International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS)
Volume VIII, Issue II, February 2019 | ISSN 2278-2540

Design and Implementation of 400A Industrial Inverter Welding Machine

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***Abstract*—Inverter-based welding machines are getting popular and favored by users due to their smaller size, fast response and high-efficiency compared to conventional welding machines. Many inverter-based welding machines include analog controllers to meet the requirement of fast transient response. This paper introduces a fully digital control algorithm for the new generation welding machines. Both constant current (CC) and constant voltage (CV) is achieved with the help of a high-speed DSP which has inner comparators and configurable logic units. In the case of digital control, optimizing the required welding properties such as hot start, arc force, and inductance is easier for the operator compared to analog controlled welding machines. All the functions are tested, and the experimental results show that efficiency is around 84%. The designed machine is a part of a project to produce a new generation of welding machines with Manual Metal Arc (MMA) and Metal Inert Gas (MIG) and Metal Active Gas (MAG) properties.**

***Keywords*—MMA, MIG, MAG, CPM, Welding, Digital Control, Peak Current Control Method, dsPIC, Inverter Welding Machines, DC/DC Converters**

I. INTRODUCTION

Conventional welding machines use grid frequency transformers to reduce the ac voltage to a lower voltage. Then a chopper circuit is used to adjust welding current. However, grid frequency transformers are bigger and much heavier than high-frequency transformers. Thus, conventional welding machines are not useful for applications where welding machines need to move around. Comparing to conventional welding machines, inverter welding machines much compact and light. In most of the inverter welding machines, grid voltage is rectified and filtered with bulk capacitors to produce a constant dc link voltage. The dc link voltage is switched at a high frequency and the power is transferred to the secondary side with a high-frequency transformer. There is also a rectifier circuit in the secondary side. After rectification, a filter inductor is used for current regulation. The filtered voltage is applied between the welding electrode and the workpiece. The duty cycle of the semiconductor switches in the primary side adjusts the welding current. When designing a welding machine from scratch, it is important to select the topology correctly before anything else. Several DC/DC topologies have been studied and concluded that two-switch forward converter and full-bridge converter are the best suitable for welding applications [1]. For this reason, full bridge topology is preferred in this study. Also, peak current control method is chosen for fast transient response, especially for welding continuity. The control of these

welding machines needs pulse by pulse current limiting and fast response because of the high bandwidth nature of the welding power demand. Hence, many welding machine producers use analog or semi-analog methods in their designs. In [2], design and implementation of a high-frequency 200 A, 5.6 kW welding machine and its analog controller is designed and analyzed. In this paper, a digital control method is used without sacrificing high bandwidth control. In [3] it is mentioned that microcontroller-based arc length control design is more stable comparing to the automatic voltage controllers over wide range. Nowadays, microcontrollers have configurable logic cells and fast comparators with blanking capabilities. This paper introduces the design and implementation of fully digital control for a new generation welding machine.

II. OPERATING PRINCIPLES

Inverter welding machines rectify the grid to produce a constant dc link voltage, then use this constant dc link voltage for high-frequency dc/dc converter. The designed inverter welding machine is shown in Fig 1. The full-bridge isolated buck converter is used in the power stage. A version containing a center-tapped secondary winding is commonly used in converters producing low output voltages. The two shares of the center-tapped secondary winding may be viewed as separate windings, hence we can treat this circuit element as a three-winding transformer having turns ratio 1:n:n[4]

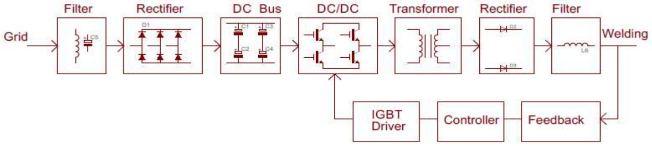


Fig. 1. Welding Machine Diagram

Welding process can be considered as a constant power load considering its static characteristics. But in its dynamic state, the load can be considered a fast-changing resistor which needs constant current. Due to the high-speed variations of the load, a high bandwidth controller is needed for the current loop, which implies a peak current control method. In current mode control, an oscillator is used as a fixed-frequency clock which is compared to a signal derived from output inductor current [5][7]. Fig.2 shows the peak current control method in the block diagram. Since the inductor current rises with a slope determined by input and output voltage, this waveform is expected to respond immediately to line voltage changes which eliminate both delayed responses and gain variation with changes in input voltage. [6]

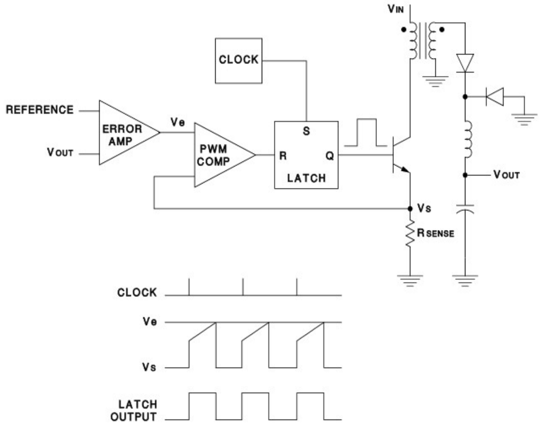


Fig. 2. Peak Current Control Method[6]

In welding applications, the error amplifier is used to command an output current, and the filter offers only a single pole to the feedback loop. This allows the user both a simpler compensation and high gain bandwidth over a comparable voltage-mode controlled converter. [6]. Also, it is mentioned that microcontroller-based arc length control design is more stable compared to the automatic voltage controllers over a wide range [3]. In this paper, peak-current control application is realized for a welding machine using dsPIC33EP128GS806. The proposed method is shown in Fig 3.

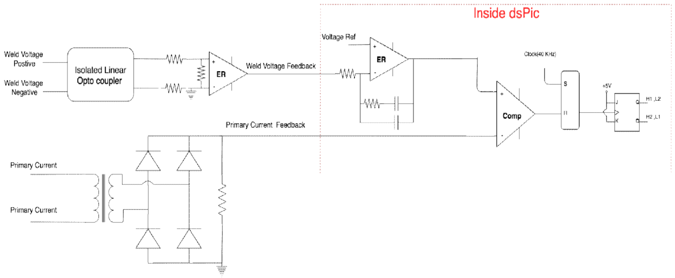


Fig. 3. Proposed Method for Welding Machine Controller

III. SIMULATION

MMA welding process is like a fast-changing resistor in normal operation. The relationship between voltage and current which can be approximated as below is linear with an offset [2]. For this reason, in simulation circuit, the equivalent resistance of the welding depends on the amount of power transferred.

$$V = 20 + 0.04 * I \tag{1}$$

In the selected full bridge voltage source converter topology, the switches are operated in push-pull PWM mode and hard switching technique is applied. In order to realize push-pull mode PWM in simulation, a negative edge triggered JK flip flop is used. Since the full bridge dc-dc converter is basically a buck converter with a transformer, in this paper the controller is designed in reference to an equivalent buck converter. Due to the applied push-pull switching configuration, the filter inductor sees twice the switching frequency of a single switch in full bridge converter which is set to 40KHz. AC Sweep property allows users to perturb control signal at different frequencies and observe the magnitude and phase plots over a frequency range of interest. In Fig. 4, the magnitude and phase of the control to IGBT current transfer function which is the inner current loop is given. This inner current loop should be much faster than the outer loop. In welding applications, a bulk capacitor with a high capacitance is not used since it is essential to control the output current directly for high quality welding. For this reason, a 33nF high current film capacitor is used to filter only high frequency harmonics. This results in the second pole to be far away from the desired cross over frequency.

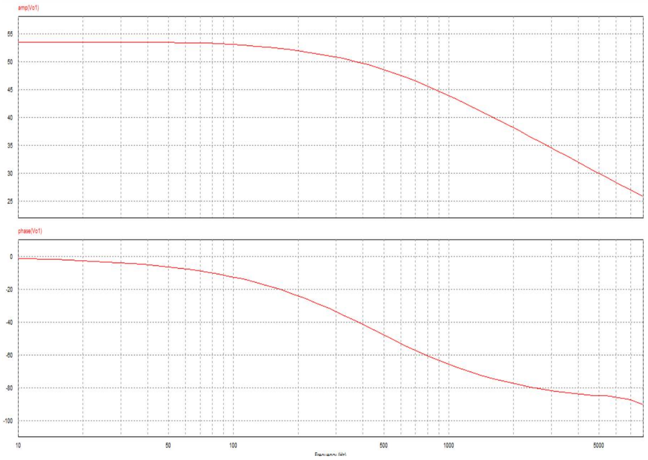
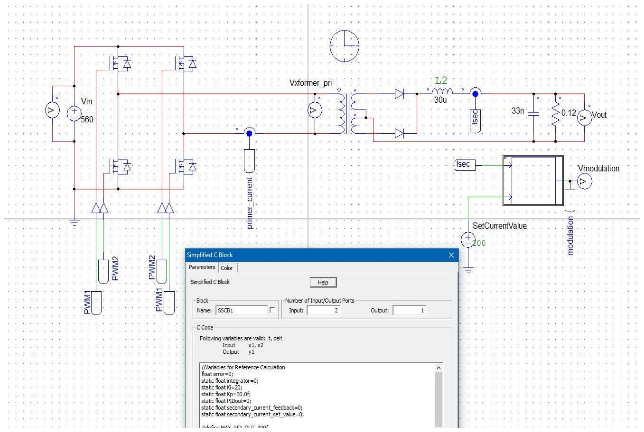


Fig. 4. Bode Plot Results of Open Loop Inner Current Transfer Function

In constant current mode (MMA Mode), output current feedback is taken, scaled and filtered. The filtered signal is regulated with PI block and used as a IGBT current reference. For constant voltage mode (MIG/MAG), output voltage feedback is taken, scaled and filtered. The filtered signal is regulated with a faster PI block and used as IGBT current reference. Fig.5 shows the digital controller of the simulation. The simulation is done considering MMA welding, so output current is measured with a hall effect current sensor and regulated with a PI controller using an interrupt service subroutine which produces a control reference. The interrupt service subroutine is adjusted to a period of 100 us to achieve a cross-over frequency of 1 kHz for the outer loop. The resulted output reference is an anolog output and can be realized with either using an output pin of the dsPIC or internal DACREF reference for the current sense comparator.



Simplified C Block

Block
Name: SSCB1
Number of Input/Output Ports
Input: 2
Output: 1

C Code
Following variables are valid: t, delt
Input x1, x2
Output y1

```
//Variables for Reference Calculation
float error=0;
static float integrator=0;
static float Ki=20;
static float Kp=30.0f;
static float PIDout=0;
static float secondary_current_feedback=0;
static float secondary_current_set_value=0;

#define MAX_PID_OUT 400f
```

Fig. 5. Digital Controller of the Welding Machine

Since the mathematical model of the full bridge converter and buck converter are the same, similar PI code can be implemented for the full bridge converter. The simplified C block in PSIM whose period is 1 us is interrupted every 100 us and PI controller is used for producing an IGBT current reference. This current reference is used in DACOUT pin of the dsPIC which is internally connected to the negative pin of the internal fast comparator. The comparator resets an internal latch as soon as the feedback signal passes the reference, which turns off the PWM signal immediately. In Fig 6, the simulation results of 340A output of the MMA welding machine is given.

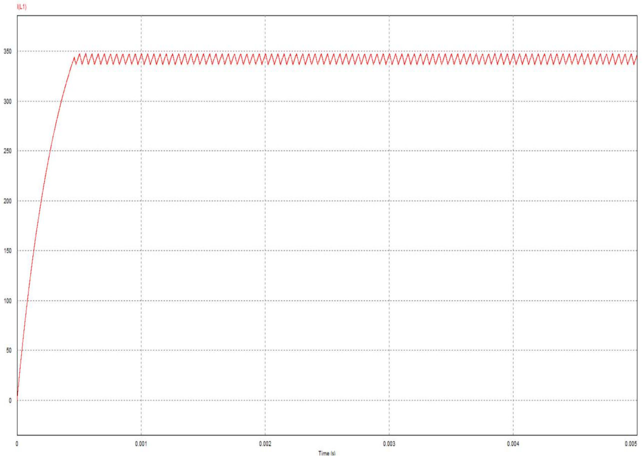


Fig. 6. 340A Output of a Welding Machine Simulation Result

Although the simulation results seem okay, in real life welding is complicated and do not show the same resistance all the time. Especially in stick welding mode, short circuits are often present because of the electrode becoming very close to the workpiece, which means that the arc length is smaller than it needs to be for a high-quality welding. When a short circuit situation occurs, the controller needs to sense it and must increase the current reference in order to increase the arc length. This process is called arc force. When the arc length reaches its normal length, the current reference goes back to its normal value. The same situation happens in the welding starting process. When the welding starts, the arc length is shorter than its usual length, so the current reference should be set a bigger value for a period of 100ms to 200ms. This process is called hot start. Both the hot start and arc force algorithms are easier and flexible for the user when designing a welding machine with a digital controller.

IV. PRACTICAL IMPLEMENTATION

The control method which is tested in simulation environment is also implemented using dsPIC which controls the implemented welding machine. The welding machine works in output current control mode. dsPIC33EP128GS806 has an internal configurable logic cell (CLC) and current limiting properties in its PWM module. Fig.7 shows the PWM signal, current reference from DACREFOUT pin of dsPIC which realizes the current limiting. Whenever the current feedback from power circuit exceeds the current reference value from the dsPIC (which is actually PID output of output current), the latch resets and PWM signals are set low. Each period, PWM clock sets the latch and PWM signals are high again. The ultra-fast comparator has also a blanking capability. When the switches are on-state, the current may go to a higher value than expected. In order not to set the latch incorrectly, a small blanking time (around 100ns) is added to the fast comparators in the code.

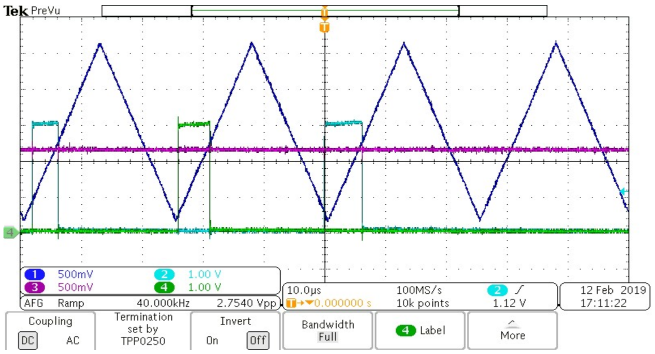


Fig. 7. Green: PWM Signal, Blue: Feedback Signal, Red: Reference from dsPIC DACREFOUT pin

The dsPIC outputs low voltage value (3. 3V) and in order to drive IGBT's a pulse transformer is needed. In order to drive the pulse transformer, a high voltage driver needed. Fig. 8 shows the isolated gate driver circuit. The isolated gate driver has an isolation level of 4kV.

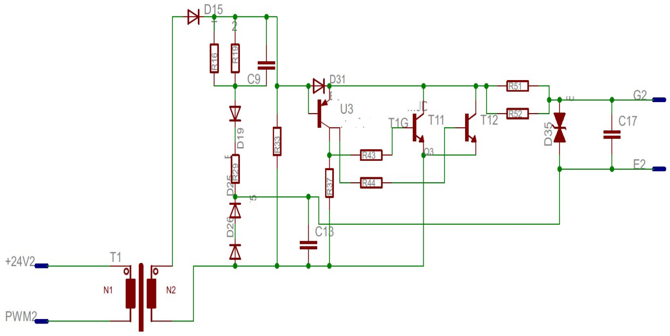


Fig. 8. Isolated Gate Driver Circuit

Whenever the PWM signal is high, the pulse transformer works as a single switch forward converter and the 2 cross IGBTs start conducting. When the PWM signal is low, the pulse transformer resets itself through a zener diode and the U3 starts conducting which drives both T11 and T12 to discharge the gate-emitter capacitance of the IGBT. Note that this circuit is for a single IGBT. D26 and D25 is 3.1V zener diodes and C18 is a 100nF capacitor. When the PWM signal is high, zener diode charges C18 to 6.2V, which is used during the PWM low signal to produce a negative voltage in order to turn off the IGBT's as fast as possible. Current tailing is minimized with this configuration. C9, R16 and R25 works as a snubber circuit. R51 and R52 are gate resistors to limit charging and discharging current. On the left-hand side there is a high-speed mosfet (IRFRC20) which is used to drive pulse transformer. The switching speed of the mosfet also determines the welding quality. Since welding is a process with many short circuits, the turn-off time of the IGBT's should be small as possible. The mosfet also has a parallel Zener diode to its drain to source terminals. When the mosfet is in off state, the pulse transformer resets itself on this zener diode. Fig. 9 shows the mosfet gate signals in push-pull configuration signals and the primary side of the pulse transformer. As a result, mosfet and the IGBT gate signals look similar.

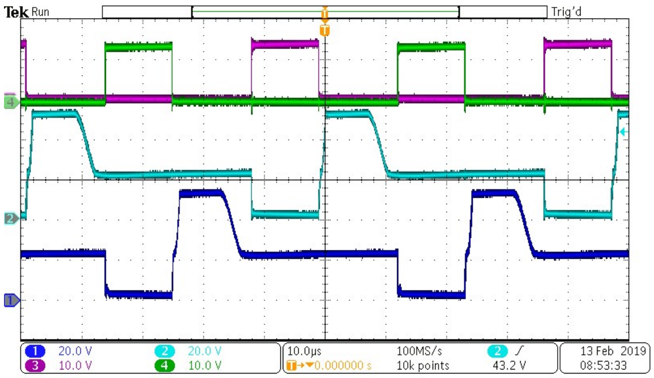


Fig. 9. Green: PWM Signal 1, Red:PWM Signal 2, Dark Blue: Pulse Transformer Input Signal for PWM1, Light Blue: Pulse Transformer Input Signal for PWM2

In this study, the switching is realized with hard switching technique. The upper left and the bottom right IGBT's are controlled with one PWM signal. The bottom left and the upper right signals are controlled using 180 degrees phase shifted version of the first PWM signal. Fig.10 shows the primary terminal voltage of the full bridge transformer. A strong ringing is present because of the hard-switching technique. Magnetizing inductance of the high-frequency transformer is calculated as 2 mH, and the transformer works in continious conduction mode. Fig.10 also shows the primary current of the transformer which is sensed using a current transformer. The output of the current transformer is recitifed with a diode bridge. Than the current is converted to a voltage signal using through current shunts equivalent to 3 ohms. The current shunt resistors are selected to stay in safe region without sacrifising the current resolution. On the secondary side, filter inductor is selected as 30 uH allowing a harder current ripple in order to achive a good quality welding. Otherwise a bigger filter inductor with a higher value would slow down the welding response. There is a small capacitance at the output, which is 33nF to filter the high frequency signals of the welding. Conventional welding machines are usually around 50% to 70% efficient whereas in this particular inverter based welding machine 84% efficiency has been observed. Using the isolated CAN BUS the inverter welding machine can be used with robotics arms and many PLC modules with a CAN BUS module of 250 kHz baudrate.

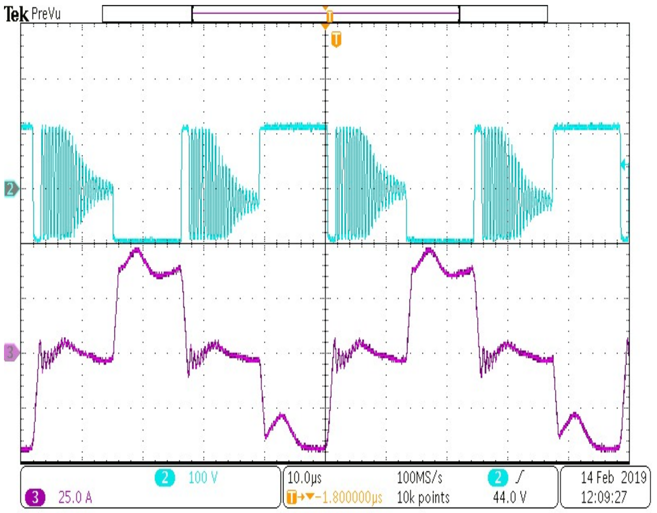


Fig. 10. Red: Transformer Primary Current (Ch.3) Blue: Transformer Primary Voltage (Ch.2)

IGBT gate driver circuit, control circuit and power circuit are implemented as close as possible to each other so that noise effects are minimized. The input 6-pulse diode rectifier, IGBTs and output diode rectifier circuit are all connected to same heatsink. Fig. 11 shows the experimental circuit. The control card and the power card have different grounds and all the feedback signals are either isolated with a transformer or using linear optocouplers. There is a resistor of 10 ohms in series with 4.7 nF capacitor parallel with the load at the output, which is used as a snubber circuit for the system.

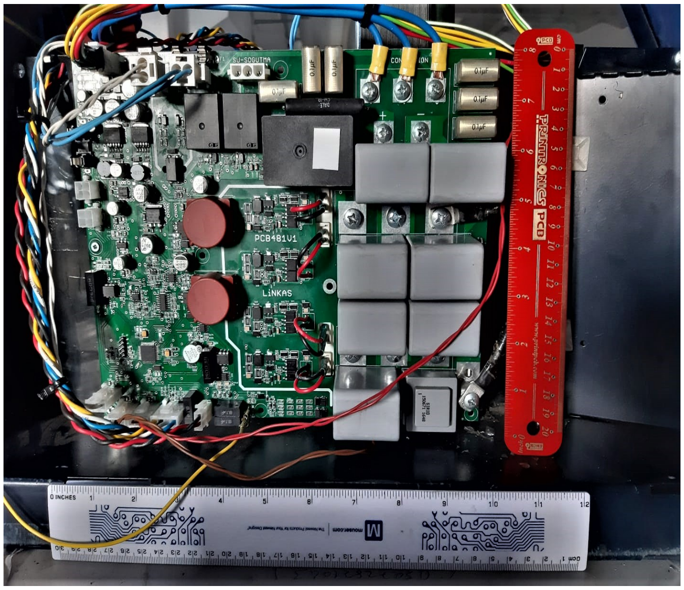


Fig. 11. Experimental Circuit

V. EXPERIMENTAL RESULTS

Fig. 12 shows the output voltage and output current of the welding machine. The current is around 370 A, and the voltage is around 40 V, which produces an of output power of 14.8 kW

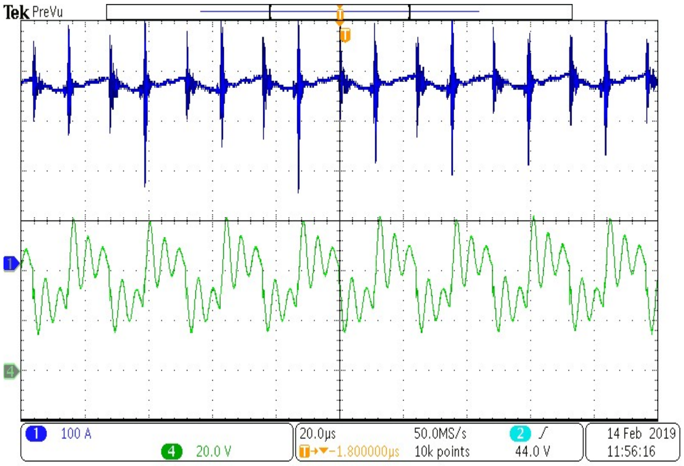


Fig. 12. Welding Current (Ch.1) and Weld Voltage (Ch.3)

When the welding starts, in order to create an arc to initialize the welding process, open circuit voltage is set around 80V and the current reference is set a higher value than its normal operation mode. This process is called, as mentioned before hot start. Fig. 13 shows the hot start process of a MMA welding.

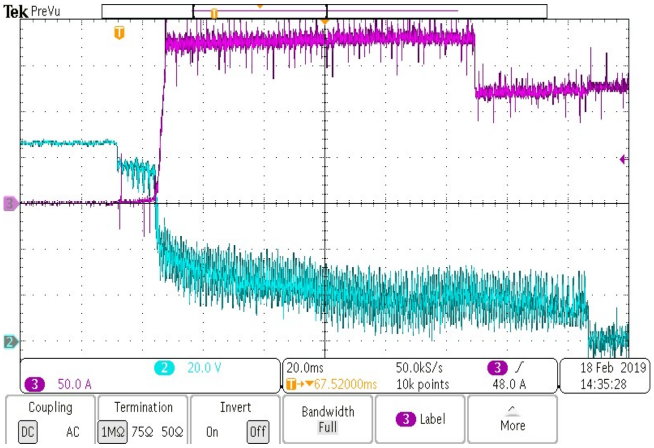


Fig. 13. Hot Start of MMA welding. Welding Current Current (Ch.3) and Weld Voltage (Ch.2)

In the beginning, welding voltage is around 84V. During the initial contact of the electrode to the workpiece, the welding current starts to increase to a level of around 180A to transfer the heat to the workpiece. After approximately 100 ms, the welding process is in steady state and the PI controller forces the output current to be regulated. However as mentioned before, short circuit situations may occur in steady-state as well. So, the controller needs to be fast enough to respond these changes before the welding process breaks away. Fig. 14 shows the arc force process of the welding machine. Here it can be observed that the welding current is responding to the change in the welding voltage with a delay of 2 ms, which implies a crossover frequency around 500 Hz for the outer voltage loop.

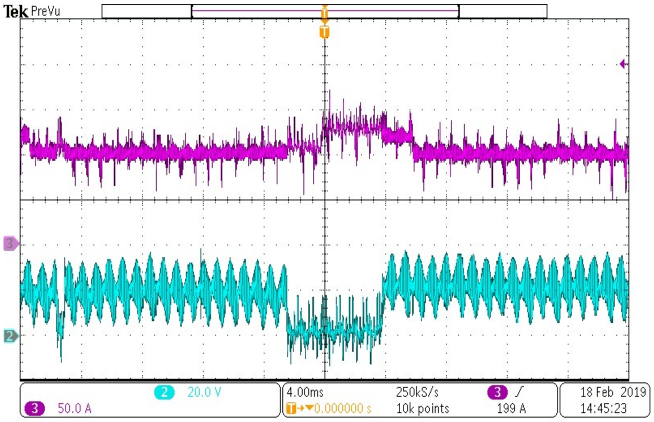


Fig. 14. Arc Force of MMA Welding. Welding Current Current (Ch.3) and Weld Voltage (Ch.2)

In this study, the nominal current of the welding machine is selected to be 400A at %65 machine operating duty cycle. This means that, the machine can give 400A for %65 of the time and the needs a rest for %35 of the time. The machine is operated for 6 min 30 sec during a total operation time of 10 min. This cycle is repeated for a full day. On the other hand, the machine should be able to give 300 A without the need of a rest. Fig. 15 shows the thermal image of the welding machine circuit after 1 hour of continious 300 A operation. The ambient temperature was around 20 degrees for this particular test.

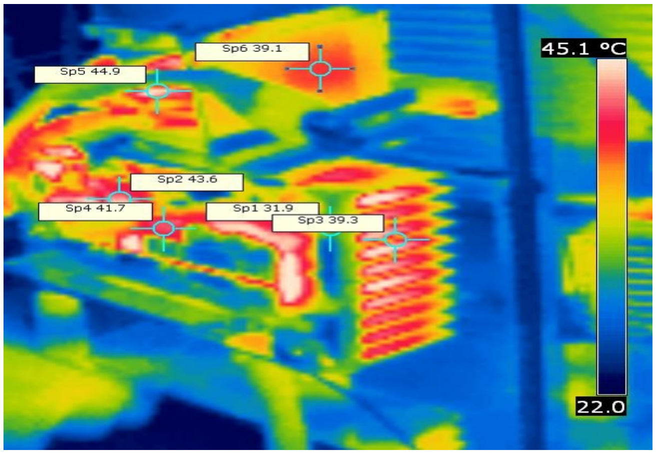


Fig. 15. Temperature Distribution

The machine is designed to give its maximum efficiency at 400A which results in 17.2 kW of power. Fig. 16 shows the power vs efficiency graph of the welding machine.

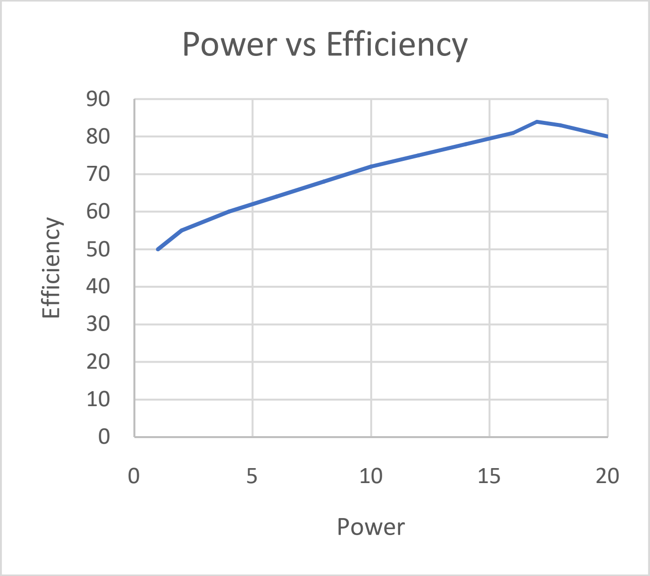


Fig. 16. Efficiency Graph

The welding quality is defined based on some certain requirements. The first requirement is, that the finished welded product should be in accordance with the aimed joint dimensions. The second one is that the joint point should be strong and there should be no cracks on the surface. Although these properties are tested with welding inspection machines, the appearance of the welded workpiece also gives an idea to the user. Fig. 15 shows a workpiece welded with MIG welding technique.

Fig. 17. Welded Workpiece

The welding workpiece has a uniform wavy surface, where width and height are very similar. Also, full thermal penetration has been achieved since the edges are in a good shape. For these reasons the welding can be considered as a good quality welding.

VI. CONCLUSION

In this study, a DSP- based inverter welding machine is designed and implemented. Peak current mode control method is used with outer current loop for MMA and outer voltage loop for MIG-MAG welding. Conventional welding machines are both inefficient and heavy whereas inverter-based welding machines are not only lighter but more efficient. Comparing to analog based conventional welding machines, digital control gives configuration flexibility. In addition, since there is an isolated CANBUS module, the machine can be used in robotic welding applications.

REFERENCES

[1] Blasco N. , Martinez A. “Evaluation of Power Converters for MMA Arc Welding”
[2] Koparan A. “Implementation of 200 Ampere, High Frequency Switching DC and AC/DC Arc Welding Mahcine”, M. Sc. Thesis, 2010
[3] Bjorgvnsson J. B. , Cook G. E. , Andersen K. , “Microprocessor Based Arc Voltage Control for Gas Tungsten Arc Welding Using Gain Scheduling”
[4] Fundamentals of Power Electronics, Robert W. Erickson
[5] Ridley R, “A New Small-Signal Model For Current Mode Control”, PhD Dissertation, Blacksburg, Virginia, 1990
[6] Switching Power Supply Topology Voltage Mode vs. Current Mode, Robert Mammano