SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I10P110

Volume 11 Issue 10, 93-104, October 2024

Original Article

Design, Development and Implementation of an Industrial Control Device to Improve Productivity and Accuracy

Giancarlo James Vilca Sánchez[1], Luis Angel Choquehuanca Quispe[2], Raúl Ricardo Sulla Torres[3]

[1,2,3]*Universidad Nacional de San Agustín de Arequipa, Arequipa, Perú.*

[1]*Corresponding Author : gvilcas@unsa.edu.pe*

Received: 07 August 2024 Revised: 07 September 2024 Accepted: 09 October 2024 Published: 30 October 2024

Abstract - *The following article presents the design, development, and implementation of a control device to improve industrial mechanical equipment through automation and optimize productivity and accuracy in such equipment. The device consists of an electronic design based on deficiencies found in current control devices; this consists of inputs and outputs necessary for optimal control of the equipment to be improved; in addition to having a built-in LCD screen for data display, this device is suitable for an electrical design of an industrial mechanical bender, digital sensors are used as limit switches, which capture discrete values for applications such as timing, conditioning or supply any specific need. The implementation shows a productivity increase of 35%, demonstrating effectiveness after implementation in real working conditions. This module can be implemented in the industry, offering production and data reading improvements for precision work with a minimum margin of error.*

Keywords - *Accuracy improvement, Control device, Digital sensors, Industrial automation, Productivity optimization.*

1. Introduction

The metalworking industry has been in the industrial sector for more than 60 years, requiring high productivity and effectiveness rates in manufacturing tools, industrial machinery and parts made from base metals such as iron and its alloys. In recent years, the metal-mechanic industry has adopted technologies such as computerized numerical control, systems integration and automation to optimize production in the manufacture of products. The importance of this industry in various productive sectors is driving development in other industries, such as manufacturing, automotive, construction, mining and agriculture. The metal-mechanic industry is characterized by the search for improvements and technological advances in manufacturing. It is proposed that a control module capable of meeting these needs in terms of production and effectiveness be implemented, achieving a human-machine interface for optimal and more efficient control in the manufacturing process. This module is designed for application in any industrial equipment; in this case, it will be implemented in mechanical bending equipment to obtain precision in terms of curved pipes and mechanical profiles used in the construction industry. This module will allow the operator to visualize data such as the timing for calculating height and implementing end-of-stroke sensors strategically located for the sensing of high and low positions, obtaining the reading through the module's inputs.

2. Related Works

In [1], it is described how ac-ac direct converters are strong candidates in power conversion systems for regulating grid voltage against line voltage disturbances and acquiring frequency regulation at discrete step levels in variable speed controllers for industrial systems. These applications require both inverting and non-inverting forms of the input voltage across the output with voltage regulation capabilities.

In [2], adapting to the wide range of input voltages supplied by redundant batteries and ensuring adequate standby time for communication systems during utility power failures is addressed. The power supplies used in 5G base stations generally include a front-end boost converter as the first stage and an isolated second-stage converter. In this context, a new topology for a regenerative snubber in boost converters has been proposed, which offers advantages compared to traditional active or passive snubber topologies, such as having fewer components and occupying less space.

In [3], it is highlighted that miniature untethered soft robots have significant application potential in biomedical and industrial fields due to their spatial accessibility and safe human interaction. However, the lack of targeted and forceful actions remains challenging to revolutionize and fully exploit their versatility.

In [4], it is discussed how product assembly involves a large amount of production data characterized by high dimensionality, multiple samples and data imbalance. A framework based on edge computing is proposed to monitor product assembly quality in the industrial Internet of Things, alleviating the pressure of processing huge amounts of data in the cloud center using perimeter computing technology.

In [5], the main objective is to develop a portable system to provide CNC machine operators with visual and tactile perception of triaxial cutting forces, thus improving work efficiency and preventing mechanical failures. A virtual machining tool simulator was integrated with a portable remote-control system to achieve this.

In [6], barriers and facilitators for the continuous use of Hearing Protection Devices (HPD) by noise-exposed workers are investigated. The cross-sectional study conducted with 524 workers in manufacturing enterprises in Guangdong, China, explores the relationship between HPD wearing behavior, knowledge and attitude about hearing protection, wearing comfort, and work-related factors.

In [7], it is described that all these applications require both inverted and non-inverted forms of the input voltage at the output with voltage regulation capabilities. The required value of the output frequency is obtained by properly arranging the number of positive and negative pulses of the input voltage across the output terminals.

In [8], it is shown that the degree of polymerization plays a vital role in the material properties. Previous molecular weight control methodologies cannot suppress or alleviate batch-to-batch variations in device performance, especially in polymer solar cells. An in situ photoluminescence system was developed along with analysis and processing procedures to track and estimate the degree of polymerization of organic photovoltaic materials.

In [9], the challenges in developing embedded software applications are discussed due to the limitations imposed by the hardware devices or platforms on which they operate and the various non-functional requirements. Modern embedded systems must be energy efficient, reliable, and have low maintenance costs to ensure the success and longevity of their application.

In [10], the development of high-efficiency electrocatalysts with low overpotential and current density at the industrial level for CO_2 Electroreduction (CO_2ER) is addressed. A feasible strategy is reported to modulate the effective coverage of *CO at isolated nickel sites by S-coordinated doping (Ni-NSC).

In [11], it is explained how surfaces of materials such as plastics, glass, metals and wood can be modified using plasma treatment techniques to improve their physical and chemical properties in an environmentally responsible manner by enhancing or conferring particular qualities.

In [12], the importance of effective thermal management is highlighted as modern electronic devices become increasingly miniaturized and integrated. Two-phase cooling methods that exploit the evaporation of thin films on structured porous surfaces are emerging as potential solutions.

In [13], Waste Heat Recovery (WHR) is discussed as an effective way to improve ship energy efficiency, reduce wasted energy, and ultimately curb greenhouse gas emissions in response to International Maritime Organization regulations to reduce emissions from the maritime sector.

In [14], the various sway systems proposed in the last decades to enhance the self-centering capacity of structures after seismic events, sometimes adding dissipative devices to control maximum lateral displacements, are mentioned.

In [15], the use of real-time hard systems, characterized by strict timeliness requirements, in safety-critical industrial sectors such as avionics, space, and automotive is addressed.

3. Previous Designs

The idea of programmable control devices dates back to the late 1960s when control systems were replaced based on relays, switches, and other components for combinational logic. Currently, these devices have been improved and implemented for precision automation applications, but given the problem of scarcity of these devices in a limited market and the very high price, it is irrelevant to consider that for simple applications, these devices may be feasible in implementations of light equipment or little control. Faced with this problem, the programmable controller industry implemented a nanodevice that can meet small needs, but this implementation does not excessively reduce the cost as it is the same product but more compact. To such problems were created PCB's ideal for simple control functions which offer the same functions and are simple to use.

Fig. 1 ELECTROALL prototype

An idea in development of an adaptable PLC device with similar inputs and outputs to an industrial PLC as the S7-1200 was designed by the ELECTROALL channel led by the electronics technician Carlos Fuentes of Peru, which consists of 8 digital inputs and 8 relay outputs (See Figure 1.), A circuit that depends on 24VDC power supply, yes as the ELECTGPL channel of electronic engineer Sebastian Caccavallo of Argentina also developed a prototype PLC similar to a logo (See Figure 2) which consisted of 6 inputs which 3 were digital and 3 analogical in the same way that the previous design of 4 outputs to relay, this circuit includes the regulation to more voltage arriving to support a voltage of 36VDC being its normal operation to 24VDC of feeding in all the circuit.

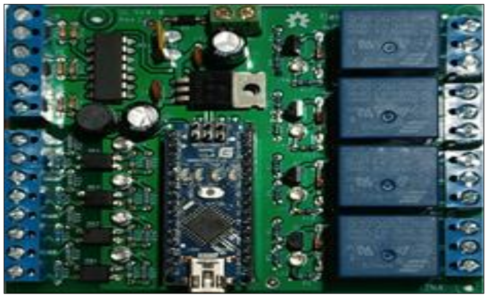

Fig. 2 ELECTGPL Prototype

This design was also implemented in Bolivia in the El Profe Zurco channel (see Figure 3), which implemented a more versatile idea in terms of the implementation of screens for a display of variables, sharing the same idea and principle of operation as the previous ones using a supply voltage of 24VDC. This operation at this voltage has been shown frequently even in industrial equipment of greater robustness, as the PLC logo 24RCE. The main disadvantage of these devices is the voltage drop, as they are limited to having a stable voltage or even working with UPS and filters to avoid the restart of the process in their microcontroller. This design consisted of using a 3D-printed chassis, which only served as a support for the screen. This brought some problems in terms of falls and protections that the screen required so that it could operate optimally.

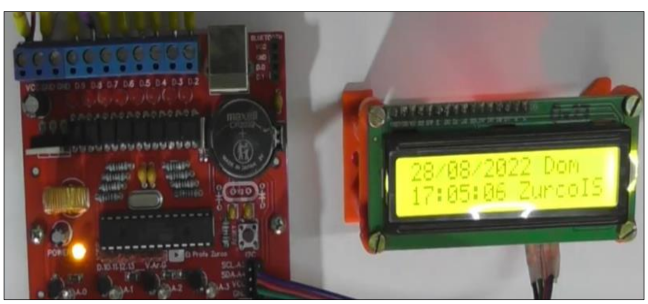

Fig. 3 Professor Zurco prototype

The approach of this idea was improved in the PICAIO channel, where a group of engineers proposed the same idea that had already been applied to an industrial scale using Arduino as the main microcontroller (See Figure 4). Which should perform the functions entrusted; the device was able to work at 230VAC, connected and installed on an industrial board with power contactors. The disadvantage found in this device was the low effectiveness in a long working day; its power supply presented failures in terms of variable voltage drops of 210VAC, which was detrimental to an operation with equipment operating at 100% in its environment, which was improving like the other designs mentioned, in addition to the power supply voltage drop was given by a linear source an effective technology but not updated as a switched-mode power supply.

Fig. 4 PICAIO prototype

These pilot prototypes and studies highlight the versatility with which a control device can work to meet various tasks, demonstrating that their technology, as errors arose, was improved to provide better efficiency in industrial applications, manufacturing, mining, etc.

4. Methodology

To develop the control device and integrate it into mechanical bending equipment, a structure that encompassed several stages was followed (See Figure 5). The study was conducted regarding the need for this and more industrial equipment to supply a number of initial inputs and outputs for specific power control. Using as improvement equipment to a mechanical bender, which uses 3 three-phase motors of 0.6HP, which operates in an environment of considerable electrical noise and single-phase voltage drops due to the use of equipment in the area, where measurements were made with a network analyzer to meet the needs of possible control and ensure the continuous work of this equipment.

It was observed that the operator presented precision errors since the measurement performed in this equipment was made with a flexometer, which served as a guide to generate a curve in metal profiles. This measurement was even taken empirically, depending on the first bending performed. We obtained measurements of the most common profiles to be bent as thicknesses of 1/8" inch and sections of 1" to 2.5", functions performed by the device as the required pressure and referential measurement according to the angle to bend, as the evaluation of the state of accessories in the electrical control panel was performed, making the change of contactors due to wear.

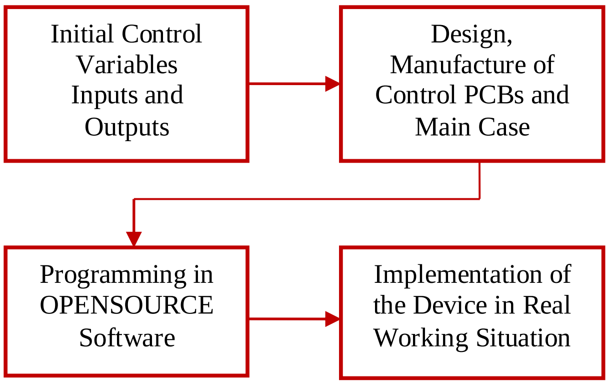

Fig. 5 Implementation stage

Due to the fact that the equipment works in an external environment, susceptible to climatic changes such as rain and heat, the choice of the sensors to be implemented had to meet robust characteristics to avoid easy damage, in addition to components that could withstand continuous work in this type of environment, for which it was decided to change the control panel to a waterproof one, in addition to generating a maintenance plan to avoid generating future failures in continuous production time.

Once these variables to be supplied were determined, the electronic design for manufacturing the main control PCB began, divided into several stages such as power supply, isolated digital inputs, microcontroller and isolated digital power outputs. These variables were obtained through measurements of the power supply network to be used by the device, the appropriate microcontroller depending on the type of input and discrete functions, choosing to use MCU of the ATMEL family and isolated outputs in case the change of control contactors at different voltages in their coils is required.

Once the selection and design of the PCB were completed, it was decided to design the 3D cover based on the model manufactured for the protection of the device in dusty environments and falling particles that could cause damage to the electronic board if it needs to be used in a small industrial board as the equipment to be implemented. The programming software for using the equipment is OPENSOURCE, so its programming is easy to perform.

Finally, we proceeded to implement it in a real environment and applied it to the mechanical bending equipment. This involved working with the operator to perform the respective queries and gather information on the required functionality.

A structure encompassing several stages was followed to develop and integrate the control device into mechanical bending equipment (See Figure 5). The study was conducted regarding the need for this and more industrial equipment to supply several initial inputs and outputs for specific power control. Once the variables to be supplied were determined, the electronic design for manufacturing the main control PCB began, which was divided into several stages, such as power supply, isolated digital inputs, microcontroller, and isolated digital power outputs.

Once the selection and design of the PCB were completed, it was decided to design the cover in 3D based on the model manufactured for the protection of the device in dusty environments and falling particles that could cause damage to the electronic board if it needs to be used in a small industrial board as the equipment to be implemented. The programming software for using the equipment is OPENSOURCE, so its programming is easy to perform.

Finally, we proceeded to implement it in a real environment and applied it to the mechanical bending equipment. This involved working with the operator to make the respective consultations and gather information about the required functionality, which would help with programming in the OPENSOURCE software.

5. Device Development

Implementing control technologies in mechanical equipment in open loop systems proves reliable and easy to improve since such improvement would convert this system to a closed loop system, obtaining more robustness to variations and disturbances. This control device is based on a control similar to a PLC logo, but with the required simplicity and low costs that make it feasible for implementation in light industrial equipment; this device includes 8 isolated digital inputs for voltages from 10 to 24VDC and 4 isolated digital outputs based on 10A relays at 220VAC, the device is designed to operate with a power supply of 127 to 250VAC single phase. The operating variables of 220VAC single-phase derived from a three-phase voltage of 380VAC were considered, and this three-phase voltage occupies the direct power supply of the motors that are the main actuators of the equipment.

It was considered in the electronic circuit that the device should support the operation tests in low voltage and with electrical noise propagated in the main electrical network due to electromagnetic interference produced by the motors, the design of the EMC filter suitable for this application was made (See Figure 6), according to the required impedance of the circuit, the approximate value of 50 Ohms and a cut-off frequency of 200Khz was chosen.

$$L = \frac{Z_O}{\pi f c} = \frac{50}{\pi . 200K} = 79.6uH \approx 82uH$$

$$C = \frac{1}{Z_O \pi f c} = \frac{1}{50 . \pi . 200K} = 31.8nF \approx 33nF$$

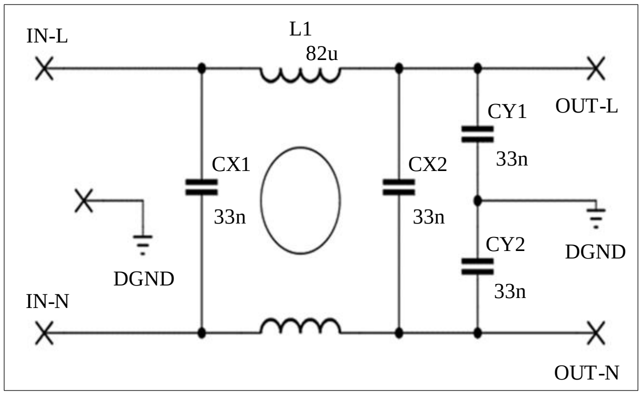

Fig. 6 EMI filter

After the filtration stage, the selection of the power supply was made; a design capable of taking advantage of the 115VAC-230VAC voltage in real working conditions for what is required in the power supply circuit, integrating a scheme with UCC28C44 with dedicated functions for DC-DC converters makes it suitable for work where low voltage and high voltage are critical, as long as the rectified voltage drops to 20%. If it is 15% more than normal, one of its qualities indicated in its DATASHEET, as well as short circuit protection, which protects the device avoiding electronic damage (See Figure 7); in addition, this source must be compact since it is required that the device is as small, light and practical to install on the PCB.

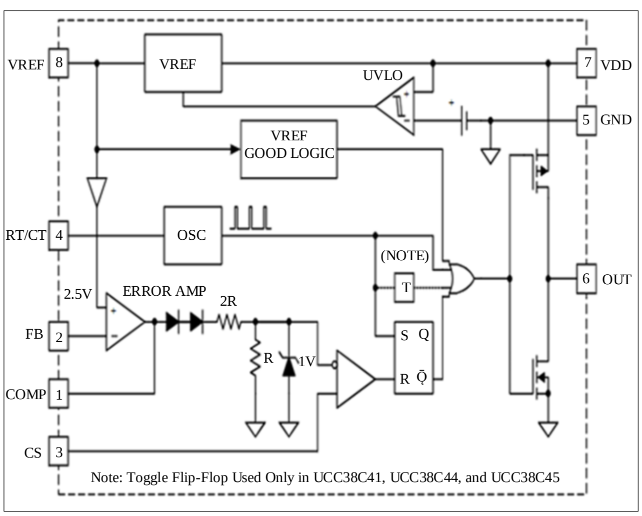

Fig. 7 Integrated UCC28C44 in main source

To complete the selection of the power supply, this must offer a higher amperage consumption than that used in the circuit for protection issues; this estimate was made due to the calculation of the approximate independent consumption of each relay, according to the DATASHEET; this presents a consumption of 0. 25W, of which, to a real measurement, this reaches 0.18W, they present an approximate consumption of 150mA, each one with a total of approximately 600mA; it was estimated that the total consumption would be 800mA with other components in the PCB opting for a source of 1A to avoid the forced work in environments where its application is continuous.

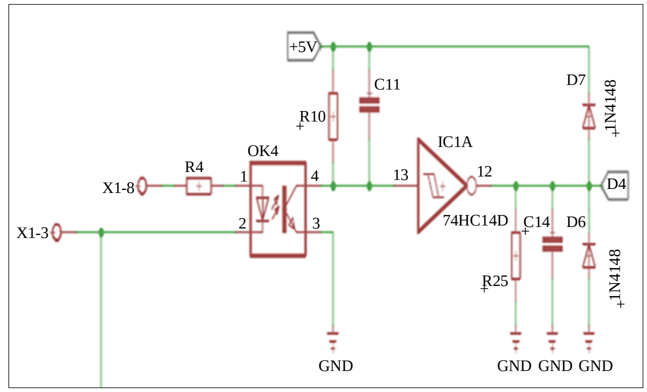

Fig. 8 Digital inputs

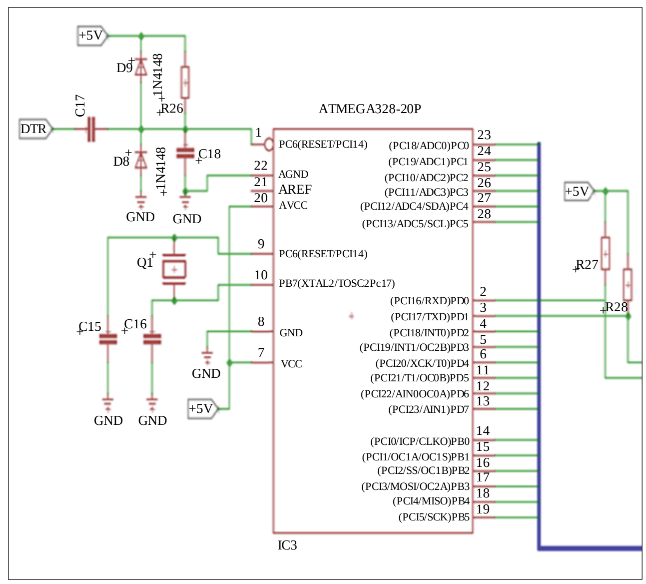

Fig. 9 ATMEGA 328- AU microcontroller

Finally, the control circuit was designed based on variables such as interference by external electrical noise, opting for a filtered optical isolation using PC817 optocouplers as main isolators at its input and additional components to avoid false triggers at the input of the microcontroller as 74HC14D Hex Schmitt Trigger Inverter (See Figure 8); the Arduino Nano module is included in the device, using as main microcontroller the ATMEGA 328-AU (See Figure 9), taking advantage of the switched output voltage source of 12VDC, a linear regulator capable of reducing the voltage to 8VDC which is a value suitable for using the Arduino Nano module in order not to overheat the internal regulation of 5V is added, It should be noted that the microcontroller outputs are 5V and 0V considered to perform functions with integrated protection in the circuit, such logic is implemented in the control outputs with the TC4469 IC obtaining a desired discrete logic reading and for a load control is the main power components to 10A relays (See Figure10).

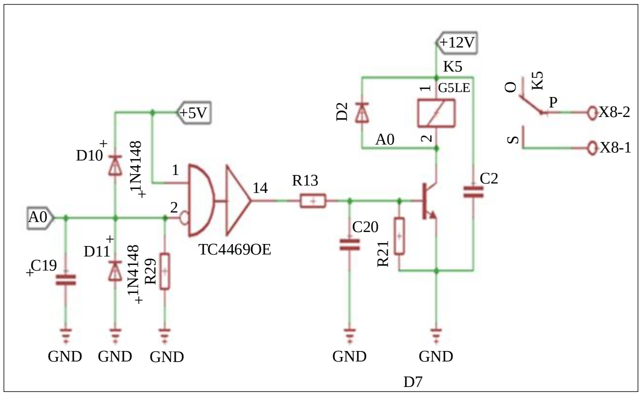

Fig. 10 Digital output to 10A relay

In addition, a diode was placed to protect against reverse voltage transients parallel to the coil, which could damage the control BJT transistors. The loads admitted in the relays are 127VAC at 10A, 250VAC at 10A and 28-30V at 10A, which can be used to control contactors at different supply voltages used in the industry as 110VAC, 220VAC, 24VAC and 24VDC, for the display of control variables was installed an LCD display 8 * 8, which is connected to the I2C ports of the control card, where you can view the timed values, alerts, digital sensing values or power on conditions, these variables will be used and displayed as required by the operator. Once the design was completed, it was determined that the number of inputs would be 8 using a common point for the use of isolated voltages from 12 to 24VDC and 4 outputs for the control of loads with voltages mentioned above, as can be seen (See Figure 11.), the design is compact. It takes up little space because it uses the layer top and bot for optimal routing of tracks.

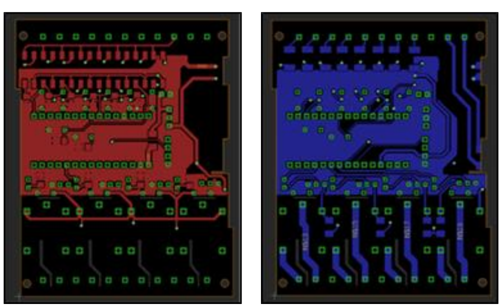

Fig. 11 Layers in PCB design

Culminating the design stage, the main case was made in the AutoCAD 3D software, starting from the dimensions of the PCB made in the EAGLE CS software, importing the file in its DXF format, the final dimensions of 8.5*6.6cm are obtained to make this design, which will protect the internal circuits of the device from contaminating particles such as metal chips or pebbles if it is handled in open places and with enough contamination. The design of the PLC logo was considered a fundamental basis for implementing and structuring the final case (See Figure 12). The design was made according to the dimensions of the components to be used according to the DATASHEET of each one of them, in addition to opting for light insulation in input and output terminals to avoid overheating due to high current intensities and to avoid contact between the cover can generate an electric shock due to internal particles that could enter.

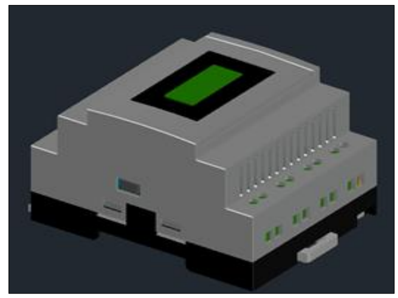

Fig. 12 Control device case

It should be noted that the design of this device was thought to improve a mechanical bender because the cost of a PLC logo is too high; its replacement by this device is more reliable even than the same PLC mentioned above because the power supply presents problems in this device, obtaining performance tests in both devices where the power supply of the PLC logo does not meet the protection characteristics as would the developed device generating an explosion in the equipment that would damage the continuous production processes (See Figure 13).

Fig. 13 PLC logo damaged by high voltage

In addition, the inputs of the PLC model 230RCE, the most used equipment in the light industry where this project is focused, require 127-220AC input to operate normally. Instead, the control device uses 24VDC from an external source; this makes it more reliable because being a low voltage prevents failures by high voltage inputs that can cause damage to the device; in addition, this preserves the safety of the operator because it does not use high AC voltages, for both models the main source is connected to the single-phase mains voltage of the industry to use because the project will be used in an industrial environment metal mechanics, electrical noise will be very high therefore an advantage is obtained for such a crucial factor as this.

6. Architecture of the device

The implementation in the equipment to be controlled, in this case, the mechanical curator, includes different components, such as limit sensors, push buttons and the control module, to perform the height control and generate precision and efficiency in production times (See Figure 14).

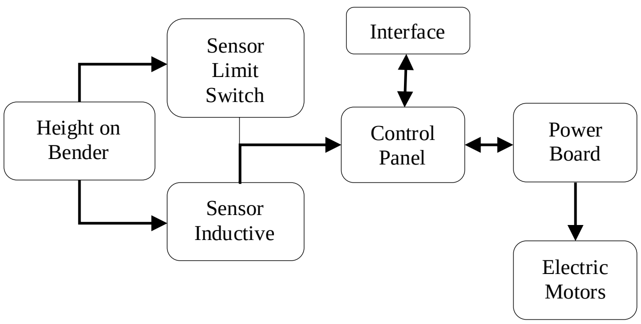

Fig. 14 Block diagram of the control in the equipment

It consists of main stages which are main sensors, which provide digital reading to the control module, are conditioned and strategically located in the equipment, the sensors to be used are XCKJ10511 with thermoplastic roller which meets the properties of moisture protection and suitable for use in industrial machinery according to the standard EN 60204-1; control stage, which is in charge of starting the equipment, low power control for proper operation according to the working conditions with the operator in charge, allowing the control of motor rotation through the drive in the contactor coil, the discrete control of the electrical part of the control is given by the condition of interlocking and reversal of rotation controlled only by the control device developed; power stage, which consists of contactors with 220VAC coils and 3 outputs for discrete control of independent electric motors in the equipment and the user interface stage, which will be responsible for displaying the values depending on the settings made by the operator, height control, set values and number of pieces made, the connection to implement does not directly influence the operation of the equipment, since these data readings do not generate data loss as would the use of an industrial PLC that governs the equipment directly.

The locations of each sensor were made depending on the use of the equipment; the end of the stroke sensor is located in the area of the main thrust motor because its support performs the function of giving a greater or lesser degree of inclination when pressing the material to be bent, this height movement is performed with the motor 1, which must be as accurate as possible, since the accuracy of the bending angle in the profile or tube to be bent depends on it (See Figure 15).

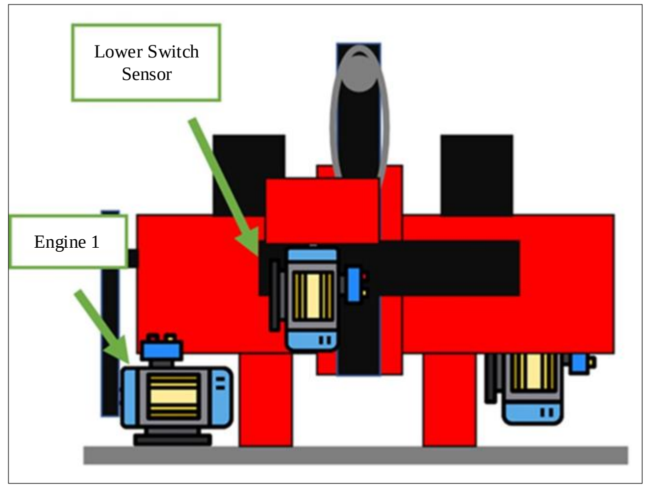

Fig. 15 Location of limit switch sensor and height motor

The inductive sensor is located at the entrance almost at the end of the bending process (See Figure 12); in order to count each time a new profile or tube has been introduced, it is strategically placed in a place where the material cannot collide damaging the sensor, it is necessary to place a metal cover for its protection. In addition, to highlight the functionality of the two remaining motors, motor 3 serves only as a thrust guide so that motor 2, being the main motor of the correct drag bending the material at its exit, this process is achieved with the necessary pressure calculated with motor 1, both motors are necessary for the equipment to be functional otherwise the productivity of the equipment would be null (See Figure 16).

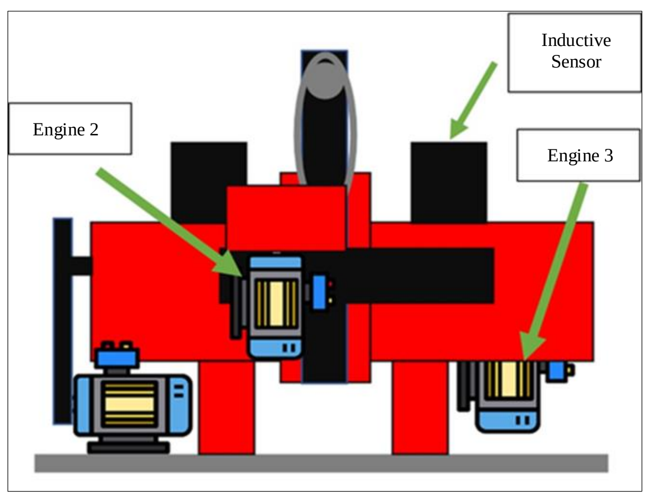

Fig. 16 Location of inductive sensor and motors 2, 3

Finally, the control device was implemented so that it could be operated from the control panel along with data displays on the control device before it corroborated the correct installation in the mechanical bending equipment. Before that, the correct installation of the mechanical bending equipment was corroborated, finding deficiencies and dangers because the equipment control was operated with only 4 contactors and push buttons which served to make the reversal of rotation of the equipment, evaluating the working conditions in the equipment, an emergency stop was implemented mushroom type double contact meeting the conditions, current protections in the motors of 7 to 10A (See Figure 17), both components meet the required conditions according to EN 60947-5-1 standards, a new electrical panel design was developed by adding these components (See Figure 18).

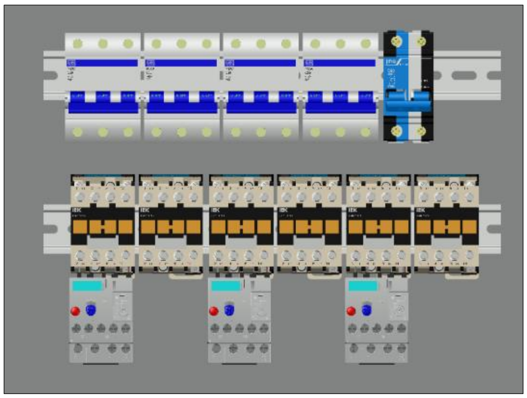

Fig. 17 Electrical panel - power stage

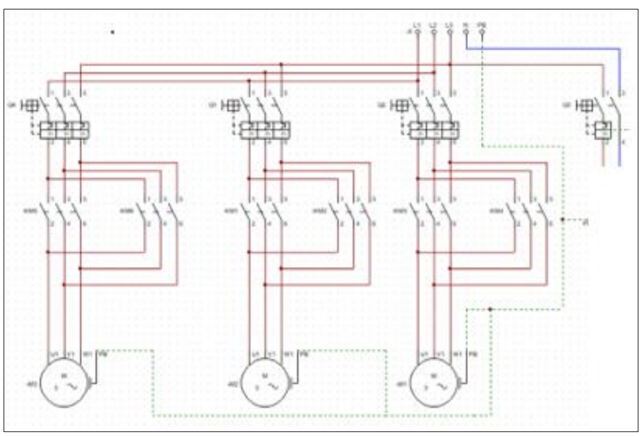

Fig. 18 Power electrical diagram

For implementation in the control panel, we had to make internal modifications, which consisted of adding contact buttons in parallel to those that were already installed; the control device was chosen to be installed next to the control panel because the operator is easier to control the equipment from there, plus it is easy to move and has internal connectors which make it even easier to control the equipment (See Figure 19.).

The control device will occupy 5 digital inputs, which will have the following tags to perform the programming: the variables ARR and ABA are control variables that occupy the height and descent data of the main motor to define the bending angle. The SET variable defines the appropriate pressure value after an initial bending adjustment has been made; likewise, the GUAR variable is the values captured by the inductive sensor to count the number of bends, and the ENC variable indicates on the interface if the interlock function is activated.

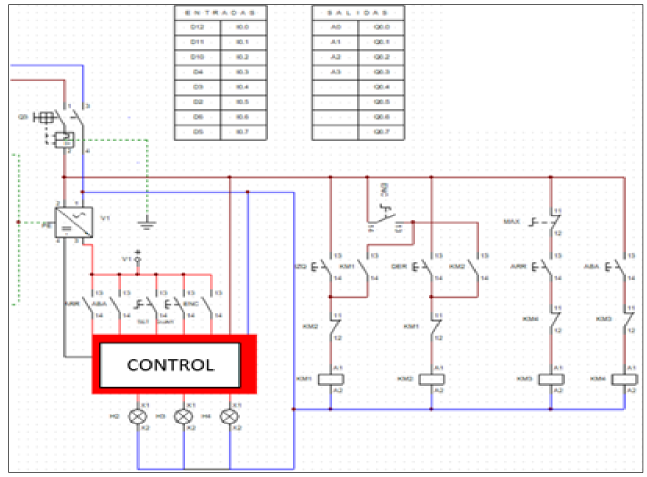

Fig. 19 Electrical diagram of control

7. Hardware Configuration

When making the connections of the control device was taken into account the additional coupling of industrial push buttons to implement for reading data on the display as the buttons only had a switch to perform this condition (See Figure 20), so one was installed in parallel to the up or down buttons, to obtain the corresponding reading on the operator interface (See Figure 21). A 24VDC source was installed on the control panel to read these digital values.

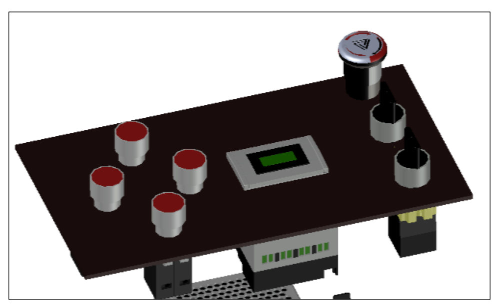

Fig. 20 Control panel top view

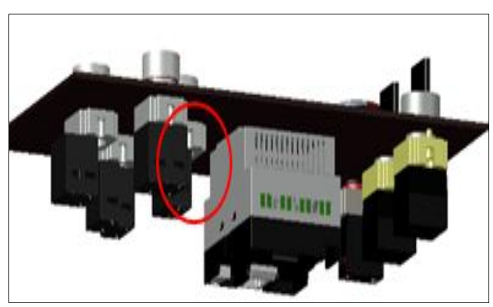

Fig. 21 Pushbuttons added in parallel

The location of control cables are connected to the distribution terminal block located on the control panel of the equipment (See Figure 22), highlighting that this control device is connected in parallel to the logic already implemented, which will help with the reading of data for height control and indicator lights incorporated into this control panel modifying an initial design in order to validate the readings or conditions made by the operator (See Figure 23).

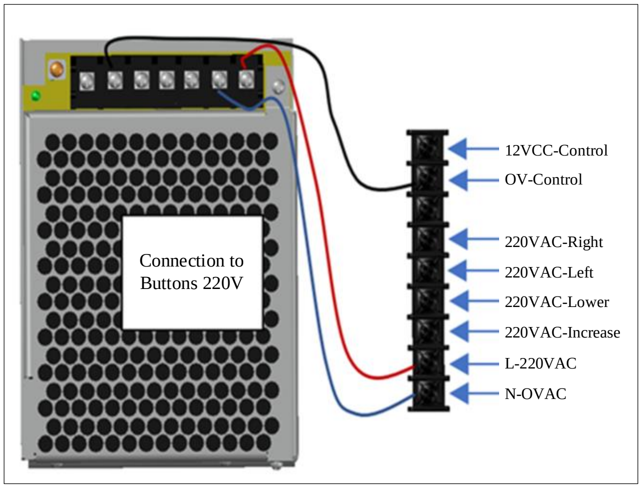

Fig. 22 Control panel connections

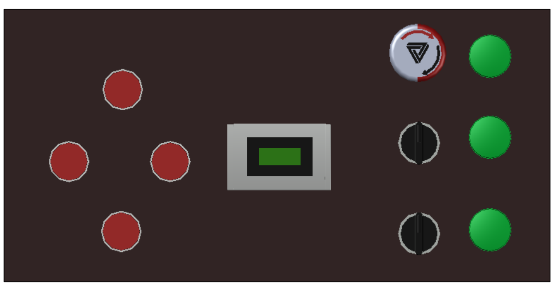

Fig. 23 Modification of the control panel

Fig. 24 Modified control panel design

Finalizing the design of the control panel for the equipment, an ergonomic structure was chosen so that the operator can manipulate these control parameters more easily than the previous model, which measures 0.8m x 0.2m x 1.35m (See Figure 24).

8. Software Configuration

The programming is done based on the conditions of the operator and includes in the programming the previous display of the name of the company to which the implementation will be made, which will be displayed at each start of operations; the operator will have ease of handling this new device as it does not interfere or make changes to the previous given; also an electrical function will be added which serves to interlock the equipment for high productivity operations, in the control panel or interface the equipment will show the following variables (See Figure 25).

- Modifiable height control variable (VAM): This value will increase or decrease in time value the height at which the motor should be lowered or raised; while this value is modified, it should be equal to the value required to give the correct bending angle, having an initial value of 0.
- Setting variable (VS): This value corresponds to the ideal degree of bending in the profiles, so the operator must make a previous calculation.
- Interlock enable variable (VE): This is a written indicator of whether the equipment has the interlock active or deactivated, which a light indicator will also visualize.
- Modifiable time variable (VTM): This value will show the up or down time, which will add or decrease values in the variable VAM, the value which corresponds to the time of pressing the up or down button. The operator will evaluate the condition in this variable to set the VAM and VS values.

Fig. 25 Interface or display of the control device

The functionality of the equipment starts with the placement of the material, which can be a profile or pipe, depending on the requirements; the operator gives the initial pressure setting for the bending angle; now that it has an initial VAM parameter, this will locate the correct value VS for the bending, starting the bending process the operator will decide if this requires the process to be continuous or intermittent,

The continuous process is achieved by activating the interlock function, in addition to this the reading of the inductive sensor at the output will act on this function when it does not detect the material will stop this process and does not generate damage to the equipment or operators by falling of the same material, once the bending process is finished the operator visualizes with a curve guide if this material is correctly bent or has a phase shift, thus ending the process of the equipment.

9. Test and Results

To evaluate the new productivity and efficiency in the equipment, the implementation of the above was performed, testing the control device against disturbances in industry and operations with other equipment, which allowed the collection of empirical data for the operation and improvements to be implemented in the equipment.

The correct location of sensors and voltage signals to be obtained for reading the control device was evaluated, which should be purely digital, discarding the use of analog sensors that have disturbances due to noise generated by other equipment in operation and high dust pollution by operation, the results in accuracy to a digital sensor than analog are shown very beneficially to the equipment as this can be regulated by the operator depending on the mode of use that this may have (See Figure 26).

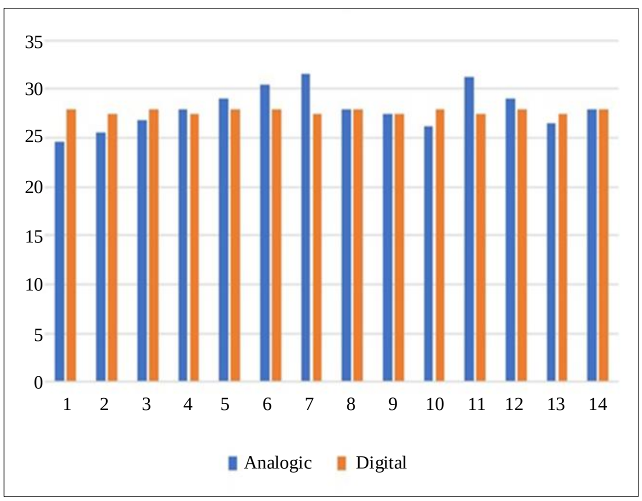

Fig. 26 Comparison in the use of sensors

Due to the variations, the use of the digital sensor was chosen; in the same way, the performance was carried out, and empirical errors of 1% in terms of bending were found using this type of sensor. The stability of this sensor was evaluated, which, with the exerted movement of the up and down motor, the VAM variable lost precision due to the lag in mechanical movements of the equipment, for it was necessary to install support that does not allow this sensor to vary depending on the use of the equipment, obtaining a successful calibration with errors of +- .05% in terms of a loss of values without this support of 5% by lags in a work routine of 10 curved profiles.

The operation was carried out with a group of operators who evaluated the system and qualified it as an exponential improvement in terms of performance and productivity of the equipment, highlighting the height control values and the interlocking mode.

Making calculations of errors in % of bending in terms of the use of the equipment pre and post-implementation, values were obtained (See Figure 27), which show an improvement in the rate of bending errors very high to which it was operated before, obtaining low rates in material losses or failures in bending because there is already control in the equipment, obtaining a 40.66% error correction compared to its previous implementation.

$\text{Precision}_{previous}$ = ((Materials Used x Total Material) / Sampling Errors) x Taotal Sampling

$\text{Precision}_{previous}$ = ((20 x 3) / (3 + 2 + 1 + 0.8 + 1 + 0.5 + 0.5 + 0.5 + 1 + 1)) x 10

$\text{Precision}_{previous}$ = 53.09%

Precision_{post} = ((Materials Used x Total Material) / Sampling Errors) x Taotal Sampling

Precision_{post} = ((20 x 3) / (1 + 0.8 + 0.8 + 0.8 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5)) x 10

Precision_{post} = 93.75%

$\text{Precision}_{obtained}$ = Precision_{post} - $\text{Precision}_{previous}$

$\text{Precision}_{obtained}$ = 93.75% - 53.09%

$\text{Precision}_{obtained}$ = 40.66%

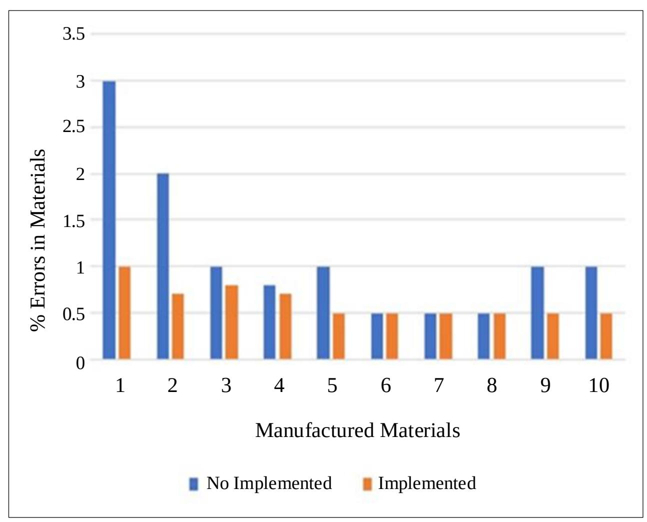

Fig. 27 Comparison of pre-and post-implementation errors

Similarly, productivity is estimated to be 35% compared to what happened previously, and the device allows the work to be continuous or even more efficient in terms of production times (See Figure 28).

$$\text{Productivity}_{previous} = \%\text{Total Material Weekly Losses x Week}$$

$$\text{Productivity}_{previous} = (20 / (3 + 4 + 2 + 3 + 2 + 2 + 3)) \text{ x } 7 \text{ Dias}$$

$$\text{Productivity}_{previous} = 7.36\%$$

$$\text{Productivity}_{post} = \%\text{Total Material Weekly Losses x Week}$$

$$\text{Productivity}_{post} = (20 / (1 + 1 + 0 + 1 + 0 + 0 + 1)) \text{ x } 7 \text{ Dias}$$

$$\text{Productivity}_{post} = 35\%$$

Tests were also performed in terms of electrical functionality, giving a useful life to the equipment of approximately 3 years of continuous production, depending on the care and maintenance that the device may have; the estimated time of functionality was estimated due to data from the manufacturer of the power supply who will suffer more damage to work in an industrial environment with a lot of electrical noise.

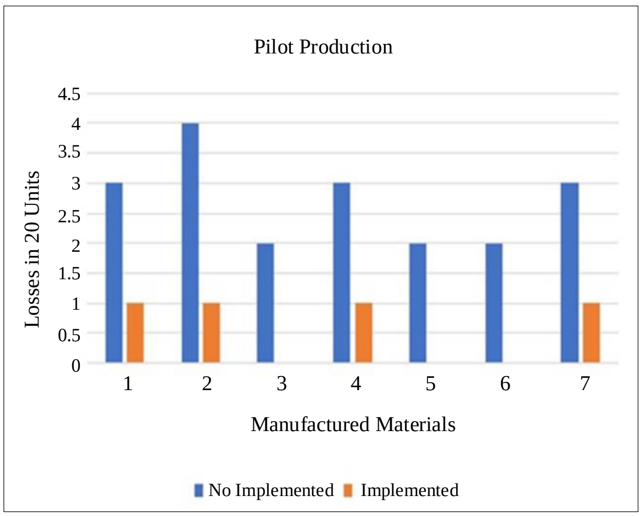

Fig. 28 Comparison of pre- and post-implementation productivity losses

Finally, the equipment will be operated in an industrial environment with the use of other machines in conjunction, such as press brakes, metal guillotine, plasma equipment, welding and laser cutters, which operate at 385VAC three-phase, with voltage drops of 373VAC and single-phase voltages of 225VAC, with voltage drops of 212VAC. The equipment has a built-in board located in the same support that serves to transfer the same. It is recommended that the operator respects the preventive maintenance in terms of motors, shafts and bearings that may be involved in the correct functionality of the equipment, in addition to the proper cleaning after each operation and verification of adequate voltage parameters before use (See Figure29), the equipment will be shown in the real working environment in which the implementations were made.

Fig. 29 Mechanical bending equipment

10. Conclusion

This implementation has demonstrated the potential use that can be given to the control device for specific tasks, which has significantly improved productivity and efficiency in equipment where they do not have control, reducing the failure rate and showing a more attractive environment in terms of functionality with the operator.

The adaptation of this device shows an advance in technology required and necessary for outdated or old equipment, as is the case of this bending machine. However, successful implementation requires the correct care of the equipment, protections and preventive maintenance that can offer the operator so that the data acquired can be similar to when the implementation was performed.

In conclusion, the implementation of the control device offers a technological solution that is sustainable and efficient in improving the productivity of mechanical or hydraulic equipment. This idea can be replicated and adapted in more equipment that requires an improvement already mentioned, contributing to the sustainability of production in companies that require it.

Acknowledgments

We sincerely thank the Universidad Nacional de San Agustín de Arequipa for their invaluable support and collaboration throughout the research process.

References

[1] Gytis Petrauskas, and Gytis Svinkunas, "Application of Single-Phase Supply AC-DC-AC VFD for Power Factor Improvement in LED Lighting Devices Loaded Power Distribution Lines," *Applied Sciences*, vol. 12, no. 12, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Danish Shahzad et al., "GaN-Based High-Power-Density AC-DC-AC Converter for Single-Phase Transformerless Online Uninterruptible Power Supply," *IEEE Transactions on Power Electronics*, vol. 36, no. 12, pp. 13968-13984, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] André Elias Lucena da Costa et al., "A Single-Phase AC-DC-AC Unidirectional Three-Leg Converter," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3876-3886, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] André Elias Lucena da Costa et al., "A Single-to-Three-Phase 12-Switch AC-DC-AC Converter," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 11, pp. 11132-11141, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] Fei Liu et al., "Control Scheme for Reducing Second Harmonic Current in AC-DC-AC Converter System," *IEEE Transactions on Power Electronics*, vol. 37, no. 3, pp. 2593-2605, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Naveed Ashraf et al., "Power Quality Analysis of the Output Voltage of AC Voltage and Frequency Controllers Realized with various Voltage Control Techniques," *Applied Sciences*, vol. 11, no. 2, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Fang Zheng Peng, Lihua Chen, and Fan Zhang, "Simple Topologies of PWM AC-AC Converters," *IEEE Power Electronics Letters*, vol. 1, no. 1, pp. 10-13, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[8] Zeeshan Aleem et al., "A Class of Single-Phase Z-Source AC-AC Converters with Magnetic Coupling and Safe-Commutation Strategy," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 9, pp. 8104-8115, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[9] Naveed Ashraf et al., "A Single-Phase Compact-Sized Matrix Converter with Symmetrical Bipolar Buck and Boost Output Voltage Control," *Energies*, vol. 15, no. 20, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] Naveed Ashraf et al., "A New Single-Phase AC Voltage Converter with Voltage Buck Characteristics for Grid Voltage Compensation," *IEEE Access*, vol. 8, pp. 48886-48903, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Iman Abdoli, and Ali Mosallanejad, "A Highly Efficient Isolated Single-Phase Variable Frequency AC-AC Converter with Fexible Buck-Boost Factor, Inherent Safe Commutation, and Continuous Current," *IET Power Electronics*, vol. 15, no. 14, pp. 1511-1525, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Saeed Sharifi, Mohammad Monfared, and Ali Nikbahar, "Highly Efficient Single-Phase Direct AC-to-AC Converter with Reduced Semiconductor Count," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 2, pp. 1130-1138, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] Naveed Ashraf et al., "A Transformer-less Multiconverter having Output Voltage and Frequency Regulation Characteristics, Employed with Simple Switching Algorithms," *Applied Sciences*, vol. 11, no. 7, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] Hafiz Furqan Ahmed et al., "High-Efficiency Single-Phase Matrix Converter with Diverse Symmetric Bipolar Buck and Boost Operations," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4300-4315, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Naveed Ashraf et al., "A Simple Circuit and Control Topology to Produce Bipolar Non-Inverted and Inverted Voltage Step-Down Features," *Applied Sciences*, vol. 12, no. 17, 2022. [CrossRef] [Google Scholar] [Publisher Link]