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Design and Building of an Automatic Alternator Synchronizer Based on Open-Hardware Arduino Platform

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ABSTRACT In power generation systems the synchronization of an alternator with the electrical network are an important and critical task. This paper presents the design and building of an automatic three-phase alternator synchronizer based on a low-cost open-hardware Arduino platform. The synchronization is performed by means of measuring a phase voltage of both the synchronous generator and the electrical grid; then the measured voltages are conditioned and sent to the Arduino board, which is programmed to determine the correct moment to connect the alternator to the grid. To validate the prototype, a laboratory setup has been built with the alternator driven by a commercial dc drive. The design and practical implementation of the system is proposed as a project-based learning (PBL) activity for undergraduate final year students at the University of Bío-Bío, Chile. A description of the constructed prototype and the results obtained are presented and discussed.

INDEX TERMS Electric machines, alternator, power systems.

I. INTRODUCTION

Electricity generation is the process of obtaining electric power from sources of primary energy. Nowadays, electricity generation can be found in different systems such as: a) electrical grid, b) islanded power systems, c) microgrids [1], [2] and d) hybrid/electric vehicles [3]–[5]. While in systems a)-c) the primary energy sources could be fossil fuels and/or renewable energies (wind, solar, etc.) in hybrid/electric vehicles the primary energy is provided by a battery.

This article is focused on generation for the electrical power network, where although in the last decade there has been an important increasing of solar photovoltaic generation plants, where no rotating machines are used; and wind generator plants where a power electronic converter interfaces a rotating machine with the electrical grid, still most of the worldwide electrical energy generation is based on synchronous generators (alternators) connected directly to the electrical grid [6]. These alternators are moved by a so-called prime mover which in practical systems could be a turbine (steam, water) or a motor (diesel, gasoline). The prime mover supplies mechanical power to the generator and usually includes a governor system to provide a linear decrease of its speed with an increase in power demand (taken from the alternator) [7]. In a typical power system, multiple synchronous generators operate in parallel to supply the power demanded by the loads. To parallel a new alternator to an existing power system (or an existing alternator), certain conditions must be satisfied [7], [8]:

- The RMS line voltages of the new alternator and the power system must be equal.
- The new alternator and the power system must have the same phase sequence.
- The phase angle of the voltages in the power system and the new alternator must be equal.
- The frequency of the new generator, called oncoming generator, must be slightly higher than the frequency of the running system.

These conditions can be verified by different methods (e.g. synchronizing lamp, synchroscope, etc.) and the final

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connection or synchronization of the new generator to the existing power system can be done manually or automatically [9]; the last alternative (automatic) is nowadays the standard option in most of practical applications.

On the other hand, to design and build electronics project related to automation, robotics and control, among others, Arduino platform has become a popular and attractive alternative in last years [10], [11], due to its low cost, simplicity and functionality. Arduino is an open-source platform consisting of both a physical programmable circuit board (a microcontroller) and a software, or IDE (Integrated Development Environment) that runs on a computer, used to write and upload computer code to the physical board [11].

Unlike most other programmable circuit boards, Arduino does not need a separate piece of hardware (called a programmer) in order to load new code onto the board (a simple USB cable is needed). Additionally, the Arduino IDE uses a simplified version of programming language C++, making it easier to learn to program. Finally, Arduino provides a standard form factor that breaks out the functions of the micro-controller into a more accessible package.

This work is focused on electricity generation for an electric power network, where the application of an Arduino platform for designing and building an automatic sychronizer for a three-phase alternator is presented. This solution differs and stands out for its simplicity compared to similar approaches where more complex systems are proposed [12]–[15]. To perform the proposed task, the grid and alternator phase voltages are measured with voltage transducers and the Arduino board ensures the connection/synchronization of the alternator to the grid in the correct instant (aiming for zero voltage difference between grid and alternator). The design and construction of the prototype is proposed as an educational project-based learning (PBL) [16] activity for last year students of Electrical Engineering at the University of Bío-Bío, Concepción, Chile.

It is worth mentioning that although several Arduino projects can be found in the web [17], most of them deals with low-power electronics applications; therefore, the implementation of Arduino into a power generation system is highlighted as an important contribution of this paper. Moreover, the low-cost of the Arduino platform and its powerful capabilities compared to typical commercial alternator synchronizers is also remarked.

To validate the proposed synchronizer, a laboratory setup is implemented. In this experimental system, the alternator is driven by a separately excited DC motor (emulating a prime mover) which is supplied by a commercial thyristor-based AC-DC power converter intended for DC drives. A speed controller is programmed in another Arduino board that regulates the operation of the AC-DC converter. Once the alternator is tied to the grid, the DC drive is controlled so that the alternator supplies active power to the electrical grid. The synchronizer design and results obtained are presented and discussed.

FIGURE 1. Synchronous generator.

II. SYSTEM DESIGN

In this section, the design of the automatic alternator synchronizer is presented, including a description of the project-based learning experience proposed, the main components used, and circuit diagrams, among others.

A. PROJECT-BASED LEARNING OVERVIEW

The University of Bío-Bío (UBB), located in Concepción, Chile, offers a four-year Electrical Engineering degree. In the final year of the program the students must be capable to design and build practical solutions for problems in the field of electrical engineering. On the other hand, at the UBB the educational model is based on a student-centered approach, where active teaching strategies such as case studies [18], problem-based learning [19] and project-based learning [20] are relevant in the pedagogical process.

In particular, the project-based learning methodology is widely used as it helps the students to visualize concepts, collect and interpret data, and associate theory with the real world. This set of competencies, linked to a real project, encourages the students to learn [21].

In the proposed PBL activity, the design and building of an automatic synchronizer for a three-phase alternator is carried out with the following considerations:

1. The generator is connected to the grid via a normally-open three-phase contact.
2. The grid and alternator voltages are measured with voltage transducers.
3. The measurements are conditioned and sent to an Arduino board.
4. From the measurements, the Arduino board establishes the correct moment for synchronization (equal voltage of grid and alternator) and sends a signal to close the normally-open contact.
5. The alternator is moved by a DC machine emulating the prime mover.
6. The DC machine is controlled with a commercial DC drive Parker® 590.

B. MAIN SYSTEM COMPONENTS

The main components used in the project are:

1) SYNCHRONOUS GENERATOR

A 3 kVA, 4 poles, 50 Hz, salient pole synchronous generator is used (Fig. 1). The field current of the generator is provided

FIGURE 2. DC motor.

FIGURE 3. Arduino UNO board.

FIGURE 4. 4-quadrant commercial DC drive Parker® 590.

by an external DC voltage source and the current is set to obtain 380 V (line-to-line) at a speed of 1500 rpm.

2) DC MOTOR

A separately excited 3 kW, 125 V, 1750 rpm DC motor is used (Fig. 2) as a prime mover for the alternator. This motor is supplied by a commercial 4-quadrant DC drive.

3) ARDUINO UNO

Arduino UNO (Fig. 3) is a development platform based on Atmega328 microprocessor. It has 14 digital input/output pins (6 can be used as PWM output) and 6 analog inputs.

4) 4-QUADRANT DC DRIVE

A commercial DC drive *Parker® 590* (Fig. 4) is used to supply and control the DC motor. To regulate the motor speed, a closed-loop control scheme is implemented considering an Arduino board as control platform.

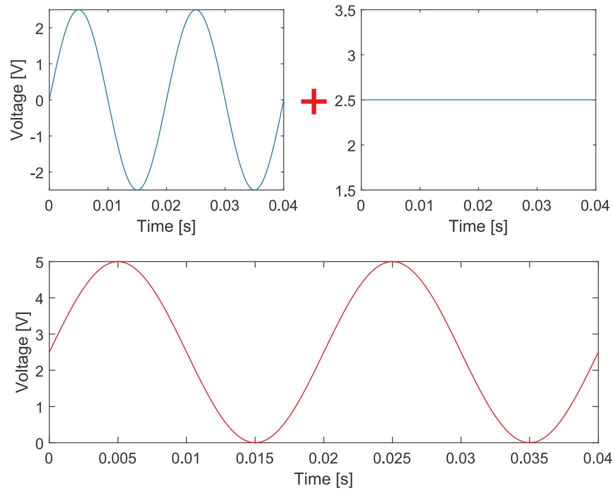


FIGURE 5. DC offset added.

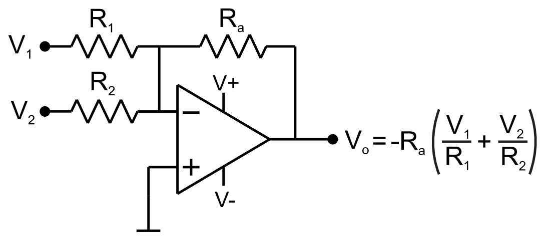


FIGURE 6. Summer circuit implemented.

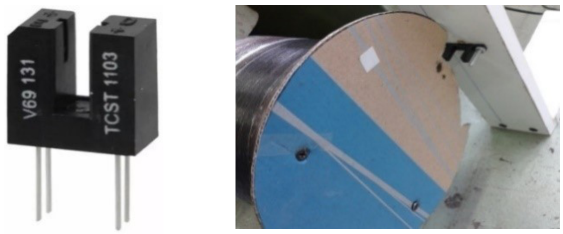
C. AUTOMATIC CONNECTION TO THE GRID

To connect appropriately the alternator to the grid, the instantaneous phase voltages (of the synchronous generator and the grid) must be equal or at least closely similar (in order to reduce the inrush connecting current).

The initial condition imposed is that the synchronous machine field current is adjusted to generate the same grid RMS voltage at synchronous speed. Moreover, the phase sequence of the grid and the alternator is the same (ABC sequence).

Therefore, it is necessary to measure the grid and alternator voltages (in only one phase) and perform its comparison to know if the phase angles are the same, to finally close a contact that connects the alternator to the grid. The voltage measurements are carried out with voltage transducers LEM LV25-P. As the measured voltages are alternating signal and the Arduino board can receive only positive signal in its input pins (between 0 and 5V), a conditioning stage must be included. The signal conditioning consists on adding a DC offset to the measured voltages (Fig. 5) in order to make them readable by Arduino. To perform the addition, an operational amplifier TL082CN in a standard summer circuit connection is used (Fig. 6).

In Arduino platform an algorithm is programmed aiming to establish if the voltages of the alternator and grid are in phase. Once this condition is accomplished an output of the Arduino board is set to HIGH (5 V) to close a relay that energizes the



(a) (b)

FIGURE 7. **(a) TCST1103 barrier sensor. (b) Obstruction disc.**

coil of the three-phase power contact that finally connect the synchronous machine to the grid.

D. SPEED REGULATION

For experimental implementation purposes, the DC motor is supplied by a Parker® 590 DC drive, which is commanded by means of another Arduino UNO platform in a closed-loop control scheme. It should be noted that the selection of an Arduino platform to regulate the speed of the DC machine was based on its simplicity and cost (compared for instance with the powerful but expensive dSPACE platform that has been widely used in control applications [22], [23])

To measure the motor speed, a barrier sensor TCST1103 (Fig. 7a) is used along with a single slot disc (Fig. 7b). The disc is mounted in the rotor shaft end and its non-slotted area obstructs the light emitted by the barrier sensor while the slot allows the light to reach the receiver end of the sensor. During the period when the light is not obstructed a pulse is generated by the sensor and sent to the Arduino board; the duration of the pulse is proportional to the length of the disc slot. This pulse allows the speed of the motor to be calculated in Arduino.

Arduino programming software (which is open-source) provides special functions for different tasks. In particular, the function *pulseIn* indicates the time that a signal is high or low (5V or 0V). This function is used to obtain the period of the pulse ($T_{pulse} = t_{pulse\_on} + t_{pulse\_off}$) emitted by the sensor, then the speed of the motor (n_m) can be easily calculated as:

$$n_m = \frac{60}{t_{pulse\_on} + t_{pulse\_off}} \, [rpm] \tag{1}$$

The measured motor speed is then compared to a speed reference signal internally generated by Arduino, and a Proportional-Integral (PI) controller is programmed to regulate the motor speed. The PI controller output will be a reference signal for the Parker DC drive which is the actuator of the speed control system. It is important to indicate that although several advanced control techniques could be used to improve the performance of the speed regulation [24], [25], the standard PI controller was selected due to its well-known simplicity and reliability for this type of application. In this work, any possible decrease in the alternator generating performance in terms of torque and dynamic response [26] due to the performance of the DC machine is neglected in the present work.

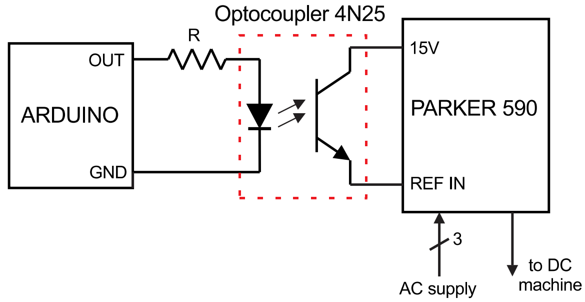


FIGURE 8. **Optocoupler connection.**

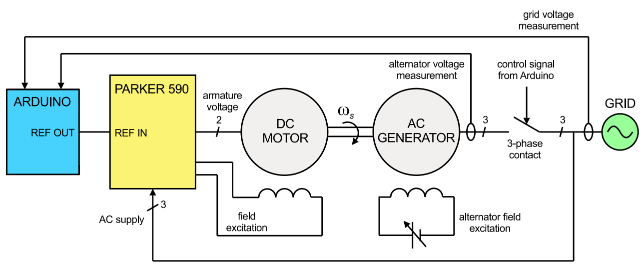


FIGURE 9. **Scheme of the implemented system.**

To operate the system, the speed set point is established in a value slightly higher than 1500 rpm (AC machine synchronous speed) to ensure the synchronous machine operate as a generator once tied to the grid. To isolate the Arduino platform from the Parker® DC drive, an optocoupler (4N25) is connected between both (Fig. 8). The resistor R is used to limit the Arduino current and the output of the optocoupler is connected to the reference input terminal of the DC drive.

Summarizing, this stage aims to regulate the speed of the synchronous machine in an adequate value to ensure the correct synchronization to the grid.

III. EXPERIMENTAL SETUP

A. SYSTEM ASSEMBLY

A general scheme of the implemented system is shown in Fig. 9.

In the Parker® 590 converter the parameters of the DC motor are set up. The PI speed controller programmed in the Arduino board is adjusted by experimental observations of its performance. The values considered are $K_p = 0.26$ and $K_i = 0.00305$. Once the speed controller works properly, the whole system implementation is mounted.

As aforementioned, the measured voltages are sent to Arduino which finally establishes the correct instant to close a three-phase contact connecting the grid with the synchronous generator. Aiming to allow certain modularity of the system, two Arduino boards are used, one for the speed control of the DC drive and one for connecting the generator to the grid. Figure 10 shows the scheme of the system mounted; a detailed view of the control platform is shown in Fig. 11.

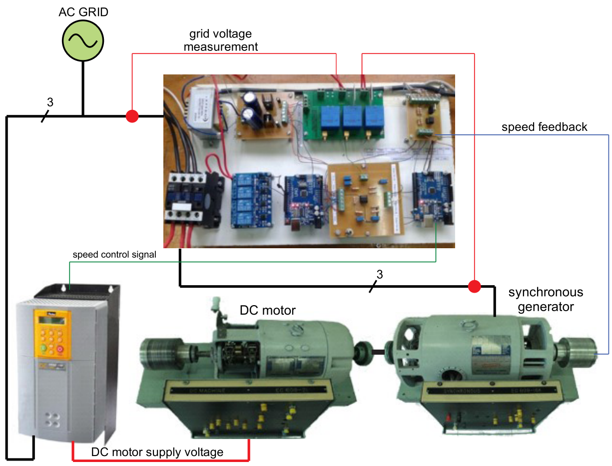


FIGURE 10. **Experimental system implemented.**

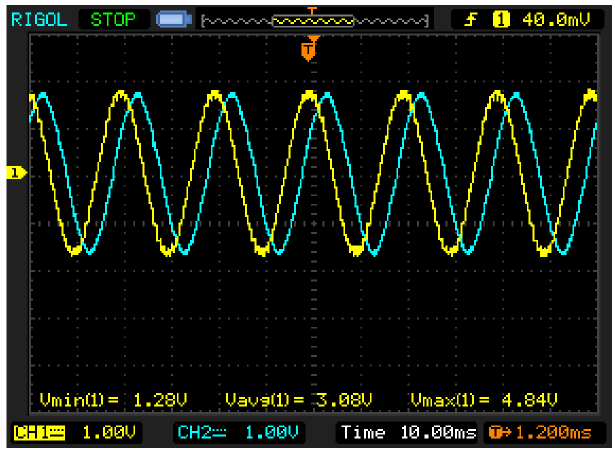


FIGURE 12. **Grid and alternator voltages with an evident phase shift (Scale: 175 V/div).**

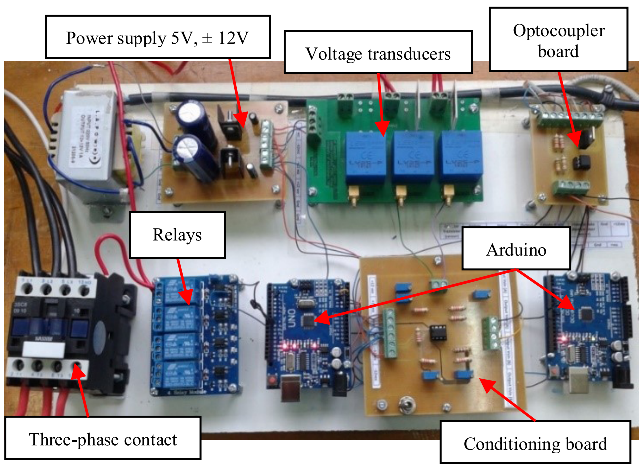


FIGURE 11. **Detail of the control platform.**

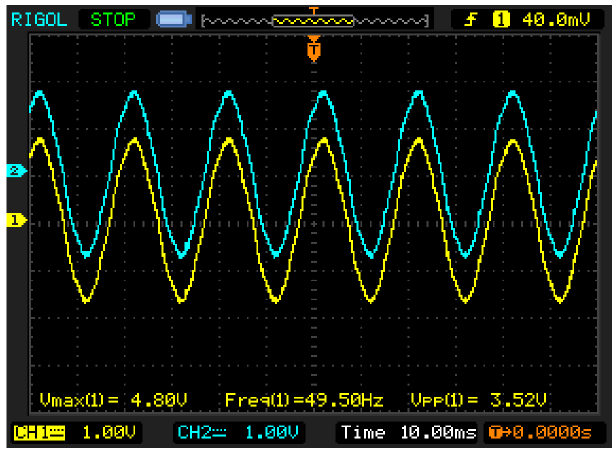


FIGURE 13. **Grid and alternator voltages just before the synchronization (Scale 175 V/div).**

B. RESULTS

The system was tested in laboratory, considering the Chilean grid of 220V, 50 Hz. Figure 12 shows the grid voltage (blue) and the alternator voltage (yellow) in certain moment where there is a phase shift between both. Therefore, even when the magnitude of the voltages is the same, the alternator should not be connected to the grid yet.

Figure 13 shows the grid and alternator voltages (blue and yellow, respectively) just before the synchronization takes place closing the three-phase magnetic contact. As can be seen the voltages are equal in magnitude and phase.

Once the connection is established, the set point of the DC motor speed controller is raised aiming to inject active power to the grid. A three-phase power meter is used to measure the power delivered by the alternator to the grid. The results are shown in Fig. 14 where it can be noted that a total of 1.25 kW is injected to the grid. Moreover, it can be appreciated certain unbalance among the phases which is due to the large use and lack of maintenance of the laboratory machines. Even though, the feasibility of the project proposed is demonstrated.

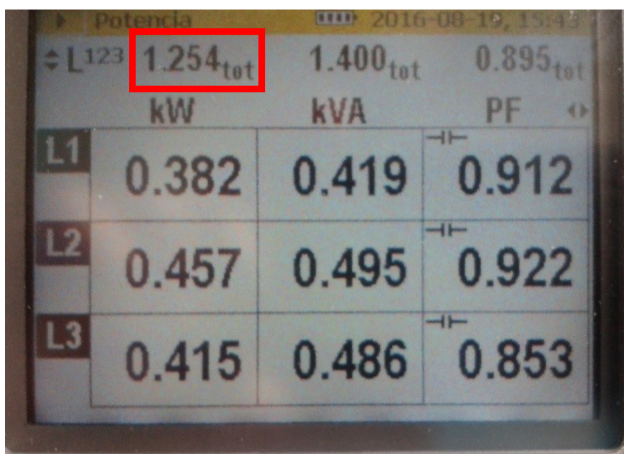


FIGURE 14. **Active/apparent power and power factor once the alternator is connected to the grid.**

IV. CONCLUSION

The design and implementation of an automatic alternator synchronizer based on low-cost Arduino platform has been proposed. The different hardware components and its use in the final system are presented. The system design was proposed as a project-based learning activity for last year Electrical Engineering students in a Chilean University. The results obtained were as expected, demonstrating the feasibility of using Arduino platform in practical applications of electrical machines and power systems.

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