Självständigt arbete på grundnivå

Independent degree project – first cycle

Elektroteknik

Electrical Engineering

Resistance spot welding equipment controller

Beijer iX T7B Softmotion based weld equipment controller

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Resistance spot welding equipment controller – Beijer iX T7B Softmotion based weld equipment controller
Olaf Hermansson
2016-07-27
Abstract

The goal of the project is to evaluate a new setup for the company Iberobot Svenska AB, using HMI and PLC, for resistance spot welding equipment controller. The purpose of the controller is to control the weld process; weld power and time. One of the question raised is if this setup could be used as an RWE controller and thereby be able to replace an old proprietary controller called TEC6000. A prototype is built compatible with current single phase RWE and literature study is conducted to answer this question. The new setup is based on Beijer iX T7B Softmotion which includes an HMI and a PLC with EtherCAT support. EtherCAT input and output modules from Beckhoff are chosen because they can handle the speed required by the weld process. The controller is implemented using theory for RMS value, timing diagram and state diagram based on weld process. The prototype is revised three times. A zero crossing detector is implemented. A control element driver using opto-triac is implemented. Measurements using oscilloscope are conducted which shows that the controller is able to start a weld, but zero crossing detection is unstable and further research into this and current regulation is needed before an end user product can be made.

Keywords: SCR, PLC, HMI, Resistance welding.
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Terminology

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### Terminology

#### Abbreviations

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<th>Abbreviation</th>
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<tbody>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
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<tr>
<td>EtherCAT</td>
<td>Ethernet for Automation Technology</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
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<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
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<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
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<tr>
<td>Op-amp</td>
<td>Operational Amplifier</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<td>PLC</td>
<td>Programmable Logic Controller</td>
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<td>RSW</td>
<td>Resistance Spot Welding</td>
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<tr>
<td>RW</td>
<td>Resistance Welding</td>
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<td>RWE</td>
<td>Resistance Welding Equipment</td>
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<tr>
<td>SCR</td>
<td>Silicon Controlled Rectifier</td>
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Mathematical notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$x(t) = x(t, D)$</td>
<td>Phase cut sine wave with duty cycle $D$</td>
</tr>
<tr>
<td>$k$</td>
<td>RMS factor</td>
</tr>
<tr>
<td>$D$</td>
<td>duty cycle of phase cut sine wave</td>
</tr>
<tr>
<td>$x_{rms-max}$</td>
<td>RMS value for full sine wave ($x(t)$ with $D = 1$)</td>
</tr>
<tr>
<td>$x_{rms}$</td>
<td>The root-mean-square (RMS) value of $x(t)$</td>
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1 Introduction

The background and problem motivation, verifiable goals, high level goals and scope of the project is presented under each subchapter below.

1.1 Background and problem motivation

Resistance spot welding (RSW) is a popular welding technique for sheet metal with operators all around the world [1]. Car manufacturing is one industry branch which uses RSW, but it is also used in contract manufacturing and welding of stainless roofs. The resistance spot welding equipment (RWE) incorporates a spot welder controller, which regulates the power applied to the materials which are to be joined.

Figure 1.1: Picture of TEC6000 resistance spot welding controller.

The company Iberobot Svenska AB [2] currently use a proprietary controller called TEC6000 (see picture in figure 1.1) in the single phase RWE which they manufacture. The controller is made of three printed circuit boards (PCBs) with a microcontroller on one of them. TEC6000 regulates weld current (which is set by operator to achieve desired power) by using silicon controlled rectifiers (SCRs). The regulator type used is a P or PI-regulator depending on user settings. TEC6000 doesn’t
support industrial fieldbus protocols, such as Modbus, Profinet, Profibus and EtherCAT; making it hard to interface with for example industrial robots and servo motors. The display is a dot-matrix liquid crystal display (lcd), with limited capabilities of viewing things like trends, pictures, drawings, schematics, et cetera. TEC6000’s program code for user interface supports a single language (e.g. Swedish or English). The controller needs to be reprogrammed if the language of the user interface is to be replaced [3].

1.2 High-level problem statement

Iberobot [2] hope that by implementing a new RWE control setup with a programmable logic controller (PLC) and human machine interface (HMI) [4], including EtherCAT [5] support, their weld system will become more flexible by increasing the possibilities of viewing things on display and communicating with components such as industrial robots and servomotors. EtherCAT topology makes it easier to manufacture the resistance welding equipment control system by making it possible to use a common interface between all components. This would also reduce the risk of manufacturing errors.

The result of this project will give a base to aid further development of end user RWE, by investigating how HMI and PLC can be used to interact with operator and control RWE respectively. By using an HMI with remote control capabilities, the welding controller could be remotely troubleshooting instead of having to be sent to service.

By using Codesys [6] made by the company 3S-Smart Software Solutions [6], which is a standard PLC development system utilized by many manufacturers, there is lot of implementation hardware to choose from. The new setup will not be limited in hardware like TEC6000 is.

1.3 Extent

The project stretched over a period of 10 weeks. During these ten weeks the following activities were carried out: pre-studies, prototype building, programming, testing and measurements, evaluation, report writing and presentation.
1.4 Scope
The project is focused on the electrical properties of the examined RWE setup, rather than the mechanical properties such as the finished weld’s mechanical strength. The result of the project is a prototype and not a finished end user product.

1.5 Concrete and verifiable goals
The goals of the project are:

- Develop a prototype RWE controller setup using HMI and PLC
- Evaluate the setup: could it be used as a RWE controller?
- Examine how an HMI can be utilized to get input from and give feedback to the operator.

1.6 Outline
Chapter 2 describes the theory behind resistance welding, thyristor control and the EtherCAT bus. Chapter 3 describes the method used when programming the HMI and PLC, and measuring and testing the electrical properties of the setup. Chapter 4 describes the workings of the finished prototype design and program code. Chapter 5 presents the result from tests and measurements of the new setup. Discussion and conclusions are in chapter 6.

1.7 Contributions
The author is solely responsible for all the project work.
2 Theory

The theory behind resistance welding (RW) is explained below, followed by explanation of different current regulation schemes, weld power topologies and the EtherCAT fieldbus.

2.1 Resistance welding theory

Resistance welding is based upon Joule heating [7] which means that heat is produced when electric current flow through a resistance. In this case the heat is then used to weld two materials together (as seen in gray in figure 2.1) [8]. There are different types of resistance welding; two of those are spot and seam welding. In spot resistance welding, the current flows through two electrodes and into the materials that are to be joined. In seam welding the electrodes are replaced by wheels which rotate over the two materials, continuously welding them together and thereby creating a weld seam [9].

The spot welding process is divided into following stages [3]:

- Prepressure: ensures proper contact between electrodes and weld material prior to weld.
- Pretest: tests with a small current the contact between electrodes and weld material.
- Preweld: the weld material is preheated and coating is removed
- Weld: the main weld which joins the weld materials together
- Postweld: used to reduce the hardness of the material in and around the weld nugget
- Postpressure: keeps the weld materials together while cooling
The resistance welding controller controls the weld time and current in the weld process by using a control element (see figure 2.1). The weld power is proportional to the weld current. The controller gets input from a current measurement coil which acts as a feedback for the regulator which the controller implements. A pneumatic cylinder is used to press the two electrodes and therefore also the weld materials together during the welding process [8]. The regulator controls the current flowing through the electrodes by using a control element. A control element driver is sometimes needed to interface the output of the controller to the voltage levels of the control element.

There are different types of resistance weld power topologies. One is single-phase and another is 3-phase. These can be implemented in different ways. Figure 2.2 shows one implementation for each topology. a) shows the single-phase topology which Iberobot [2] currently uses, with silicon controlled rectifier (SCR) as control element followed by weld transformer. The output of this topology is a phase cut sine wave (see figure 2.3). An ideal equivalent electrical diagram for this implementation is shown in figure 2.4. b) shows a 3-phase system utilizing a frequency inverter as control element followed by the weld transformer and the secondary side of the weld transformer is then rectified and...
outputted as direct current (DC). The frequency inverter can be implemented using a rectifier circuit followed by insulated-gate bipolar transistors (IGBTs). This topology is referred to as Mid-Frequency Direct Current (MFDC) and was studied in 2013 with 1000 Hz by researchers at Mid Sweden University [9].

Figure 2.2: Two different weld power topologies. a) Single phase with SCR as control element followed by weld transformer; output is a phase cut sine wave. a) 3-phase with frequency inverter as control element. The secondary side of the weld transformer is rectified; output is direct current (DC) [9].
Two silicon controlled rectifiers in parallel is often used as control element in single phase topology. The cathode of one SCR is connected to the anode of the other (see figure 2.4). One SCR is used to conduct on positive half cycle and the other on negative half cycle of the input sine wave. The SCR is put into conduction mode (fired) at a phase angle determined by the duty cycle D set by the regulator and conducts until next voltage zero crossing [8]. This type of regulation creates a phase cut sine wave with a theoretical RMS value according to equation 2.1 (see appendix A for full mathematical deduction).

\[
x_{\text{rms}} = a \sqrt{\frac{D}{2} + \frac{\sin(2\pi D)}{4\pi}}
\]  

(2.1)

where \( a \) is the amplitude of the full sine wave and \( D \) is the duty cycle. One drawback of using SCR is that the root-mean-square (RMS) current can only be changed once in each half cycle of the mains frequency [8].
By normalizing equation 2.1 the equation for $x_{rms}$ as a function of the RMS value for the full sine wave ($D=1$) $x_{rms-max}$ can be written as:

$$x_{rms} = x_{rms-max} \sqrt{\frac{D}{2} + \frac{\sin(2\pi D)}{4\pi}} = x_{rms-max} \sqrt{D + \frac{\sin(2\pi D)}{2\pi}}$$

(2.2)

The square-root, and everything inside it, is from now on referred to as the RMS factor $k$:

$$k = \frac{x_{rms}}{x_{rms-max}} = \sqrt{D + \frac{\sin(2\pi D)}{2\pi}}$$

(2.3)

The crest factor $C$ for a signal $x(t)$ is:

$$C = \frac{\max(|x(t)|)}{x_{rms}}$$

(2.4)

A phase cut sinusoidal wave, with duty cycle $D$, with corresponding equation 2.1 (RMS value) and equation 2.3 (crest factor) is visualized in figure 2.3.

Figure 2.5 and 2.6 shows two different control element drivers for SCR. The driver in figure 2.5 utilizes a pulse transformer. The two secondary
coils create a voltage difference between cathode and gate for each SCR thereby putting one of them into conduction mode (which one depends on which half cycle). The input signal is amplified using a NPN bipolar junction transistor (BJT). A fly-wheel diode is used to safely discharge the primary side when the BJT is in cut-off mode.

The driver in figure 2.6 utilizes an optically isolated triac (opto-triac). The opto-triac is controlled by the input, through a current limiting resistor, and when fired connects the anode to the gate of the SCR. Two diodes are used to ensure that the triac doesn’t short-circuit the anode to cathode of the two SCRs.

Figure 2.5: SCR control element driver with pulse transformer.
2 Theory

2.3 Zero crossing detector

The controller needs to detect zero crossing on the voltage across the SCRs in order to synchronize the trigger time according to the duty cycle. Zero crossing can be detected in multiple ways, two of which are shown in figure 2.7 and 2.8. Both of the circuits shown are using the same zero crossing detector, but the input is connected differently. One is connected across the SCRs (K1 and K2) and the other one is connected to L1 and L2. The connection in figure 2.8 requires that the controller knows the phase shift between the voltage across the SCRs and the voltage across L1 and L2. The other connection in figure 2.7 on the other hand requires that the zero crossing detector can work properly (with correct output) while the voltage across K1 and K2 goes from $400V_{rms}$ to the peak on-state voltage drop of the SCR.

The zero crossing detectors shown in figure 2.7 and 2.8 uses an operational amplifier (op-amp) connected as a comparator. The output of the comparator is connected to the gate of an N-channel metal oxide semiconductor field effect transistor (MOSFET). The output of the zero crossing detector is pulled to 24V by a pull-up resistor when the MOSFET is not pulling it down to 0V. In order to accommodate for the
inversion done by the MOSFET circuit the input of the zero crossing detector is connected to the op-amps inverting input.

![Zero crossing detector diagram](image1)

**Figure 2.7:** Zero crossing detector using operational amplifier and N-channel MOSFET. Input is connected across the parallel SCRs.

![Zero crossing detector diagram](image2)

**Figure 2.8:** Zero crossing detector using operational amplifier and N-channel MOSFET. Input is connected across the mains input L1 and L2.
The circuit shown in figure 2.7 can be made more sensitive by adjusting the op-amps null offset and changing the transformer to one with a higher voltage output. Voltage clamping is needed if the peak voltage on the secondary side exceeds the power supply for the op-amp. Figure 2.9 shows a zero crossing detector with Zener diode voltage clamps and null offset adjustment circuit with potentiometer.

Figure 2.9: Zero crossing detector with improved sensitivity for small signals. Input is connected across the mains input L1 and L2.

2.4 EtherCAT

Ethernet for Control Automation Technology (EtherCAT) [5] is an open fieldbus standard developed by Beckhoff Automation GmbH. EtherCAT is used to interface a master, e.g. a programmable logic controller (PLC), with a set of slaves (e.g. distributed input and output modules or servo amplifiers). Like many other fieldbuses it runs over Ethernet. EtherCAT was designed to overcome the drawbacks of the Ethernet protocol from a control and automation point of view. One of the drawbacks is the large communication overhead when frequently sending small quanti-
ties of data. EtherCAT overcomes this drawback by letting all the devi-
eses in the network share the same Ethernet telegram when communi-
cating. This is done by using a logical ring topology. Each slave on the
EtherCAT bus has two pairs of receiver (Rx) and transmitter (Tx) inter-
faces (see figure 2.9). Telegrams are sent from master and passed
through one slave at the time. The fieldbus memory management unit in
each slave reads the data addressed to it and adds output data to the
telegram while retransmitting it to the next slave through its outgoing
line Rx interface. If a slave doesn’t detect a carrier signal from the next
slave on its return line Tx interface, it connects its outgoing line Rx
interface to its return line Tx interface thereby closing the ring. When the
telegram has passed once through all the slaves it is returned to the
master by again passing through all slaves using the return line interfac-
es. The slaves can be seen as one large device which sends and receives
Ethernet telegrams. The telegrams are sent from the master at regular
times determined by the EtherCAT bus cycle time [5].

Figure 2.10: EtherCAT logical ring topology with one master and two slaves.

EtherCAT implements a distributed clock (DC) which is synchronized
between all bus nodes including master and slaves. Because of the
EtherCAT bus logical ring topology, the delay between all nodes is
deterministic and the DC can therefore be accurately adjusted with a
synchronization error of less than one microsecond [10].
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Beckhoff Automation GmbH EtherCAT input terminals support four different technologies [11]:

- Standard sampling: One value per input channel is transmitted to the master each EtherCAT bus cycle.

- Oversampling: Each input channel is sampled several times each EtherCAT bus cycle and the input states are transmitted as an array to the master.

- Timestamping: One positive and one negative flank are detected and transmitted each EtherCAT bus cycle with timestamps synchronized to the distributed clock.

- Multi-timestamping: Several negative and positive flanks are transmitted with corresponding timestamps to the master each EtherCAT bus cycle.

Beckhoff Automation GmbH also has EtherCAT output terminals with four different technologies [11]:

- Standard sampling: The output can be changed once each EtherCAT bus cycle.

- Oversampling: The output can be changed, between each EtherCAT bus cycle, according to an equi-time-distance array of output states.

- Timestamping: One positive and negative flank with DC time can be sent to the terminal. The terminal will automatically change the outputs according to the flanks and DC times independent of EtherCAT bus cycle.

- Multi-timestamping: Same as timestamping, but supports several positive and negative flanks each EtherCAT bus cycle.
3 Methodology

Design and evaluation methodology is described below including method for investigation of old RWE setup with TEC6000.

The prototype is based on the same weld power topology as the old setup to make it compatible with RWE currently controlled by TEC6000. The proposed controller setup is based on knowledge from the old design with TEC6000. That includes study of program code, user manual and circuit diagrams for all printed circuit boards (PCBs). The following were investigated in the old design:

- How zero voltage crossing is detected
- How RMS current is measured
- How the two SCRs are triggered
- Operator settable weld parameters

New ways, different from the old setup, of handling zero crossing detection and triggering SCRs are examined. Current measurement is adopted to use the new setups EtherCAT [5] topology.

The new setups finite state machine is based on the six stages in the weld process described in the theory chapter. Each stage is implemented as one state in the finite state machine, except for pre-weld, weld and post-weld which are combined into one state. The program implemented in the PLC makes no difference between pre-weld, weld and post-weld.

The regulator inside the weld controller of the new setup is implemented using the theory for RMS value for a phase cut sine wave described in chapter two. Namely how the duty cycle of the signal affects the RMS value of the weld current and what the theoretical maximum RMS current is. This nonlinear regulator approach was chosen because an nonlinear regulator approach for single phase with SCRs has previously been proven more effective than PID regulator [1].
Equation 2.3 and its inverse (duty cycle as a function of RMS factor) are implemented in the controller as a lookup-table with linear interpolation. The program Matrix Laboratory (Matlab) is used to generate the table values (with equation 2.3) by generating a code in structured text that creates the table as a global constant. The table is made up of ten rows with duty cycle and RMS-factor pairs.

The zero crossing detector and control element driver are first tested on a breadboard (solder free prototyping board) and then implemented on a stripboard (PCB for prototyping).

All the chosen EtherCAT terminals come from the same manufacturer. The manufacturer which creates EtherCAT terminals with the speed needed for the weld process is chosen. The manuals for the EtherCAT terminals are studied in order to understand how to connect, configure and communicate with them from Codesys [6] softPLC. The impact of EL3403 [12] low pass filter is theoretically modelled in Matlab.

Testing and debugging of PLC program is performed online in the PLC. The prototype is revised during the project in order to correct the problems which arise during testing and measurements. Measurements are performed using a Tektronix THS720P [13] with 10x 50MHz voltage probes and a 1mV/A current probe.

The capabilities of the HMI are investigated by studying the manual and by building a graphical user interface (GUI) for the prototype.

The choice of weld power topology is based on the single phase topology used with TEC6000.
4 Design

The new setup is implemented using a Beijer iX T7B Softmotion panel [14] with HMI and built-in Codesys softPLC as shown in figure 4.1. The communication between HMI and softPLC is done over Codesys Softcontrol Direct Access protocol. The regulator set point (which can be either RMS factor or RMS current) is sent from the HMI to the controller as an array of values. Each value in the array is a set point for a single period enabling the HMI to configure a different set point for each period.

![Figure 4.1: Block diagram of Beijer iX T7B Softmotion with HMI and Codesys softPLC.](image)

The prototype has a single phase topology (see figure 2.2a and 2.4) with a Semikron [15] SKKT92B12E [16] SCR as control element (see figure 2.2). The control element driver shown in figure 2.6 is used to interface the EtherCAT multi-timestamping output terminal to the parallel SCRs. The opto-triac used is a BRT13H. The old setup has the same topology,
but uses the control element driver with a pulse transformer (see figure 2.5) [17][18].

Figure 4.2 shows a picture of the finished prototype. The prototype is revised three times. The difference between each revision is explained below.

![Prototype of the new setup showing everything but the HMI](image)

A prototype graphical user interface (GUI) is made in the HMI for controlling the weld parameters. The GUI is made of textboxes which the operator can use to input the parameter value of choice. Buttons at the bottom of the screen enables the operator to move between different pages. The current page is indicated by the corresponding button being green. A picture of the GUI is can be seen in figure 4.3.
Weld parameters

Prepressure: # periods

Preweld: # % # periods

Postpressure: # periods

Weld: # % # periods

Repetition: # periods

Postweld: # % # periods

Figure 4.3: Graphical user interface (GUI) for operator settable weld parameters in HMI.

A block diagram showing the PLC program layout and external communications is shown in figure 4.4. The weld state machine controls the transformer controller, which handles the half period calculation and fault detection (e.g. overheat or missing zero crossing). Two flags, one for each type of zero crossing, are outputted to the weld state machine.
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Figure 4.4: Block diagram showing the Codesys softPLC program layout and external connection to Beckhoff EtherCAT terminals.

The following EtherCAT terminals from Beckhoff are used in the prototype:

- EK1100: EtherCAT bus coupler used to connect the rest of the terminals to Beijer iX T7B Softmotion [19]
- EL1809: 16-channel input with standard sampling [20]
- EL2809: 16-channel output with standard sampling [21]
- EL2212: 2-channel output with multi-timestamping and over-excitation. [22]
- EL2258: 8-channel output with multi-timestamping [11]
- EL3403: 3-phase power measurement terminal [12]

The EL3403 is used to measure the RMS current and is part of the feedback loop to the regulator [12]. The old setup uses an analog to digital converter (ADC) to sample the current measurement coil signal [23]. The RMS value is then calculated in the microcontroller using the sampled values [24].
The EL2212 [22] is used, in the first and second revision, to generate the trigger signal used to trigger the SCRs through the control element driver. The EL2258 [11] replaces the EL2212 [22] in the third and last revision of the prototype.

The old setup with TEC6000 uses two zero crossing detectors. One is connected to L1 and L2 (see figure 2.8), and the other one is connected across a shunt resistor on the current measurement coil [23]. TEC6000 then measures the phase shift between current and voltage across L1 and L2 in order to calculate the zero crossing of the voltage across the parallel SCRs (across K1 and K2) from the zero crossing of the voltage across L1 and L2 (see figure 2.3) [24].

In the new setup EL1258 is used to detect zero crossing by detecting flanks on the zero crossing detector output signal (also called zero crossing signal). The zero crossing detector is built on stripboard and connected to K1 and K2 (see figure 2.7). The flanks are transferred, together with corresponding timestamps, from EL1258 to the PLC over EtherCAT.

The first revision of the prototype uses the zero crossing circuit shown in figure 2.7. The op-amp used is a TL081 with junction gate field effect transistor (JFET) input. A null offset adjustment circuit (see figure 2.9) is added to the zero crossing detector in the second revision. Zener diode clamping and higher voltage output of transformer are used in the third revision of the zero crossing circuit. Everything else is the same in third revision as in second revision. The transformer ratio in revision one and two is 1:80, and in revision three 1:18.

A regulator is implemented in the transformer controller. The regulator get zero crossing timestamp and current measurement from EtherCAT terminals, half period from transformer controller, set point (either RMS factor or RMS current) from weld state machine, and set the process data output to EtherCAT multi-timestamping output terminal. Each time the regulator get current measurement from EtherCAT terminal, it calculates a new maximum RMS current based on the measured current and corresponding RMS factor used when setting trigger time. The calculated maximum RMS current is used when the set point is an RMS current. The duty cycle is then calculated using the inverse of equation
2.2. If the set point is an RMS factor then the regulator calculates duty cycle directly from the set point using the inverse of equation 2.3. A time diagram for the regulator is shown in figure 4.5. The delay of one period between zero crossing detection and firing of SCR is added because of two reasons. One is: the zero crossing information transfer is delayed at worst three milliseconds (one PLC task cycle). The other one is: the multi-timestamping output terminal needs a couple of EtherCAT bus cycles (minimum two) for scheduling the output events [11].

![Timing diagram for regulator showing zero crossing signal, PLC task cycle, trigger signal and resulting current through SCR. The two dashed sine waves are for reference.](image)

Figure 4.6 shows the state diagram for weld state machine. Weld inactive is the start-up state. In this stage the controller waits for the operator to either active press signal or weld signal. If one of those is activated the state machine moves to the next state: pressure. The magnetic valve controlling the pneumatic cylinder is activated in the pressure state. The first state in the weld sequence (pre-pressure) is then moved to if the operator has activated the weld signal, otherwise it stays in this state while the pressure signal is high or moves to weld inactive state if the
press signal is deactivated. The weld state machine stays in the pre-pressure state the amount of time specified by the operator and then moves on to the pre-test state. In the pre-test state the controller fires the SCRs during one whole period and then waits for current measurement from EL3403. If the current is above a threshold the contact between the electrodes are considered enough and the state machine moves onto the weld state. In the weld state the controller fires the SCRs during a number of periods specified by operator and then moves on to the post-pressure state. In the post-pressure state the controller waits an amount of time specified by the operator before continuing to either repetition or wait weld signal low. The wait weld signal low state is there to ensure that the weld signal is deactivated before another weld can be initiated, unless repetition is configured. If repetition is configured, the controller should wait an amount of time (repetition time) before running the weld sequence again without the operator having to deactivate and reactivate the weld signal. If the weld signal is deactivated during the repetition state the state machine moves to weld inactive. The magnetic valve is activated during every state corresponding to the weld sequence, and is also active if the press signal is active and the state machine is not in the repetition state.
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Figure 4.6: State diagram for the weld state machine implemented in Codesys softPLC.
5 Results

The results from oscilloscope measurements, human machine interface literature study and theoretical response of EL3403 low pass filter are presented below.

5.1 EL3403 low pass filter

The EL3403 3-phase power measurement terminal implements a low pass input filter with a cutoff frequency of 260 Hz [12]. Figure 5.1 shows how the RMS value for 50 Hz phase cut sine wave is affected by the low pass filter. The maximum percentage difference between filtered and unfiltered signal is 3.39%.

![Figure 5.1: RMS value after EL3403 260 Hz low pass filter as a function of duty cycle.](image)

5.2 Zero crossing detector

Results of oscilloscope measurements of zero crossing detector input and output for the three revisions are presented below. Figure 5.2 shows the characteristic of first revision zero crossing detector built on breadboard. The output square wave is a 24V logic signal with the same
frequency and phase as the input sine wave. The output is approximately 24V during the positive half period and 0V during the negative half period. Figure 5.3 shows the same results for the zero crossing detector built on stripboard.

![Figure 5.2: Characteristic of first revision zero crossing detector built on breadboard.](image-url)
Figure 5.3: Characteristic of first revision zero crossing detector on stripboard. Output is only connected to oscilloscope.

Figure 5.4 shows the first revision prototypes zero crossing detector output while triggering SCRs. The output of the zero crossing goes low when SCRs are triggered during positive half period. As seen in figure 5.5 the zero crossing detector input signal, which is a sine wave while not triggering SCRs goes low (close to zero volt) when the SCRs are triggered.
Figure 5.4: First revision zero crossing detector output with triggered SCRs. Note that the current is inverted.
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Figure 5.5: First revision zero crossing detector input is close to zero when SCRs are triggered. Note that the current is inverted.

The zero crossing signal characteristics in the second revision are shown in figure 5.6 and figure 5.7. The peak absolute value current in figure 5.6 is 30 A and in figure 5.7 140 A. The second zero crossing pulse from the right, in figure 5.6, is wider than the two previous pulses. The same is with the third pulse from the left. In figure 5.7 the three pulses to the right and the third pulse from the third pulse from the left in zero crossing signal are longer than the half period (10 milliseconds).
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Figure 5.6: Second revision zero crossing signal while triggering SCR. Note that the
current is inverted.
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Figure 5.7: Second revision zero crossing signal while triggering SCR. Note that the current is inverted.

In the third revision, with Zener diode clamps, a voltage spikes appears at the instant when the SCRs are triggered. This is visualised in figure 5.8. Figure 5.9 shows the same characteristic on the zero crossing detector input.
Figure 5.8: Third revision zero crossing detector output signal while triggering.
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Figure 5.9: Third revision zero crossing detector input signal with spikes at the instant when SCRs are triggered.

5.3 Trigger signal – EL2212

EL2212 multi-timestamping EtherCAT output, which is used in revision one and two, controls its output current with pulse width modulation (PWM) [22] as shown in figure 5.10 and 5.11. In the measurement in figure 5.10 the SCR is fired (the current begins to rise) after fourteen pulses and in figure 5.11 after six pulses. During measurements it was noticed that sometimes it didn’t trigger the SCRs at all.
Figure 5.10: EL2212 EtherCAT terminal output signal with corresponding current through SCR.
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Figure 5.11: EL2212 EtherCAT terminal output signal with corresponding current through SCR.

5.4 Trigger signal – EL2258
EL2258 multi-timestamping EtherCAT terminal is used to output the trigger signal (control element driver input signal) in prototype revision three. Unlike EL2212 used in revision one and two, this terminal does not use a PWM signal to control its output current [22]. The SCRs are triggered during two half periods in figure 5.12. The trigger signal is a single pulse lasting the duration the SCRs conduction, from time of trigger to zero-crossing.
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Figure 5.12: EL2258 EtherCAT terminal output signal with corresponding current through SCR.

5.5 Human machine interface

The HMI is programmed using iX developer. iX developer comes with a graphical library containing user interface elements in vector graphic. The graphical library contains various buttons, charts, sliders and meters [25]. Some examples are presented in figure 5.13. In addition custom buttons can be created from pictures [25].

iX developer supports multiple pages, alarm management, recipes and multi-language. Recipes are used to combine several related values. Several recipes can be stored in the HMI and loaded at any time by the user. Multi-language is handled by language management that stores texts and translations in the HMI database. The translations can be either manually written in iX developer, automatic using built-in support for translation services (i.e. Google Translate and Microsoft Translator) or by importing a text file from a translation software. The HMI user can switch between the stored languages at run-time [25].
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Trend viewer together with data logger can be used to track changes in PLC variables and present them to the user as curves. Figure 5.14 shows an example of the trend viewer with two curves [25].

Figure 5.13: Examples of graphical elements in Beijer iX developer library [25].

Figure 5.14: Example of trend viewer from Beijer iX library showing two curves with legend [25].


6 Conclusions

The results from the oscilloscope measurements of trigger signal shows that the EL2212’s trigger signal is unreliable because of its PWM output. Sometimes it triggers on the sixth pulse and sometimes on the 16th pulse of its PWM output signal. There were tries when it didn’t manage to trigger the SCRs at all. The EL2258 used in revision three can from measurements be seen as more reliable with a single pulse, outputted each triggered half period, starting at the time of trigger and ending at zero crossing.

The HMI can be used to give feedback to the operator by viewing a trend of the measured current in the previous weld or welds. The input of weld parameters by operator can be solved by either sliders or text-boxes using number keyboard.

Multi-language management makes it easier, than with TEC6000, for Iberobot [2] to convert the GUI into another language. This would enable the controller to be used by a wider network of operators by increasing the number of people able to use the RWE. In addition to multi-language the GUI supports various graphical representations (for example buttons with indicative graphics) which could help overcoming language barriers. These advantages of the new setup could make it easier for customers to hire weld operators with different ethnical backgrounds.

One environmental aspect of a module based system is the idea that when something breaks, only one module needs to be replaced instead of the whole system. On the other hand a module based system might create a material overhead. It might be that every module need its own enclosure or need extra parts to be compliant with several types of other modules.

The zero crossing signal is an essential part of the new setup and the old setup. The controller can’t get correct zero crossing information if the zero crossing signal doesn’t work correctly. The zero crossing circuit in the first revision goes low when SCRs are triggered during positive half
period. The signal should be high during positive half period and it is assumed to be because of the op-amps input voltage offset. An input voltage offset adjustment circuit with potentiometer is added in revision two to solve the problem. Measurements show that the zero crossing signal is better, but still there is a problem with wider pulses during SCR triggering. The transformer is changed to one with higher voltage output and a Zener diode clamping circuit is added in revision three. The length of the output pulses in the third revision are the same when the SCRs are triggered as when not triggered, but there is a voltage spike at the instant when SCR is triggered.

The result indicates that this setup can be used as a RWE controller and because it is compatible with current RWEs these can be retrofitted. Retrofitting old equipment is a more sustainable solution instead of building entirely new equipments. Further evaluation of current regulation and a more thorough research into the zero crossing detection is needed before an end user product can be made. A different solution, to than the one tested in this thesis, for zero crossing detection is to use an oversampling analog input EtherCAT terminal and detect the zero crossing with an algorithm implemented in PLC.

One drawback with the new setup is the delay between zero-crossing and triggering of SCR. This is inherited from the EtherCAT fieldbus and acts as a dead time for the regulator which can make it unstable or less accurate.
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Appendix A: Mathematical development of root mean square value for phase triggered sinusoidal as a function of duty cycle D

Equation A.1 describes a theoretical phase triggered (see figure A.1) sinusoidal signal.

\[
x(t) = \begin{cases} 
0, & 0 \leq t < \left(1-D\right)\frac{T}{2} \\
0, & \frac{T}{2} \leq t < \frac{T}{2} \left(2-D\right) \\
\frac{a \sin \left(\frac{2\pi t}{T}\right)}{T}, & \text{else} \\
x(t+nT), & n \in \mathbb{Z}
\end{cases}
\]  

(A.1)

Where \(a\) is the amplitude, \(D\) is the duty cycle and \(T\) is the period of the phase triggered sine wave (see figure A.1).

Figure A.1: Phase cut normalized sinusoidal wave with duty cycle D.

The root-mean-square value (rms) \(x_{rms}\) of \(x(t)\) is according to definition:
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Appendix A: Mathematical development of root mean square value for phase triggered sinusoidal as a function of duty cycle D

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\[ x_{rms} = \sqrt{\frac{1}{T} \int_0^T x^2(t)dt} \]  
(A.2)

Using equation A.1 this can be rewritten as:

\[ x_{rms} = a \sqrt{\frac{1}{T} \left( \int \frac{T}{2} \sin^2 \left( \frac{2\pi t}{T} \right) dt + \int \frac{T}{2} \sin^2 \left( \frac{2\pi (1-D)t}{T} \right) dt \right)} \]  
(A.3)

Using that the primitive function to \( \sin^2 \left( \frac{2\pi t}{T} \right) \) is

\[ F(t) = \int \sin^2 \left( \frac{2\pi t}{T} \right) dt = \frac{t}{2} - \frac{T \sin \left( \frac{4\pi t}{T} \right)}{8\pi} \]  
(A.4)

Equation A.3 can then be rewritten as

\[ x_{rms} = a \sqrt{\frac{1}{T} \left( F \left( \frac{T}{2} \right) - F \left( \frac{T}{2} (1-D) \right) + F(T) - F \left( \frac{T}{2} (2-D) \right) \right)} \]  
(A.5)

\[ x_{rms} = a \sqrt{\frac{1}{T} \left( \frac{T}{4} - 0 - \frac{T(1-D)}{4} + \frac{T \sin (2\pi (1-D))}{8\pi} \right) + \left( \frac{T}{2} - 0 - \frac{T(2-D)}{4} + \frac{T \sin (4\pi - 2\pi D)}{8\pi} \right)} \]  
(A.6)

\[ x_{rms} = a \sqrt{\frac{1}{T} \left( \frac{T}{4} - 0 - \frac{T(1-D)}{4} - \frac{T(2-D)}{4} + 2T + \frac{T \sin (2\pi D)}{8\pi} \right) + \left( \frac{T}{4} - 0 - \frac{T(1-D)}{4} + \frac{T \sin (2\pi D)}{8\pi} \right)} \]  
(A.7)
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Appendix A: Mathematical development of root mean square value for phase triggered sinusoidal as a function of duty cycle D

\[ x_{\text{rms}} = a \sqrt{\frac{1}{T} \left( T - T(1 - D) - T(2 - D) + 2T + \frac{T \sin(2\pi D)}{8\pi} \right)} \]  \hspace{1cm} (A.8)

\[ x_{\text{rms}} = a \sqrt{\frac{1}{T} \left( \frac{2TD}{4} + \frac{2T \sin(2\pi D)}{8\pi} \right)} \]  \hspace{1cm} (A.8)

The finished equation then becomes

\[ x_{\text{rms}} = a \sqrt{\frac{D}{2} + \frac{\sin(2\pi D)}{4\pi}} \]  \hspace{1cm} (A.9)