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Original Article

Development and Design Of a 4000 Amp DC Rectifier for Industrial Metal Scrapping

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Abstract *- This paper presents the development and design of a high efficiency 4000A at 12VDC DC rectifier for metal scrapping, overcoming the limitations of conventional systems such as low energy efficiency of 90-96%, inaccurate current control and frequent maintenance. The proposed system uses PWM modulation with Half-Bridge type IGBTs (15kHz), controlled by an ATmega328P microcontroller and SG3525N integrated circuit, achieving 5 times higher efficiency. An HMI system that allows precise current/voltage adjustments (±2% error), adapting to different metals needed in different ranges, such as copper, aluminum, etc. Advanced protections include alerts, a predictive maintenance system, real-time monitoring, and fast response to failures through an ATMEGA 328P microcontroller and vacuum contactors. Compared to conventional SCR-based rectifiers, the equipment provides 24% higher energy efficiency than SCR, 40% lower downtime and operating costs, and improved purity of recovered metal. This work demonstrates how modern power electronics can optimize industrial metal recycling processes, combining efficiency, automation and robustness for sustainable recovery.*

Keywords *- High-current DC rectifier, Electrolytic metal recycling, IGBT-based half-bridge converter, Modbus TCP/IP control system, Predictive maintenance in power electronics.*

1. Introduction

In the metal recycling industry, mainly in metal scrapping and the efficient recovery of materials such as copper, aluminum, and steel, these are fundamental to the economic profitability of recycling companies and environmental sustainability. Conventional DC rectifier systems used in this field often have limited energy efficiencies, mainly due to heat losses in passive components, lack of dynamic current control and obsolete technologies based on thyristors or non-optimized silicon diodes. These limitations result in high energy consumption, premature component wear and poor adaptability to different types of metals and loads. This paper presents the design and implementation of a 4000A high-efficiency DC rectifier (greater than 90%), developed specifically for metal recovery in the recycling industry. It consists of high-efficiency IGBTs (Insulated Gate Bipolar Transistor), controlled by an integrated circuit with blocking and soft start properties, as well as a microcontroller for the respective protections and alarms of this rectifier and real-time monitoring via Human Machine Interface (HMI), optimizing the energy consumption according to the metal processed. The system incorporates advanced protections against IGBT degradation and copper bar wear (through analog thermal sensors), as well as alerts, short-circuit protections, duty cycle overrun through thermal switch in heatsinks and liquid cooling, obtaining a 40% reduction in maintenance downtime.

This development sets a new standard in energy efficiency and automated control for high current applications and demonstrates how modern power electronics can transform intensive industrial processes into routine and simple to control. The results, validated in real scrap environments, show a 25% reduction in operating costs and a 99% increase in purity of recovered metals, highlighting its potential for the sustainable recycling industry.

2. Related Works

Over the years the innovation of new current rectifiers has been increasing with the incorporation of new technologies, some with deficiencies due to high switching frequency or loss of energy efficiency, In [1] where the current distortion in Current Source Rectifiers (CSR) at high frequency caused by narrow pulses at the sector limit is studied proposing a compensation that avoids erratic switching and improves the response using low blocking voltage MOSFETs validated by a 3 kW prototype that demonstrates lower distortion and better dynamic performance of the system, furthermore where energy efficiency is paramount in [2] where a high efficiency isolated step-down converter is developed for ultracapacitor charging employing switched inductors and a current doubling synchronous rectifier reducing circulating currents and recycling leakage inductance energy which decreases the voltage stress on the switches allowing high current charging

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with high efficiency reaching 96, 53 % at 350 W and 94.31 % at 1 kW with 380 V input and 14.6 V output, charging a 250 F ultracapacitor in CC/CV mode in one minute with experimental validation, Likewise, the study is carried out against a design using SCR thyristors and its application in [3] where the dynamic interactions between a high current PEMEL connected through a rectifier-thyristor and the transient stability of the rotor angle in synchronous generators are analyzed, evaluating whether the PEMEL can be modeled as an impedance load, power or constant current by means of a dynamic electrochemical model and a current control for a 12-pulse rectifier using Matlab/Simscape simulations on the Belgian system showing that a 100 MW PEMEL improves the dynamic response of the SG to disturbances by increasing the fault clearance time and showing that such interaction depends on the number of PEMELs connected in parallel as well as the design of a full bridge rectifier in [4] where he proposes a new topology for low voltage Inductive Power Transfer (IPT) systems with high voltage input, overcoming problems such as high conduction losses and difficulty in compensation design due to the 400 V/24 V ratio by means of a SCFB inverter and a reverse current doubler rectifier achieving three key improvements: voltage reduction in the primary switches by half, inherent 1/4 voltage conversion simplifying the design, and current reduction in the rectifier by half versus conventional full bridge complemented with LC-LCC compensation and parameter optimization for higher efficiency validated with a 1.2 kW prototype maintaining efficiencies above 94.5 % and a maximum of 96.63 % between 8 and 50 A. According to the application in [5] reference is made of the equipment for another chemical process using hydrogen where an optimal design methodology for output inductance in parallel interleaved Current Source Rectifiers (CSR) intended to feed high power electrolyzers is presented highlighting that, although interleaved configurations improve power quality and reduce leakage, traditional methods are not suitable for this type of topology, a common mode equivalent model is proposed which allows to analyze the circulating currents and the ripple in the inductances demonstrating in a practical case of 3 MW that it is possible to reduce up to 69 % the size of the inductance with respect to conventional methods.

As well as different methods for protections and equipment responses such as in [6] where he proposes a voltage sensorless current predictive control strategy for a three-phase PWM rectifier in order to overcome limitations such as integral drift, dc polarization and poor dynamic response in conventional controls by means of an improved virtual flux observer with band-filter feedback removed that corrects dc polarization and the incorporation of Lagrangian interpolation to refine current prediction in two-step prediction algorithms experimentally validating that the system achieves high power factor, higher prediction accuracy and better dynamic performance. Reference is also made to proposed designs with the same HALF - BRIDGE function principle such as in [7] where an Active Resonant Voltage Balancer (ARVB), acting as a series resonant converter injecting current at the midpoint of the bus to cancel the fundamental component and reduce ripple, achieving to decrease the dc bus volume up to 4 times with a moderate increase in losses validated through a practical case with a single-phase half-bridge rectifier, showing its feasibility in applications where weight and volume optimization is a priority. Also referenced where peak current is detrimental in an initial startup, in [8] presents an Isolated Half-Bridge (IHB) converter with soft switching for automotive applications requiring high voltage reduction, achieving ZVS on the primary side to minimize losses and EMI; incorporates a current doubler rectifier with series capacitor to balance currents and reduce DC shifts in the transformer, achieving 24-60 V to 1 V conversion with 92.7 % efficiency and 52 W/in³ power density, improving 4.5 % efficiency and reducing EMI by up to 9 dB with respect to conventional IHB topologies.

For [9], various power decoupling techniques in the specialized literature are compared to reduce or eliminate the ripple at 120 Hz inherent in single-phase AC-DC converters. Among these techniques are active decoupling circuits, which incorporate new switches and passive elements in the circuit, increasing costs and losses in the converters. In this study, the Complete Single-Stage (ECS) of power decoupling is defined. The switches responsible for controlling the power factor in the proposed converter also control the output voltage and ripple at 120 Hz using the phase shift technique. In this way, capacitors of lower value can be used, allowing the widely used electrolytic capacitors to be replaced by film capacitors, which have a long lifetime compared to the former. Moreover, the proposed converter is isolated and presents high efficiency.

Simulation and experimental results are presented for a 1 kW prototype with efficiency up to 93 %, demonstrating that power decoupling is obtained and that the definition of the ECS topology can be incorporated into the literature. Furthermore, an adaptability in variability do absence of supply voltage is implemented in [10] where a single-phase half-bridge rectifier with active dc bus balancer (ARVB) is analyzed, showing that the incorporation of the ARVB allows eliminating the fundamental component of the ripple current on the dc bus, which allows a significant reduction of the volume and size of the bus and the converter in general. For point [11], a Zero-Voltage Switching (ZVS) dc-dc-dc converter employs two parallel phase-shift controlled half-bridges in the primary and a current-doubling rectifier in the secondary. The topology allows a wide ZVS range, minimum circulating current and low ripple, as well as component optimization according to the electrical stress level. An experimental prototype validates the effectiveness of the design. Applications are quite numerous, as in [12], where an Asymmetric Center-Tapped Rectifier (ACTR) is used to reduce Common-Mode (CM) noise in half-bridge LLC converters, widely used in electric vehicle on-board chargers. The ACTR achieves CM noise cancellation between primary and secondary windings without adding components. Its effectiveness is validated in a 1.1 kW prototype (800 V input, 300-450 V output), demonstrating significant EMI reduction. As far as chemical processes are required, an example is obtained from [13] in which a rectifier would be used, which integrates electrorefining in arc furnace mini-mills to produce rolled steel from 100 % scrap with low copper (0.21-0.43 wt%). An industrial process with electrorefining cells was modeled, and financial analysis was performed. 73 USD/t for 0.43 % Cu and 783.24 USD/t for 0.21 % Cu. Profitability is low with a negative NPV and an IRR less than 10 % for 0.43 % Cu and moderate for 0.21 % Cu. Critical sensitivity to electrolyte cost and scrap price. It is concluded that the process requires optimization for techno-economic feasibility. Finally, the extraction or cleaning of the electrolytes is required, which requires a precision grinding machine.

In [13], the nodulation of the electrolytic copper in the electrorefining process affects the efficiency and quality of the process. The effects of Ni(II) and Sb(III) impurities on nodule growth were studied experimentally using a model bump on the cathode to simulate the current distribution. These impurities induce a microstructural transition towards a field-oriented texture and Base Breeding (BR), generating rough surfaces with coarse grains. The initial formation of irregularities increases the effective surface area and concentrates on the current location, promoting self-promotional growth of nodules and irregular macroscopic deposits. The low conductivity of the electrolyte accelerates this phenomenon, so maintaining stable current control is critical to minimize local current concentrations and preventing rapid nodule growth. Preventing the transition to BR mode is key to controlling rapid nodulation.

3. Methodology

This article presents the design and implementation of a DC current rectifier, to be applied to the recycling industry, such as metal scrapping, including digital and analog electronics for the control of the same, protection and versatility compared to other equipment with the same purpose and better control from the perspective of the operator. The comparison of a SCR thyristor equipment against the proposed design will be made, highlighting the control of current, voltage, cooling system and a friendlier handling with the operator from peripherals, obtaining improvements such as process efficiency, reduction of operating costs. The main features of this design are:

- Current and voltage control, to only one voltage control.
- Modifications of variables, such as current and voltage, from an HMI to simple knobs.
- Echo power electronic control system.
- Alarms for high temperature, short circuit, power semiconductor wear and duty cycle overrun protection.
- Implementation of the MODBUS TCP/IP communication protocol for equipment communication.

Table 1. Components used

Type	Model	Quantity
Microcontroller	ATMEGA 328P-AU	1
Control board	PWM1	1
IGBT	SKM400GB12T4	4
SCR	BISCR10016X	4
Contactor	CHINT NC1-8011	1
Contactor	CHINT NC1-0910	1
PC	Lenovo CORE I3-10100	1
Pump	1/2Hp Centrifuge	1
Relays	Schneider encapsulated 220VAC	2
Thermostat	KSD301 50°C	4
Current transducer	Hall effect sensor 0-300A 0-10VDC	3
Thermomagnetic circuit breaker	C8 CHINT	2
Transformer	18:1 core ETD-49	1
Diodes	VS-VSKD9108	16
GATEWAY	BE7200	2
Ethernet cable	RJ45 extension	2

The monitoring will be done through a program made in LABVIEW software installed on a PC the equipment, together with the electronic card based on ATMEGA 328P-AU, will use the MODBUS TCP/IP communication protocol to send variables. Simulations and operations were carried out in each stage of the unit, which was divided into sections, such as control, power, and sensing. Simulations were performed in MULTISIM and PROTEUS software for the different stages mentioned. The PCB design with ATMEGA 328P- AU was done in PROTEUS software, the programming of the board was done in ARDUINO IDE software, and the implementation was done according to the proposed design done in AUTOCAD 3D software.

To better understand the design, a flowchart of the steps to be implemented is shown (See Figure 1) starting with the objective to supply which is the metal scrapping, the conceptual design will be raised to define several aspects that are needed for the implementation of this equipment, electrical calculations of semiconductors, transformers and bars, as well as thermal calculations regarding the method of liquid cooling used, the prototyping of the equipment and simulations, along with tests in each sectioned stage of the equipment to corroborate its optimum performance, performance tests from 1000 to 3000Amperes of a total of 4000Amperes and comparison tables in terms of a SCR equipment.

It details the sectioned part of control, power, and sensing to identify the flow of operation to the protections, alarms, and short circuits that are occurring.

It should be noted that the operation will require a considerably high voltage for an electronic control, electrically referred to as Low Voltage 380VAC, compared to the industrial electronic voltage used from 10VDC to 24VDC.

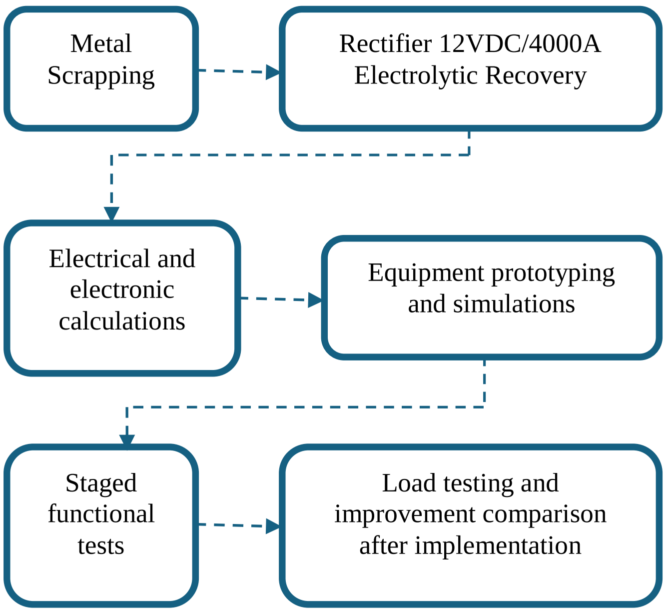

Fig. 1 Design flow diagram

4. Developed System

The materials and methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described. The purpose of the equipment is to dismantle components or industrial machinery, in this case for cleaning and electrorefining of ship components by using a rectifier with current and voltage control, thus optimizing the recovery of metals such as copper, aluminum or steel, using the process of electrolysis or electric arc cutting, the equipment has 3 stages in its operating architecture (See Figure 2). To obtain an early identification of failures or replacement of components due to wear, avoiding production stops due to these problems. The operation mode of the equipment starts from its rectification and filtering which belongs to the power stage formed by rectification module, contactor and SCR, in addition to which control voltages will be distributed to cards, contactors, pump, fan, IGBT and transformers, the control stage of the equipment is formed by the distribution and control card, which will have the ATMEGA 328P-AU as the main microcontroller and the integrated circuit SG3525N for PWM control of the equipment, This card will be in charge of communicating with the HMI, enabling on and off of the equipment, status in case of faults and enabling loads according to the eco mode, together with the predictive maintenance of semiconductors will be performed by measuring the Rsd value of each IGBT, to finish the sensing stage is made up of non-invasive sensors which will provide protection variables to the equipment and alarms, together with the eco mode.

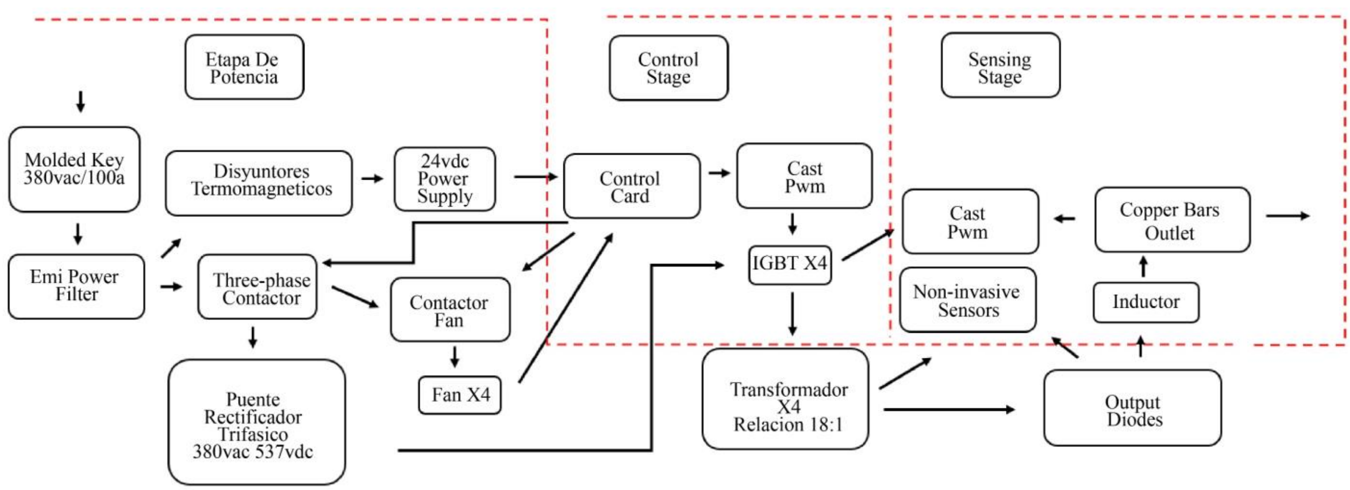

Fig. 2 Operating architecture

The functions of each stage are detailed starting with the power stage, responsible for the distribution of main voltage and sub voltages to the system, the voltage used is 380VAC which is filtered by an EMI power filter and will be distributed to a contactor and thermomagnetic circuit breakers, the contactor will enable the three-phase voltage for subsequent rectification of 573VDC, the voltage will be distributed between the terminals of each IGBT in HALF-BRIDGE configuration (See Figure 3). Likewise the thermomagnetic circuit breakers will handle the fan load and coolant pump and 24VDC power supply required for the control and sensing cards, the IGBT control will be directly governed by the integrated SG3525N through an equal electronic distribution in signals to avoid false triggers and startup failures, in addition to taking advantage of the SOFT START function that has the integrated avoiding premature wear in power capacitors.

Each IGBT will send signals to its respective transformers, which will be connected in parallel to take advantage of more power modules and provide even more output current to the equipment. In the output stage, there will be the sensing of each stage prone to vibration or over-temperature diode output.

For the operation of the equipment functions and visualization of variables, there is an HMI integrated in a desktop PC, which is communicated via MODBUS TCP/IP, allowing an easy handling of variables and visualizations of the same, in addition to an easy integration of more rectifiers with the same operating system and communication protocol.

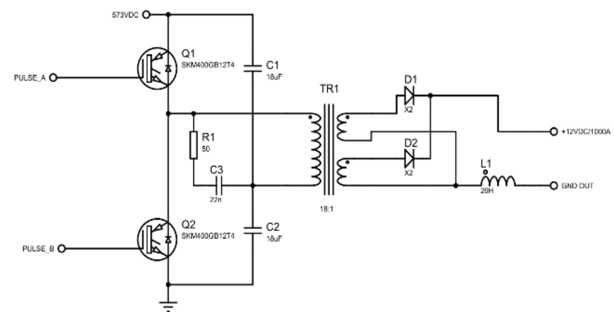

Fig. 3 HALF-BRIDGE distribution

The Gateway will be used to communicate between the PC and the rectifier. The variables to be controlled in the HMI are: Current: setpoint value as required for metal scrapping, corresponding to a calculation according to the density of each material.

Table 2. Density values, applications according to the type of metals

Metal	Process	Typical density	Remarks
Copper	Electrorefining/scrapping	20-40 A/dm^2	Very good conductor; high performance with acid electrolytes (copper sulfate + H_2SO_4)
Aluminum	Electrolysis/cleaning	10-20 A/dm^2	Requires special electrolytes (usually not acidic); slower
Steel	Deoxidation or reverse electrolysis	5-15 A/dm^2	Mostly used for cleaning or coating, does not dissolve easily without aggressive acids.

The respective calculations are made for each piece according to the size of the plate, for example, 40cm*60cm. The respective calculations are made for each piece according to the size of the plate, for example, 40cm*60cm.

- Copper 24dm^2.
  Minimum: 20*24 = 480Amperes
  Maximum: 20*24= 960Amperes

- Aluminum 24 dm^2.
  Minimum: 10*24 = 240Amperes
  Maximum: 20*24= 480Amperes

- Steel 24 dm^2.
  Minimum: 5*24 = 120Amperes
  Maximum: 15*24= 360Amperes

An advantage compared to a thyristor rectifier is that while more amperage is required, the amount of SCRs in parallel to its output must be increased to achieve and reach its optimum performance, obtaining an advantage in terms of space and robustness of control to amperage variability, since a SCR rectifier only controls the voltage but not the optimum current for each metal.

Voltage: according to the setpoint value, it is required to modify the amperage value as shown, since it is of utmost importance to have a stable voltage value, or it would cause problems of porosity, higher energy consumption, and electrochemical quality.

Table 3. Voltage setpoint according to the type of metal

Metal	Potential Standard Range	Typical Operating Voltage
Copper	+0.34 V	1.5 - 3.5 V
Aluminum	-1.66 V	3.5 – 5.0 V
Steel (Iron)	-0.44 V	2.0 – 5.0 V

To these values are added the overvoltage generated by chemical resistance, ionic drop and thermal effects. Due to this, it is typically operated in the range of 2-8 V, not exceeding the 12VDC that the equipment can offer. As for the design of the electronic board with ATMEGA 328P-AU and PWM control with the SG3525 integrated (See Figure 4) was performed in PROTEUS software, which also allowed the simulation of the proposed electronic design, the circuit will work at a switching frequency of 15Khz optimal for a fast reaction or loss of power based on heat in transformers, it will have an auxiliary bypass circuit based on its integrated outputs, Since the loss of signal would be detrimental to the operation of the equipment, this control device must be distributed in such a way that there is no loss of voltage from the SG3525N signal, for which more integrated to compensate this function as the optocoupler A3120 and CD4093 was added.

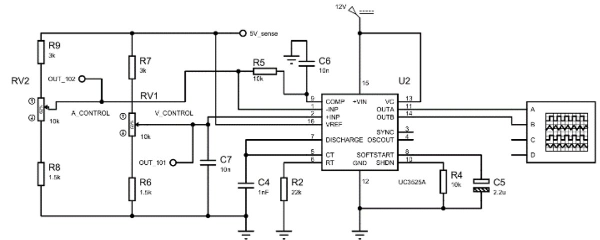

Fig. 4 Simulation of SG3525 according to amperage and voltage setpoints

The ATMEGA 328P-AU will control the opening of pulses through the SHDN pin of the SG3525N integrated against failures due to over temperature, short circuit or over duty cycle (See Figure 5), as well as the over current sensing circuit as protection against excessive duty cycle failures from the hall sensor located in the output transformer oscillation output (See Figure 6), along with the echo control will be given by the activation of fans and cooling pump whenever required, the system will detect any anomaly given and send an alert depending on the status on each control pin in (See Figure 7).

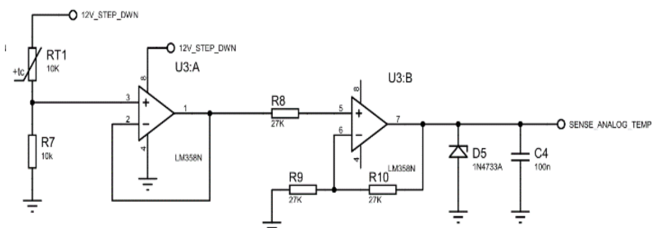

Fig. 5 Analog temperature sensing

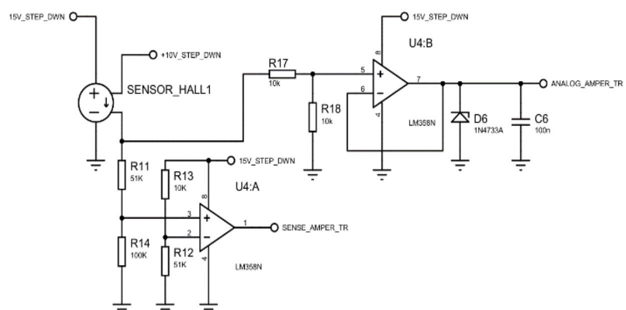

Fig. 6 Transformer AC current sensing

There will be several linear power supply voltages on the main board in order not to generate conflicts and avoid maximum consumption in each integrated used, the equipment will also have a timing on and off the system if it is required to use it for hours, using the IC DS1307 to supply this function (See Figure 8), this will be activated with the configuration in LABVIEW HMI panel. The distribution of pins corresponding to the control and sensing in the ATMEGA 328P-AU, each pin was chosen depending on the required function being analog or digital, avoiding an imbalance in digital use in analog or vice versa (See Figure 9).

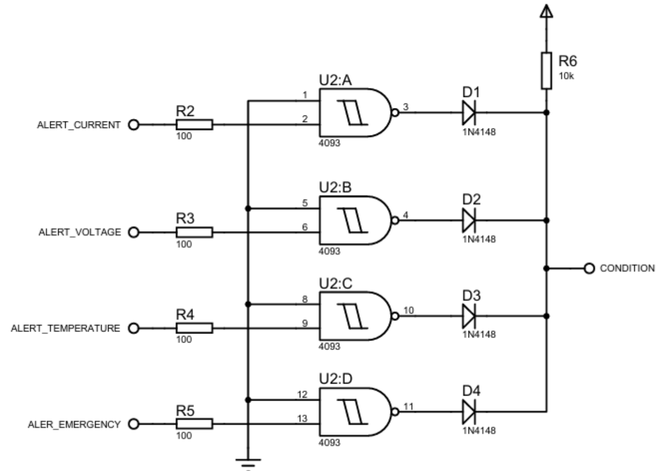

Fig. 7 Protection status control

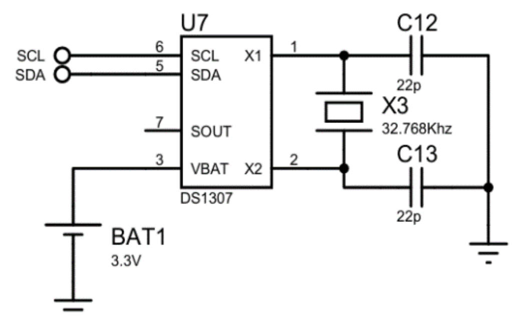

Fig. 8 Real-time clock DS1307

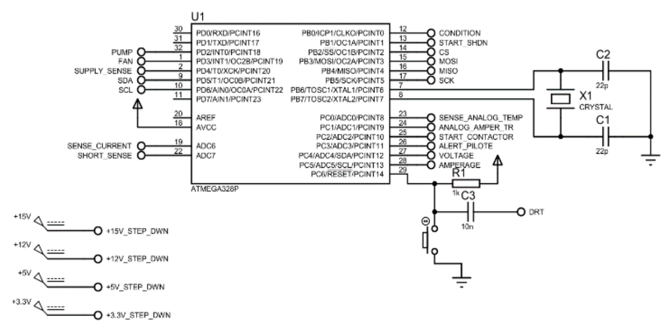

Fig. 9 ATMEGA 328P-AU

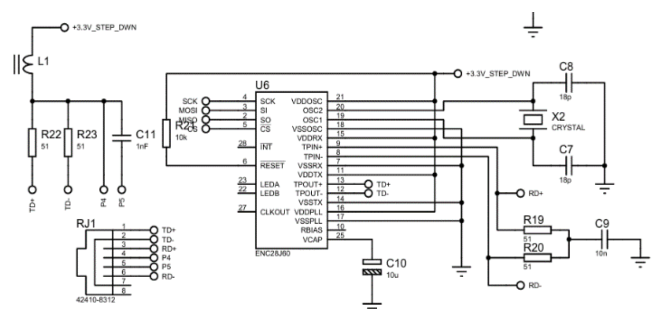

Fig. 10 MODBUS TCP/IP communication through ENC28J60

The integrated ENC28J60 is used to communicate via MODBUS TCP/IP. The only purpose of this communication is to avoid excessive wiring to a panel control with wired logic in current SCR control devices (See Figure 10). The communication diagram is given as follows (See Figure 11), where the PC plays the role of master and the control board in slave mode. Also, more rectifiers can be added to this HMI panel, obtaining more robustness and being more compact compared to a SCR rectifier.

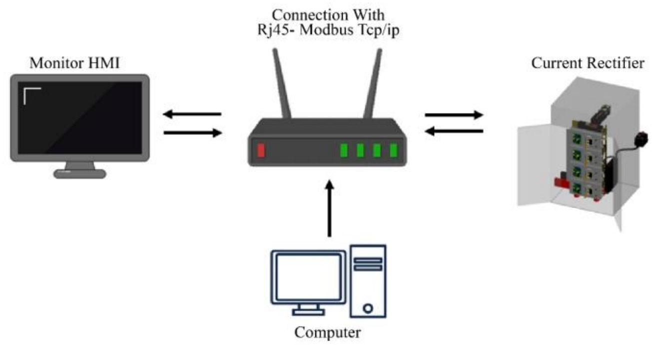

Fig. 11 MODBUS TCP/IP communication

The design of the HMI is done by programming in LABVIEW software, this HMI will allow the control of current variables, voltage adjustments, over current warning, current system temperature, cooling system operation, absence of coolant or low level, preventive corrections of components in poor condition mainly IGBT, duty cycle exceedances and timings for prolonged work and programmed time (See Figure 12).

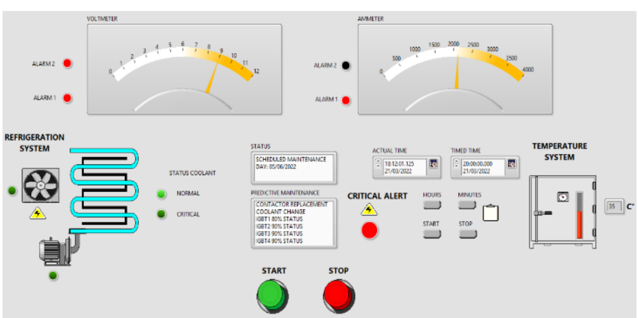

Fig. 12 HMI of the equipment made in LABVIEW

For the choice of power and control devices and semiconductors, rigorous care was taken due to the precision required for the application and an easy replacement accessible in the market, which is why, by means of the following equations, the choice of these components was given:

Calculation for the choice of IGBTs:

- Input voltage: 380VAC
- Voltage after rectification: 537VDC
- Voltage per module HALF-BRIDGE: 268V
- Output current per module: 1000A
- Switching frequency 15KHz
- Output voltage: 14.5VDC

RMS current in IGBT:

$$I_{RMS=}\frac{Iout}{\sqrt{2}}x\frac{Vout}{Vin\_modulo}$$

$$I_{RMS=}\frac{1000}{\sqrt{2}}x\frac{14.5}{268}$$

$$I_{RMS=}\approx 38A$$

IGBT Peak Currents:

$$I_{RMS=}2*38A=76A\ \cong 100A$$

Voltage selection:

$$V_{MAX=}1.2*Vbus=1.2*537V\ \approx 645V$$

4.1. Using Values from a SEMIKRON SKM400GB12T4 IGBT

Conduction loss at 175°C:

$$P_{cond=}Vce*I_{RMS}*D_{MAX}=2.05*38A*0.5\ \approx 39W$$

Switching loss at 175°C:

$$P_{sw=}(Eon+E_{off})*f_{sw}=75mJ*15Khz\approx 1125W$$

Thermal verification:

$$T_{J=}T_a+(R_{th(j-c)}+R_{th(c-a)})*Ptotal$$

$$T_{J=}25°C+(0.02+0.038)*1164W$$

$$T_{J=}25°C+(0.02+0.038)*1164W$$

$$T_{J=}72°C\ de\ 175°\ is\ considered\ safe$$

4.2. Choice of HALF-BRIDGE or FULL-BRIDGE System

Power loss influencing energy efficiency:

$$P_{sw=}2*(Eon+E_{off})*f_{sw}$$

$$P_{sw=}2*75mJ*15Khz$$

$$P_{sw=}2250W\ HALF-BRIDGE$$

$$P_{sw=}4*75mJ*15Khz$$

$$P_{sw=}4500W\ FULL-BRIDGE$$

The adaptability to a voltage of 380VAC makes it more versatile in terms of a choice of 1200V IGBT compared to a full bridge, which requires a 1700V IGBT, being more expensive and occupying a larger space than considered in the application.

To occupy a smaller and more compact space, it is considered that the equipment requires a considerable size of 80cmx80cm, to which the corresponding proposed accessories were distributed in an optimal way, separated by stages for easy maintenance or replacement of parts (See Figure 13).

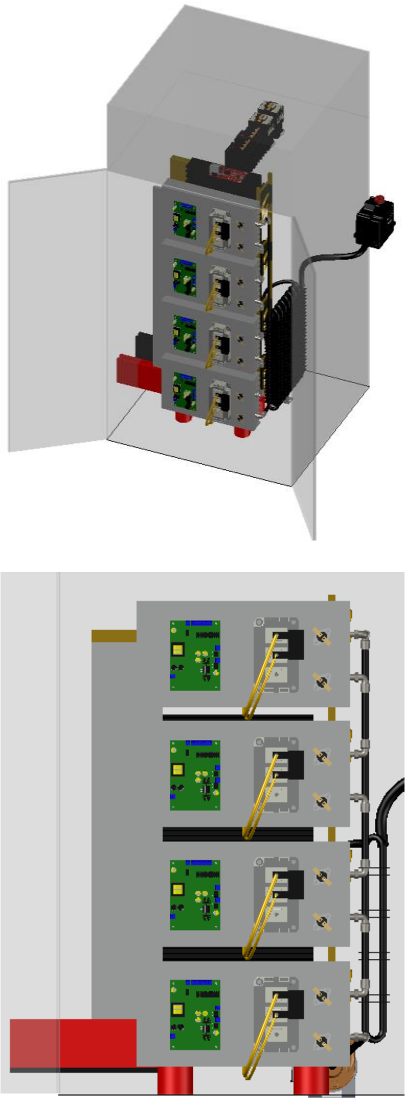

Fig. 13 Current rectifier according to the design

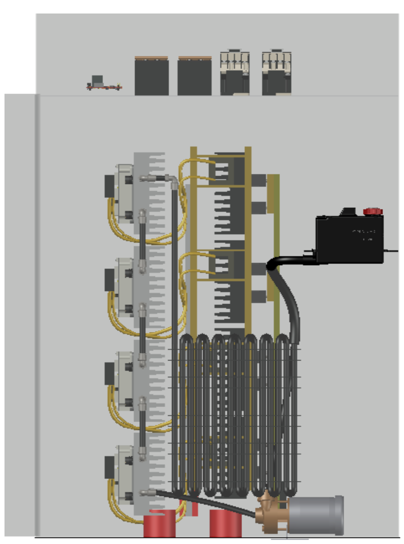

Fig. 14 Distribution of components according to stages

Regarding the distribution of stages, the output stage was separated from the input stage to facilitate the exchange of components such as IGBTS or output diodes, as well as the cleaning of the radiator or maintenance of the coolant centrifugal pump, change of contactors and revision of the control card in the equipment (See Figure 14).

A comparison was made between an HMI panel and a control panel, obtaining a more attractive result to the operator because the HMI could visualize more than one rectifier at a time, the control is more accurate and presents much earlier alerts to a system failure compared to the control panel implemented for an SCR rectifier (see Figure 15).

Fig. 15 SCR grinder control board

After design and operation tests, a Colombian market grinding machine with the same HALF-BRIDGE power system was also compared, which presents the following deficiencies in comparison to the implemented grinding machine:

Table 4. Comparison to the implemented grinding machine

Scrap grinding machine	Rectifier for general use
Digital current control	No such control
Digital voltage control	Analog potentiometer
Coolant-based temperature control and eco mode in working mode	Fans on, power loss in stand BY mode
Short circuit protection	No protection
Amperage oversizing protection	No protection
Electronic predictive maintenance	No such function
Digital timing based on actual hours	Analog timing

Before implementing the equipment in an industrial area for metal scrapping or to supply another function, the working environment must be a voltage of 380VAC, a suitable place free of falling materials or metal particles and acids from the electrolytic process. The particularity of the present designed equipment is that it must have a considerable space for the opening of doors for later maintenance; a limited space would harm this benefit in the equipment, since the program will corroborate the changes made in a note of preventive maintenance implemented in the HMI. Due to the high cost of components, the project was simulated with recycled parts obtaining a variability in terms of calculations made with new components (See Figure 16). The efficiency of the prototype turned out to be advantageous to previously mentioned grinders, the energy efficiency is also higher compared to a SCR grinder due to relatively high-power losses and abrupt energy consumption. A technical comparison shows that:

Table 5. Comparison of grinding machines

Feature	SCR Rectifier	Designed Rectifier
Type of control	Thyristor phase control	PWM regulated (half-bridge)
Operating frequency	50/60 Hz (Mains)	15 kHz - 100 kHz
Waveform	Pulsating, distorted	Smoothed and regulated
Current accuracy	Low	High (closed loop control)
Power factor	Low (0.6 - 0.8)	High (>0.95 if PFC is implemented)
Estimated energy efficiency	65% - 75%	90% - 96%
Heat loss	High	Moderate to low
Fluctuation response	Slow	Fast (digital control)

Because in industry there are several pieces of equipment with the same characteristics, efficiency is calculated based on the data collected from these already implemented designs; the efficiency comparison for an SCR grinder goes from 65 to 75% opting for a typical value of 70% and an electronic rectifier from 90 to 96% opting a typical value of 94%. For a workload with a total consumption of 4000Amperes at a voltage of 6V for copper scrapping, it is obtained that:

70% efficiency rectifier to SCR:

$$P_{input} = \frac{6V*4000A}{0.7} = 34.2KW$$

94% rectified IGBT efficiency:

$$P_{input} = \frac{6V*4000A}{0.94} = 25.5KW$$

Obtaining the thyristor equipment that occupies 8.75KW more to provide the same amount of current and voltage required for the scrapping.

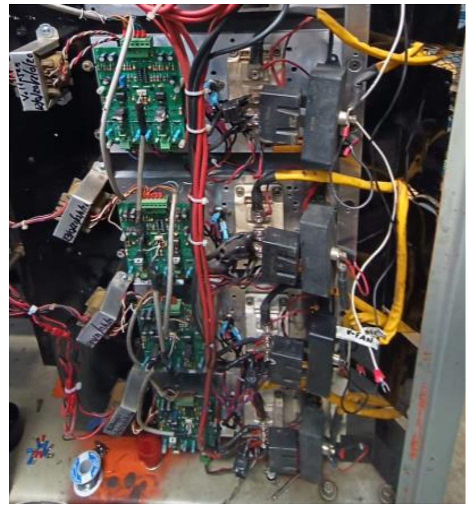

Fig. 16 Prototype rectifier prototype

The prototype was tested 15 days after installation, using only low voltage and amperage values used for copper and aluminum scrapping, using direct and inverse polarities for the recovery of copper from cables for maritime use and cleaning of aluminum from boat parts used for maritime patrol, used in a company located in Mollendo, Arequipa, for fishing purposes.

5. Test and Results

To evaluate the effectiveness of the implemented equipment as the reduction of the use of power supply, comparison of current and voltage control type, energy efficiency and downtime due to failures, these values were acquired during the implementation of the prototype, a 5000Amperes SCR rectifier was taken as a reference, which provided very outdated values and with a considerable energy increase compared to the implemented design. A comparison of these values and the calculation of the energetic efficiency obtained for the copper scrapping for copper bars of 100cmx20cm placed next to 5 in parallel: 6V- 3000Amperes.

$$P_{useful} = 6V * 3000A = 1800W$$

Rectifier SCR 70%:

$$P_{input} = \left(\frac{1800W}{0.7}\right) = 2.6KW$$

$$P_{output} = 2.6KW - 1.8KW = 800W$$

IGBT rectifier 96%:

$$P_{input} = \left(\frac{1800W}{0.96}\right) = 1.87KW$$

$$P_{output} = 1.87KW - 1.8KW = 70W$$

After implementation, there is a reduction in energy efficiency of 11.4 times, in terms of downtime due to failures.

The data was collected by operators, which indicated the following:

Table 6. SCR failure probability data

Based on the time factor	SCR
Semiconductor replacement	1 year
Fuse replacement	6 months
Startup errors	3 months
Correction of faulty wired logic	6 months
Change of contactors	3 months
Fan replacement	6 months
Maintenance downtime	1 month
Thermistor replacement	3 months
Diagnostic complexity	1 week
Untimely shutdowns	4 months

According to the comparisons, a probability simulation was performed in the continuous use of the designed grinding machine, with the same points according to the criterion of 1 year maximum, obtaining the following results:

Table 7. Probability of failure data for IGBTs

Based on the time factor	SCR
Semiconductor replacement	3 years
Fuse replacement	0
Startup errors	0
Correction of faulty wired logic	1 year
Change of contactors	9 months
Fan replacement	2 years
Maintenance downtime	2 weeks
Thermistor replacement	0
Diagnostic complexity	1 week
Untimely shutdowns	1 year

The success rate of the rectifier with IGBTs was more satisfactory due to the use of a more robust and compact design compared to the SCR, in addition to using smaller components due to the high switching frequency used, as well as components that are more accessible in the market for replacement. As for the voltage and current control, an exponential curve is obtained versus a constant as the part is placed in the electrolytic bath. The data was obtained with the copper scrapping at 6V -3000Amperes and the system response in 30 minutes, observing the deface generated by chemical resistance, ionic drop and thermal effects of the exposed chemical bath.

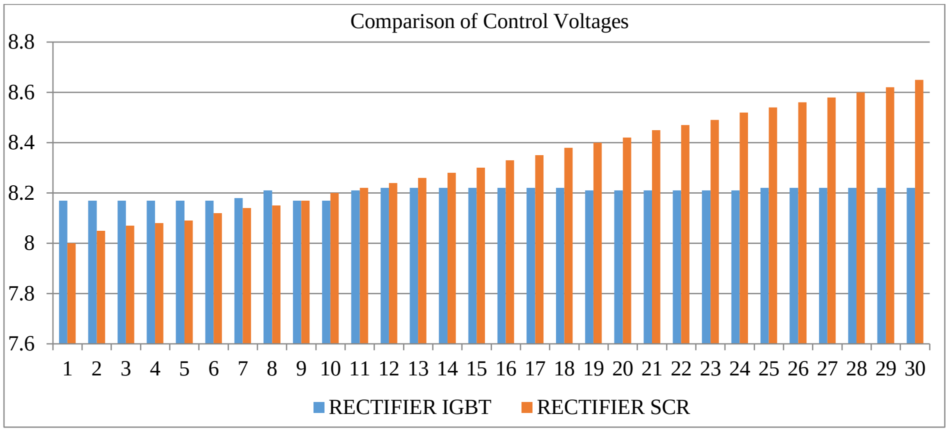

Fig. 17 Comparison of IGBT and SCR rectifier voltage values

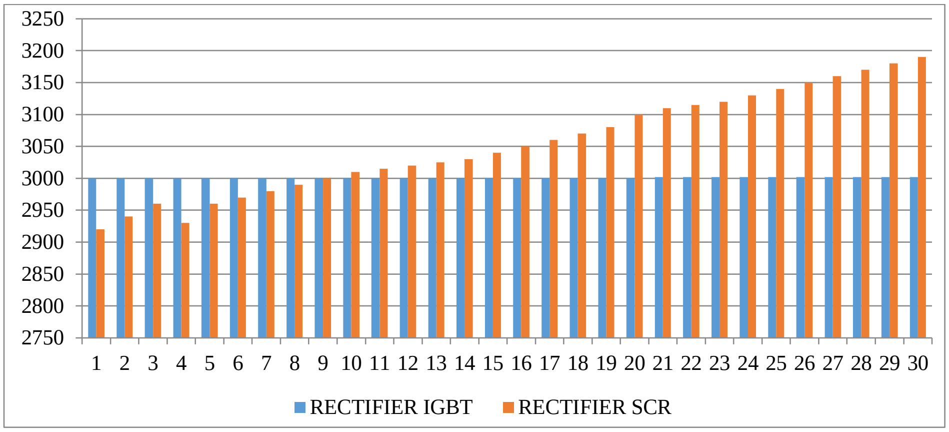

Fig. 18 Comparison of amperage values between IGBT and SCR rectifiers

6. Conclusion

This study has allowed the development of a 4000 amperes electronic half-bridge rectifier oriented to metal scrapping for industrial purposes, as an efficient and modern solution compared to conventional SCR-based technologies. From the comparative analysis between both approaches, it is concluded that the IGBT-based design significantly reduces energy losses, improves output voltage stability and allows a more precise current regulation, which is key for the selective recovery of metals such as copper, aluminium and steel. The incorporation of an ATmega328P microcontroller, Modbus TCP / IP communication and sensors enables remote monitoring, precise control and real-time diagnostics, aligning the system with Industry 4.0 principles. In addition, it was demonstrated that energy efficiency is greater than 5 times between equipment, compared to typical SCR equipment values, lower consumption, lower operating costs and longer equipment life. In summary, this solution is technically robust and scalable and represents a sustainable and cost-effective alternative for high-current industrial applications in the context of the circular economy and advanced recycling.

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