+ to N- ,therefore the turn

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off losses will be high. The on state resistance Rds_{on} for an IGBT is less as compared to the Power MOSFET, which leads to low conduction losses. The IGBTs have become the device of choice for break down voltages above 1000V, while the MOSFET is certainly the device of choice for a device breakdown voltage below 250V [16].
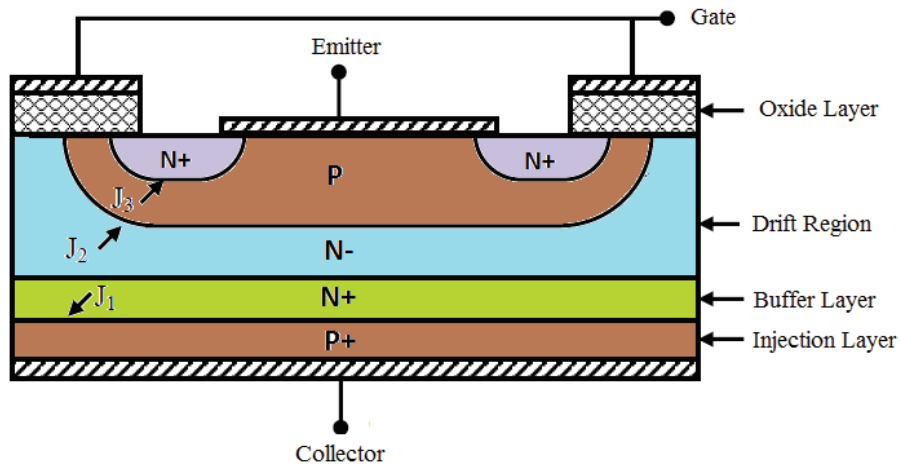
Figure 18 Structure of IGBT

The IGBTs were used as switches in the full bridge converter for the RSE. The rectifier unit rectifies the three phase voltages and stores this as DC voltage in the capacitor bank. The full bridge inverter contains the IGBTs which are driven by the control circuit and the driver module at a frequency of 100 to 1000 Hz for different machines. The DC link capacitors in the RSE store more energy. There is thus a risk of a rupture of the IGBT device and casing in the case when a circuit failure condition occurs. This rupture can damage the converter, drive down time, and may cause personal injury and may lead to machinery certification problems. The failure may be caused by a fault in the control circuit or any failure in any of the IGBTs or the diodes in the module. The IGBT module may survive during the thermal stress but this will degrade the device parameters, which can reduce the safe operating area for the device, which can lead to losses in the devices [17].The capacitors can also be damaged by a shorted IGBT. This results in a low impedance current path, thus generating excessive heat and pressure, which can also cause a violent case rupture for the capacitors.

2.3.2 Protection against rupture

Figure 19 shows some of the possible placements of the fuses [18]. The capacitors can be protected by having a conventional fuse as mentioned (A) on the AC line side. High speed fuses as mentioned in (B, C, D) can be used for the protection of the IGBT against a rupture. The two fuses, namely those as C, are placed in the DC link, and by placing these fuses at this location, they are able to provide protection against all faults. However, placing a fuse at B, in series with the capacitor bank, provides almost the same protection, with the advantage that the fuses do not carry the active power producing current but only the AC current. The placement of the fuse D in series with the IGBT, appears, at a first glance, to be the most expensive, but the current in each fuse is less than that in the DC link fuse.
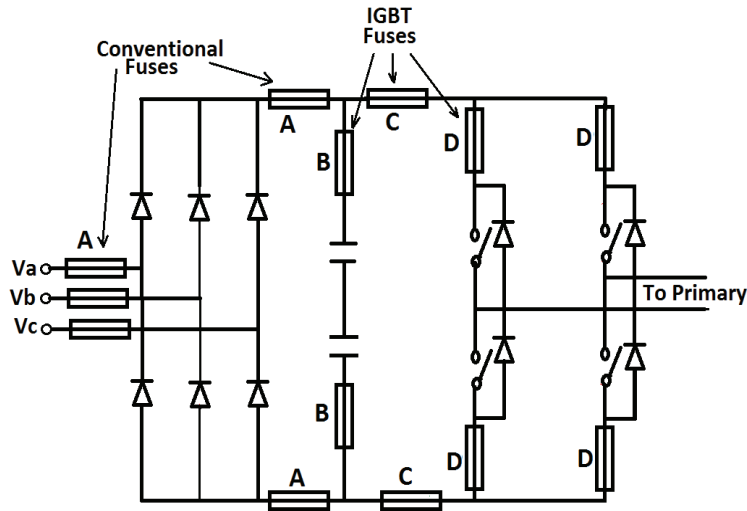
Figure 19 Fuse placement for inverter based resistance welding

Machine

It is important to note that the inductance of the circuit L changes when a fuse is introduced into the circuit. This increased value ΔL is a fixed quantity which is dependent on the fuse used. The added inductance $L + \Delta L$ will result in added voltage peaks of $(L + \Delta L)di/dt$ to the supply, which the other devices will now have to bear during the operation [18].

The use of a Typower IGBT fuse instead of standard High speed fuses [19] in the DC Link will introduce less inductance. It is important to note that these fuses can only protect against a violent rupture of the IGBT modules, but, they cannot protect the device junction as it may be damaged within a few nano seconds.

2.4　POWER TRANSFORMER AND OUTPUT RECTIFIER UNIT

The output signal from the inverter is fed to a single phase with two secondary windings and a full wave rectifier mounted on the transformer to ensure a short rise time for the welding current. This high frequency voltage from the output of the inverter, allows the designer to reduce the size of the bulky transformer as compared to that of the traditional 50Hz transformer. Commercially available transformer as shown in Figure 20 with integrated rectifiers and a current transformer for the secondary side current measurement have been used in the RSE.
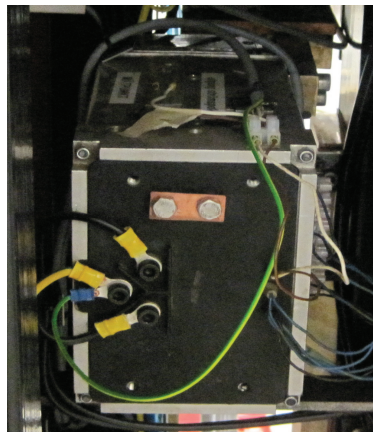
Figure 20 Transformer used in Inverter type RSE

The signal from the output of the transformer is fed to the full wave rectifier. The rectifiers rectify the currents that are within the range of 10 to 200 kA. The forward voltage drop in the rectifier is one of the main sources of power loss in the design.

2.5 CONTROL UNIT

The control unit consists of a microcontroller, to produce PWM signals and a driver circuit, for the controlled commutation of the switch from the ON state to the OFF state and vice versa. A DSPIC33FJ16GS502 controller circuit as shown in Figure 21 has been used to drive the high frequency full bridge and the half bridge circuits [9], [10].
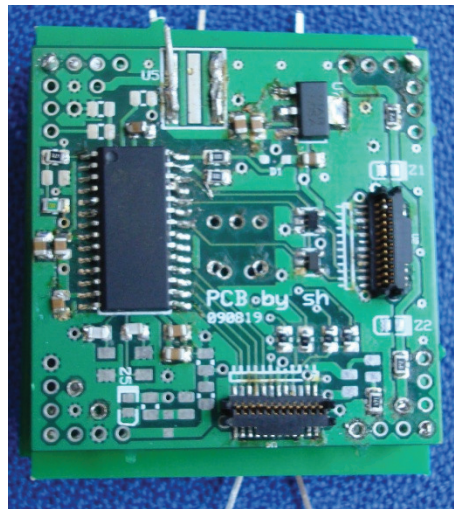
Figure 21 Controller ciruit used in [9],[10]

The controller has four PWM channels and eight output pins. In order to provide complementary outputs, these eight I/O are grouped into H/L pairs. The PWM module is ideal for power conversion applications such as AC/DC converters, DC/DC converters, Inverters, UPS and Battery chargers [20]. The controller circuit can also be used to drive the full bridge converter in the RSE.

The power transformer in the full bridge circuit is bridged between the junction of switches $S1$, $S2$ and $S3$, $S4$ as shown in Figure 15. The switches $S1$, $S4$ are switched "on" simultaneously for an adjustable time during one half period and then switches $S2$, $S3$ are simultaneously "on" for an equal time during the alternate half period. The transformer primary voltage is $+V_{dc}$ when the switches $S1$ and $S4$ are switched on, or it is $-V_{dc}$ when switches $S2$, $S3$ are switched on. All four switches cannot be on at same

time as this leads to the destruction of the IGBT. The driver circuit should have protection in order to avoid such a situation.

The control unit TEC 6000, [21] used in the IBEROBOT's normal equipment, is used to drive the full bridge inverter and is regulated by using feed-back from the current transformer. The control unit TEC 6000 has a user friendly interface with a LCD display and a master control switch for the selection of all settings. There is a possibility of setting the welding power as either a percentage of the transformer output or as the current intensity in Amperes. There is a weld current regulation that automatically compensates for current deviation during the weld cycle. The weld log can store 100 carried out welds, with a RS-232 interface for the continuously transfer of weld log data to a computer.

Ideally, the gate driver should be placed very close to the IGBT, however this is not always possible. During the design of the machine, twisted pair cables, preferably those which are shielded must be used between the driver and the IGBT gate in order to avoid electromagnetic interference EMI from the surroundings of the RSW machine. In order to avoid the voltage peaks across the gate of the IGBTs it is possible to use TVS. Another important factor is that there should be less loop area between the driver output and the IGBT gate, as this will minimize the parasitic inductance between the driver circuit and the IGBT.

For good regulation, the control circuit requires measurement of different electrical parameters, which may be the input voltage, DC link voltage, the output current. These signals are acquired by some measurement circuits such as the voltage divider, current shunts, and Hall sensors. Careful designing of the circuits is required in order to avoid an error in the feed-back signals.

3 CURRENT MEASUREMENT

The welding control system requires precision sensing of the secondary side welding current, which is of the order of many kilo amperes. Due to the high magnitude of the welding current, a short time duration and a high magnetic field in the vicinity of the conductor, specialized equipment are required, to measure the secondary side welding current. For high quality welding spots, the equipment must have an option to set different welding current profile, depending on the material and its thickness. To follow the pre-set values, the welding current must be sensed by the equipment and used as a feed-back signal to control the power transistors.

In some RWEs, Toroidial coils [22] are used for current measurement. Another proposed method [23] uses a steel ring placed around a section of the secondary loop of the welding equipment. The deformation in the steel ring due to electromagnetic forces, induced by an electric current, was measured using a strain gauge and then converted to a signal voltage proportional to the secondary welding current.

Resistance shunts exploiting the voltage drop associated with an electrical current flowing through the resistor can also be used for current measurement. This approach is not commonly used in industrial equipment, because of a lack of electrical isolation, changes of shunt resistance with temperature, voltage drop and energy loss [24].

Current sensing in free space [25] can be made by placing a Hall Effect sensor in close proximity to the current carrying conductor as shown in Figure 22. The magnetic field produced around an infinitely long conductor with a circular cross-section can be expressed in Equation 5.

$$B = \frac{\mu_o I}{2\pi r} \text{............}(5)$$

where r is the distance from the center line of the conductor to the sensor and μ_o is the permeability of the free space, I is the current flowing through the conductor and B is the flux density.

Free space current sensing is difficult to implement when the magnetic field is not sufficiently high. For low current magnitudes, core is sometimes required for the flux concentration. Thus a current measurement technique, based on the free space flux measurement is more suitable for installations where a high current is flowing as in the case of RSW.
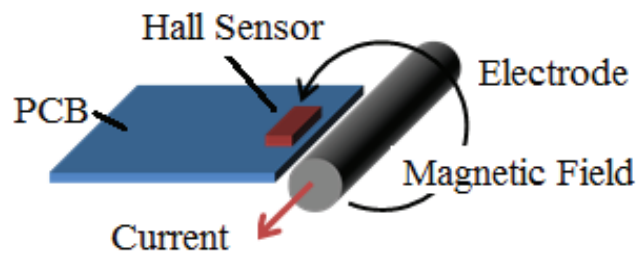
Figure 22 Free space current sensing

3.1   HALL SENSOR SYSTEM

A Hall sensor system for the measurement of secondary side welding current was developed [26]. An electronic circuit for the current monitoring in a spot welding machine was developed. A Hall sensor was used that has a wide measuring range up to 3Tesla.

The circuit developed as shown in Figure 23 is powered by a 24V DC voltage supplied from the control circuit of the RSE. A DC/DC converter IC is used to provide ±12V for all the Operational Amplifiers used in the design. The Hall sensor is biased by the current source in which the sensor has the best temperature stability and a linear response. The current source circuit is basically a buffered non-inverting amplifier driven by a constant input voltage. The circuit maintains a constant voltage across Rs as shown in Figure 24. As a result, the current flowing through the Rs will be constant.

The sensor is placed near the conductor, which senses the magnetic flux produced by the amount of current that passes through the welding electrodes. The Hall Effect element converts the magnetic flux density

linearly into a Hall voltage. The signal from the Hall sensor is amplified by means of an Instrumentation amplifier circuit.
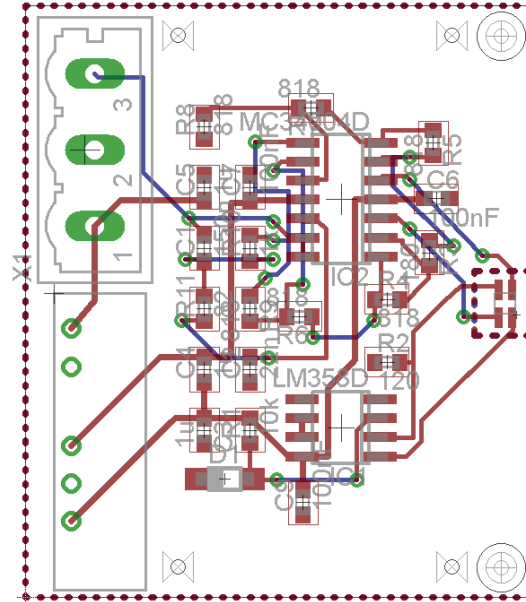
Figure 23 Hall element current sensing system

The circuit of the instrumentation is constructed from the buffered differential amplifier stage. The traditional three operational amplifier circuit is used. All the resistors for the amplifier are chosen to be equal except R_{gain}. A general expression for the overall voltage gain in the instrumentation amplifier is given by Equation 6.

$$Av = (1 + \frac{2R}{R_{gain}})............(6)$$

The gain of the amplifier can be changed by simply changing the value of one resistor i.e R_{gain}. The sensor voltage is amplified by means of an instrumentation amplifier so as to have a voltage range of 0 - 5V.
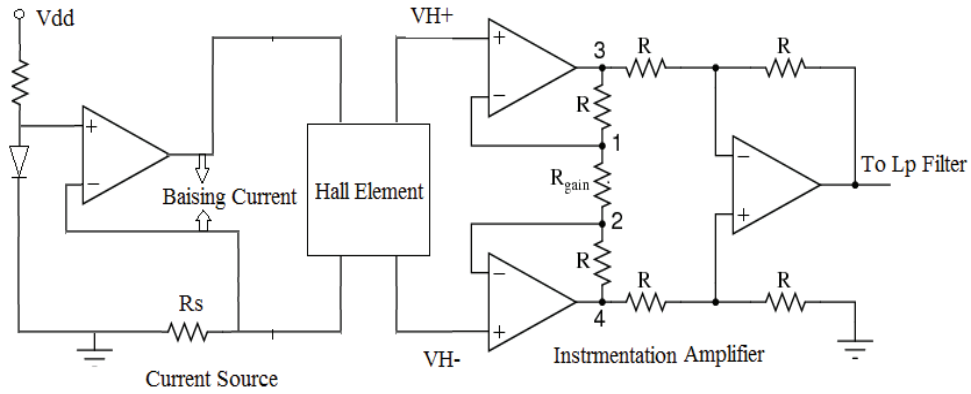
Figure 24 Hall snesor current measuirng circuit

A low pass filter is implemented, after the amplification, in order to remove the high frequency disturbances in the signal generated from the equipment. The response of the designed filter is shown in the Figure 26 the cut-off frequency for the filter is 10 kHz.
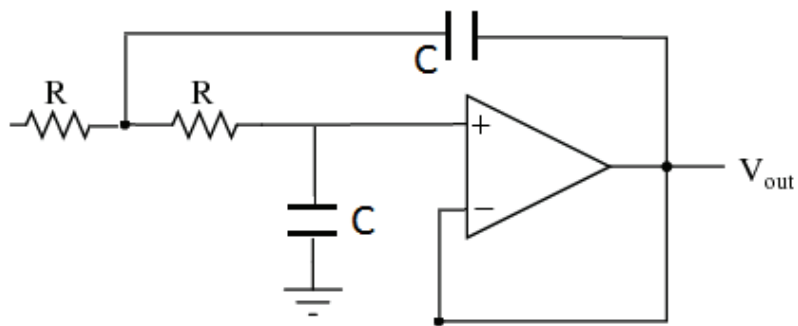
Figure 25 Low pass filter

28

Y2   Y1
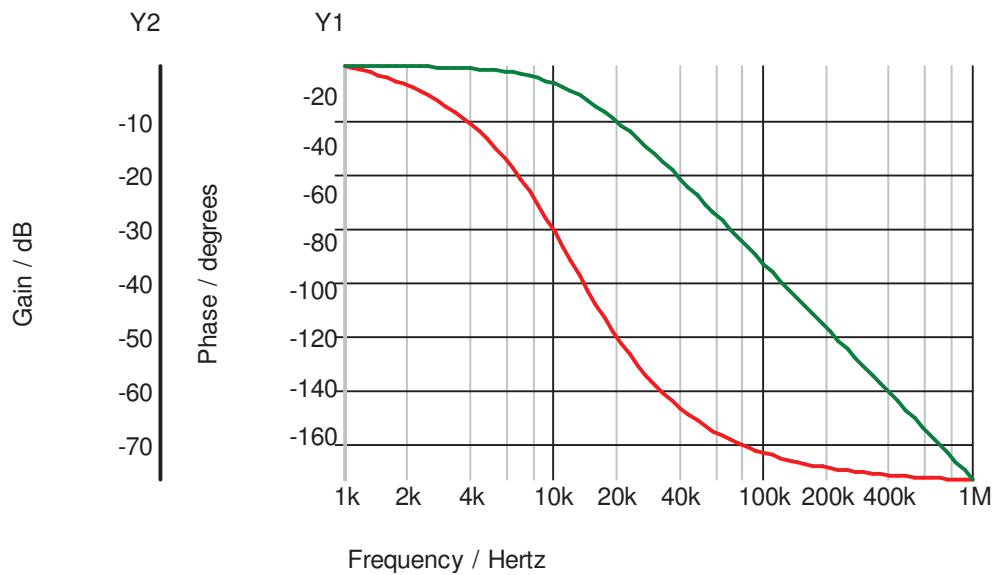
Figure 26 Simulated response of the low pass filter

3.2 COMSOL MULTIPHYSICS MODEL

The technique for the current measurement using a Hall sensor appears to be both simple and elegant, but several difficulties arise, when implementing it on the secondary side of real welding equipment. This technique is sensitive to a positioning error between the conductor and the sensor. To make an effective current sensor, it is necessary to control the positioning of the sensor. The measurements can also be affected by the presence of metals and tools in the near vicinity of the sensor. The influence of the sensor position and the presence of tools or other materials in the proximity of the sensor which had an effect on the sensor reading was investigated [26]. COMSOL Multiphysics software [27] is used to investigate these effects.

A model of a circular copper conductor of radius 14mm and length 300mm, carrying a current of 100kA was made in a simulation model. The current through the conductor produces a magnetic field around it. A sensor of area 2x3x1mm was placed at distances 1, 4 and 7mm from the circular conductor, and the flux distributions on the sensor surface were calculated.

Figure 27 shows the modeled conductor and sensor the red line show the magnetic field produced when the current is passed from the conductor.
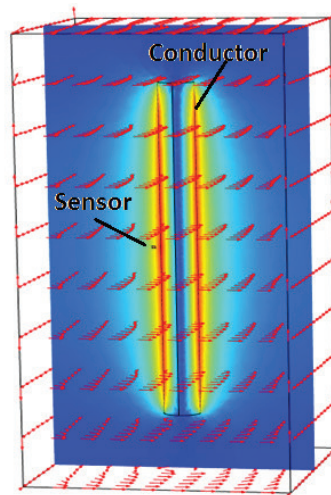
Figure 27 COMSOL model for current carrying conductor and sensor

The simulated results indicate that, for an accurate measurement, the sensor circuit should be isolated from any metal object within, the vicinity of the sensor. The keep out distance of the metal piece was estimated for different accuracy levels. Table 1 summarizes the keep out distance of the metal piece for different accuracies. For example, in order to achieve an accuracy of 98%, the minimum allowable distances of the metal piece from the sensor are 38,40,47mm, when the sensor is 1,4,7mm apart from the conductor respectively. A sensor aligned closer to the conductor is thus less sensitive to close metallic objects.

Table 1 Accuracy margin and the keep out distance

Accuracy	Keep out distance		
	1mm	4mm	7mm
98%	38	40	47
96%	30	32	38
94%	26	27	33
92%	22	24	29
90%	20	22	26

4   SUMMARY

4.1   STUDY THE INFLUENCE OF THE ALIGNMENT AND NEARBY METALLIC OBJECTS ON THE HALL SENSOR SYSTEM FOR CURRENT MEASUREMENT IN RESISTANCE SPOT WELDING MACHINE.

4.1.1   Paper I

A technique for measuring the current of a stationary spot welding unit using a Hall sensor system is implemented. A Hall Effect sensor is used to sense the strength of the magnetic field produced by the current, flowing through the welding electrodes, on the secondary side of a welding transformer. In contrast to a current transformer, the Hall Effect sensor can read a DC current and can thus be utilized in direct current welding equipment. In this paper, the influence of the sensor position and the presence of tools or other materials within the proximity of the sensor, which have an affect on the sensor readings, is investigated. COMSOL Multi-physics software is used to investigate these effects and a circuit design is implemented according to the conclusion drawn from the simulations.

4.2   A STUDY OF THE IGBT RUPTURE PHENOMENON IN MEDIUM FREQUENCY RESISTANCE SPOT WELDING MACHINE.

4.2.1   Paper II

Inverter drive resistance spot welding machines are becoming a good choice for welding because of their increased machine efficiency and output power. The DC link capacitors in spot welding equipment store a large amount of energy. In the case of any failure, there is a risk that an IGBT in the inverter will exhibit a violent rupture. This rupture can damage the converter, drive down time and can cause personal injury, which may lead to machinery certification problems. An IGBT failure detection and a solution for the protection against these failures in resistance welding machines have not been reported in the literature. A literature study of the

IGBT failure, rupture, fault detection and protection has been carried out for inverter drives in power applications. On the basis of the findings some protection schemes and important measures in the design of the machine have been adopted, which have resulted in a reduced risk of IGBT failure.

4.3 **HIGH FREQUENCY FULL BRIDGE CONVERTER USING MULTILAYER CORELESS PRINTED CIRCUIT BOARD STEPUP POWER TRANSFORMER**.

4.3.1 Paper III

The power density of the converter is increased by increasing the switching frequency. This increased switching frequency results in a reduction of the bulky magnetic parts of the converter. The intention of the work was to develop a high frequency full bridge step-up converter. The efficiency of the converter was 74.86% at 2.4 MHz which was not sufficient to that required for this topology. The developed control circuit, using DSPIC33FJ16GS502 micro controller, which produces the pulse width modulated (PWM) to drive the switches can, however, be used to drive and control the full bridge circuit in the RSE.

4.4 AUTHORS CONTRIBUTIONS

The exact contributions of the authors of the four central papers in this thesis are summarized in Table 2.

Table 2 Author's Contributions

Paper #	Main authors	Co-authors	Contributions
I	JS	AM KB LS	JS Literature study, implementation and testing. AM Discussion, review of the paper and testing. KB Discussion, review of paper and supervision LS Testing.
II	JS	AM SH KB	JS Literature study, and testing. AM Discussion for solution, review. SH Testing. KB Review of paper and supervision
III	JS	AM RA HB KB	JS Literature study, component testing, converter implementation. AM Testing the converter design and review of paper. RA Power transformer design and testing. HB Discussion and review. KB Review of paper and supervision.
1. Jawad Saleem (JS) 2. Abdul Majid (AM) 3. Radhika Ambatipudi (RA) 4. Hari Babu Kotte (HB) 5. Stefan Haller (SH) 6. Linda Schuberg(LS) 7. Kent Bertlisson (KB)			

5 THESIS SUMMARY

The thesis summarizes the development of compact high power resistance welding equipment, which is used to join overlapping sheets of steel by running a large current and melting the pieces together.

The first chapter explains the different resistance welding processes with its major focus on the spot welding process. The structure of the inverter based spot welding machine and the process of resistance spot welding is discussed in detail. Advantages and disadvantage in relation to the source, such as single phase, three phase or invert drive, used in the spot welding process are discussed. This selection of source plays an important role in the overall performance and efficiency of the spot welding machine.

Chapter two explains the different components involved in the rectified resistance spot welding equipment. The RSE consists of a three phase input rectifier unit, inverter unit with IGBTs as switches, a medium frequency power transformer with an output rectifier, a control unit and a driver circuit. Different topologies of isolated converters, which are able to provide bi-directional flux in the transformer, are discussed. The full bridge topology is selected for the RSE, and IGBTs are used as switches. The structure of the IGBT and some of the advantages over the other switching devices for this application are discussed. The DC link capacitors in the RSE store more energy. This causes the risk of IGBT device and casing rupture, in the case when a circuit failure condition occurs. This rupture can damage the converter, drive down time, and may cause personal injury and may lead to machinery certification problems. The protection scheme, in order to avoid a violent rupture by introducing fuses, is also discussed.

The controller unit consists of a microcontroller circuit and the driver circuit for the controlled commutation of the switch from the ON state to the OFF state and vice versa. A DSPIC33FJ16GS502 controller circuit has been developed, which can be used to drive the full bridge converter switches in the RSE.

Chapter 3 explains the Hall sensor current measurement technique developed to measure the current from the secondary side of the inverter based RSE, and explains the influence of the alignment of the sensor and the presence of nearby objects on the sensor reading in the developed system.

5.1 FUTURE WORKS

Based on the work presented in the thesis, the aim has been to increase the understanding of resistance welding. The possibilities of increasing the switching frequency further should be studied and an attempt made to investigate and understand the main loss mechanism.

There is a desire to increase the usability of spot welding techniques to thicker metals and other materials. The actual settings of the current and the weld time is, in the majority of cases, determined by trial and error methods. By performing accurate physical simulations using COMSOL Multi-physics as shown in Figure 28, much better settings in terms of strength and energy consumption could be established. After a simulation has been correctly set up and validated against measurements, it can be used to compare more complex control.
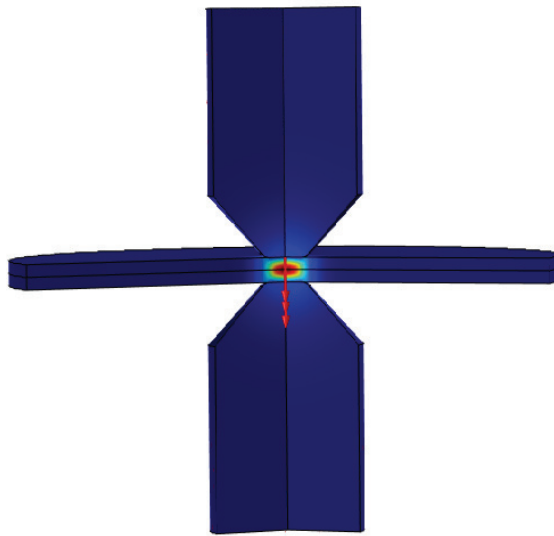
Figure 28 COMSOL model for RSW system

Recently, a commercially available transformer has been used by us in the RSE. The electrical simulation of an ideal resistive welding system has been developed to determine theoretical boundaries and to establish the design criteria for the transformer. The ideal elements provide useful

information concerning the theoretical boundaries which would be further investigated.

A literature study of the transformer used in the medium frequency resistance spot welding application [28]-[31] reveals that different ohmic resistances of the secondary winding of the transformer or different characteristics of the output rectifier diodes can lead to an early core saturation, producing disturbing current spikes, which appear on the primary windings, which can activate the over-current protection, and switch off the RSE. To eliminate the current spikes an advance control system has been proposed and designed by [31]. A new transformer with an additional auxiliary winding can be developed with the help of Timrå Elbyggnad AB [32]. The core prevention control proposed by [28] can also be developed.

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