



Basic Control Schemes for Three-Phase Inverters in Photovoltaic Applications

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ABSTRACT

This paper describes some basic control schemes that have been used to optimize the electrical energy consumed by various applications that require the use of electrical machines for their operation, specifically induction motors (such as machinery actuators, electric vehicles, hydraulic pumps, servovalves, robots, etc.) powered by a photovoltaic system. From a practical prototyping perspective, the goal is to use new technologies to implement the designed control techniques through the use of modern components such as 32-bit open-architecture microcontrollers, microcomputers, or FPGAs.

Keywords: Energy optimization, induction motors, three-phase inverters, power drives, direct torque control, photovoltaic systems.

INTRODUCTION

In Mexico, the rational use of certain non-renewable resources has been promoted in recent years, and there has been a growing trend toward using energy sources that have a lower environmental impact, such as renewable energy. Within the context of renewable energy, solar energy plays a very important role. However, the largest solar energy projects are still limited to the commercial and industrial sectors. Despite this, and although they are still very few in number, there are pilot projects in the residential and rural sectors, which for several years now have been providing real-world data that will help identify the benefits and technical solutions needed to improve their performance in both off-grid systems and systems connected to the national power grid.

Photovoltaic Systems

Grid-Connected Photovoltaic Systems (GCPS) are a viable alternative for reducing electricity bills. Photovoltaic technology is a clean and reliable technology, proven over more than 50 years, that is currently experiencing rapid growth and has enormous potential in Mexico due to the solar radiation conditions found across most of the country.

One of the main advantages of photovoltaic systems is that they require virtually no maintenance throughout their useful life (approximately 20 years); furthermore, their operating costs are practically zero since no fuel is required to generate electricity. However, their initial investment costs are still high compared to other technologies; although these costs are expected to continue to decline significantly over the next few years, as they have been doing over the past decade.

Induction Motors and Power Drives

Induction motors are of great interest in the industrial world due to their simplicity, robustness, low cost, and

minimal maintenance. There are applications where it is beneficial and advantageous to optimize the performance of the motor- power drive assembly under steady-state conditions: paper machines, fans, pumps, centrifuges, electric traction, etc. However, there are many other applications where the transient operating mode lasts as long as—or even longer than—the steady-state mode, such as rolling mills, elevators, cranes, electric vehicles, machine tools, robots, the textile industry, etc. Hence the importance of studying the possibility of optimizing performance in both steady-state and transient operating modes.

Controlling the motor of a hydraulic pump is a typical application where energy optimization can be applied. The same applies to applications with quadratic torque-speed characteristics, such as air conditioners and air compressors, where the motor operates at a constant speed while the process's output power is controlled by mechanical means. In variable-speed applications, the motor operates for long periods under conditions below its rated power—for example, in electric vehicles, where rated power is used only during starts and when climbing hills. The use of properly controlled power converters reduces the total losses of the drive. (Bonnett, 1994).

METHODOLOGY

Issues to be addressed

Low power supply

On the one hand, there is the current problem of implementing photovoltaic systems in a modular fashion; regardless of the application, the construction method is practically the same, involving first arranging several solar panels to connect them to a charge controller and then to a battery bank. Finally, the connection to the load is made in two ways, which brings with it several drawbacks; the first involves connecting directly from the battery to devices that generally operate on 12 volts DC, which are mostly lamps (Fig. 1).

The first drawback of the first connection method described above is that the charge controller is generally expensive, although there are some lower-priced options that are also of lower quality; so sometimes people choose to omit it from the system. Although at the moment of connection there may be no noticeable difference in operation between having it and not having it (that is, the lights continue to work), the truth is that in the long run, the service life of the batteries is seriously affected; therefore, proper design and sizing of the controller are essential.

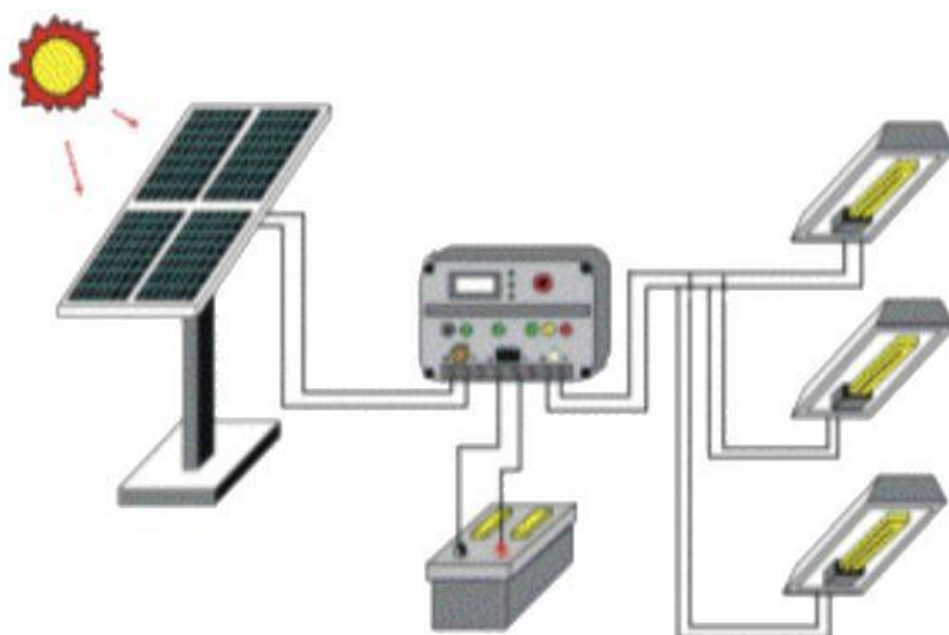


Fig. 1. Typical photovoltaic system for lighting.

Another drawback is that systems that do have battery charge controllers are generally small, since they are designed for low power—usually just lighting, at best, using LED bulbs. Other applications that have already been developed to operate with a direct connection to the batteries, in addition to lighting, include radios (both transmitters and receivers), televisions, fans, hydraulic pumps, and even refrigerators (Fig. 2); however, they cannot be used simultaneously, as this brings us back to the issue of system sizing, which is generally designed for low power (only a few hundred watts). The second way to connect a load to the system is through an inverter (a device that converts direct current to alternating current), which allows you to connect any type of device commonly used at home or in the office, such as household appliances, televisions, power tools, computers, etc. (Fig. 2).

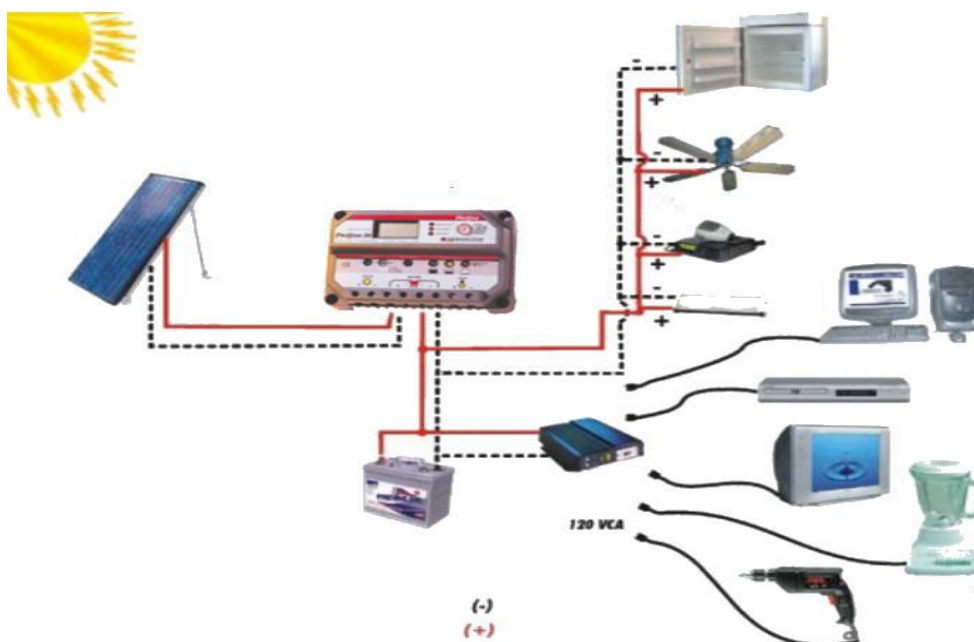


Fig. 2. Common applications powered by both DC and AC.

The drawbacks of this type of connection include, for example, the fact that the inverter is also an expensive, low-efficiency device designed for low power (generally 100 to 500 watts); as a result, people often choose not to include it in their installations, and where it is needed, only a few devices can be connected due to its low power output (it is also a module that may or may not be part of the system).

Thus, the common problem with both topologies is the low power output, which makes them impractical for most applications in an average household.

High power demand from a single load.

On the other hand, there is the issue of inverter design and control for applications in which the photovoltaic system must supply a large amount of power to a single load. Such is the case with operating a three-phase electric motor to drive a hydraulic pump that extracts drinking water from a well and supplies it either for community consumption or for irrigation purposes (Fig. 3). Currently, there is no inverter designed for this purpose, due to the fact that such motors can consume several kilowatts. Furthermore, controlling this type of application is more complicated because a motor of this size presents several challenges not found in the other types of loads mentioned, such as inrush current (which can be 8 to 10 times the rated current), operation at different speeds depending on the required flow rate, and the design of various protective measures to prevent malfunction.

Therefore, the second challenge is the design and construction of specific power drives for demanding applications that include AC electric motors.

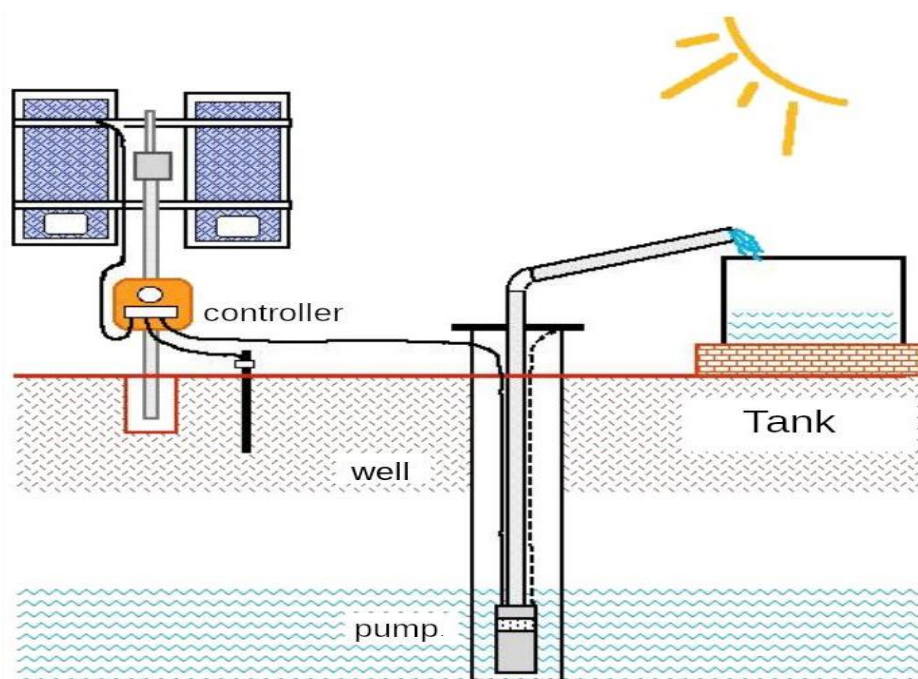


Fig. 3. Photovoltaic system for pumping.

Preliminary hypotheses

- a. It is possible to develop and build a high-efficiency, integrated photovoltaic system for general-purpose electricity supply applications, with a generation capacity of up to 10 kW and the ability to operate either off-grid or connected to the national power grid. Therefore, it could be installed in both urban and rural areas.
- b. It is possible to modify this technological development in terms of inverter control in order to control an electric motor for a specific application that is very useful in rural communities, such as water pumping—whether for community consumption or for irrigation purposes if there is agricultural production.

Strategies for solving the problems

To design and build a comprehensive photovoltaic system that meets high energy consumption needs (at least 10 kW) as efficiently as possible, several factors must be taken into account:

- A solar cell array capable of delivering a high energy density must be designed.
- The best possible battery array for energy storage must be designed, taking into account its subsequent use.
- It is important to design and build a suitable battery charger (with the best power-to-time ratio) based on the proposed battery array.
- A high-efficiency, high-power three-phase inverter (up to 10 kW) must be designed and built for applications that generally require alternating current power (specifically for a well water pump with a 10-hp motor).
- The inverter's control stage must be designed with the understanding that the most complex application will be
- the control of an electric motor powered by the three-phase inverter.
- The control algorithm must account for electricity savings based on the load demand at the time the application is in use.
- Depending on the application, the coupling stage for a bidirectional electricity meter must be designed and
- built, as well as any necessary stages for connecting to and disconnecting from the national power grid.

General control and power schemes

The electronic power converter controls the flow of electrical power between the motor and the power supply depending on the motor's load conditions. The converter is a power conditioner that acts as a frequency and voltage converter. In order to have a control law that serves as input to the control unit, sensors are needed to provide feedback—or, failing that, state observers—to determine the values of certain state variables such as voltages, currents, fluxes, torque, speed, or position. Using these control laws, the system's operating point can be adjusted by correcting either torque, speed, or position to bring them to a setpoint value (Fig. 4).

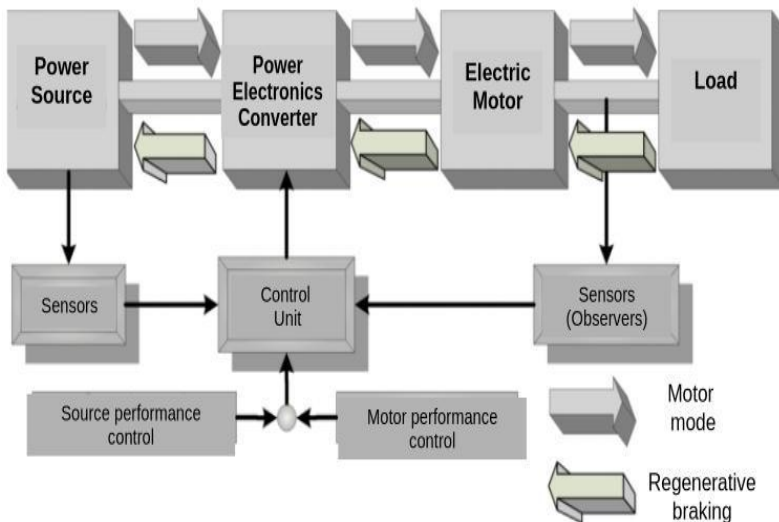


Fig. 4. Diagram of a variable-speed device.

The preliminary system that can be built in a laboratory to begin experimental testing is an AC-DC-AC converter encapsulated in a single module, which consists of a three-phase bridge-type rectifier at the input (built with diodes), an array of capacitors that form the DC bus, and finally a three-phase half-bridge voltage inverter with six power switches, in this case IGBTs. The system will be designed to provide different levels of output power depending on the modular components used; it can reach a maximum of 50 A per phase, with a maximum three-phase supply voltage of 480 V, and a switching frequency of up to 20 kHz, with the capacity to deliver a three-phase output power of up to 20 kVA.

Both the modules that make up the inverter and the module used for dynamic braking will consist of N-channel IGBTs with MOS-type gates and low inductance—an important feature, as they are capable of withstanding short circuits of up to six times the rated current for which they are designed. The diodes that allow current to flow are fast diodes with the same voltage and current characteristics as the IGBTs. In this case, the simplified system topology—configured to perform the specific function of controlling electric induction motors—is shown in Fig. 5.

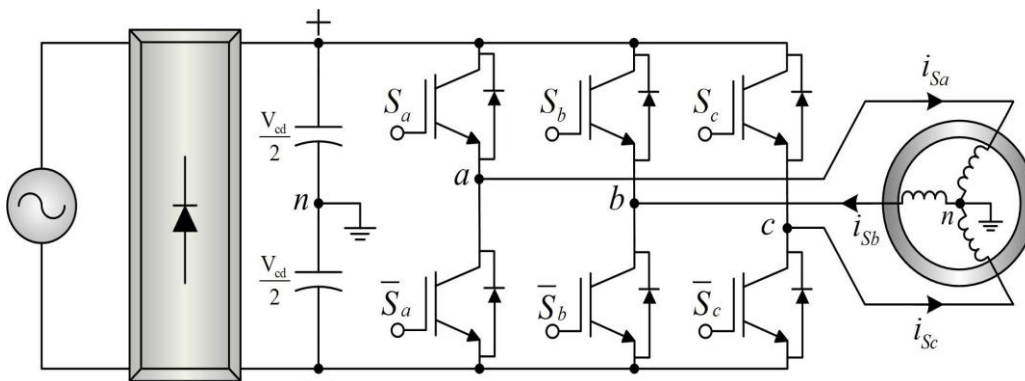


Fig. 5. Topology of the power drive.

Subsequently, using the same topology, the three-phase power supply and rectification components can be replaced with a high-capacity photovoltaic system for specific applications, such as powering a home or operating a water pumping station with a capacity of at least 10 hp.

Improvements in motor performance.

Conventional variable-speed drives operate at constant flux, maintaining a constant voltage-to-frequency ratio in the converter. One way to improve efficiency is to achieve a balance between copper and iron losses, which requires reducing the motor's flux (Fig. 6).

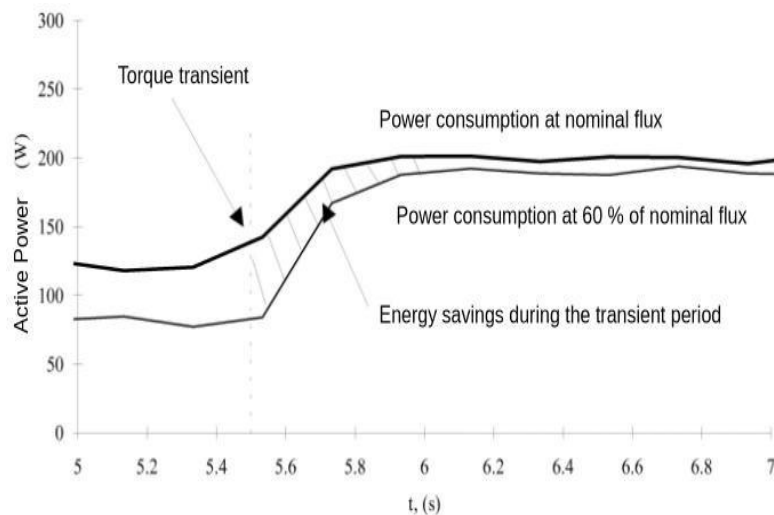


Fig. 6. Comparison of power consumed by the drive during the torque transient (0.25 p.u.) for 100% and 60% of rated flow.

In many electromechanical actuator applications, the induction motor does not operate at its optimal point because the setpoint torque can vary depending on position or speed (Boglietti, 1986). For this reason, it is worthwhile to analyze the reduction in flow to optimize system performance. The efficiency gain achieved by applying the optimal flow rate, compared to the conventional constant flow rate, is significant, especially at low loads and also at low speeds (Fig. 7).

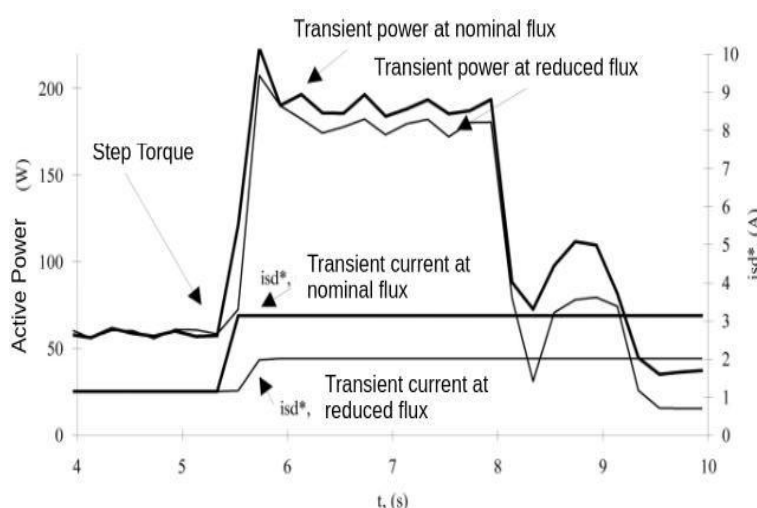


Fig. 7. Power consumed by the drive during transitions to rated flow and reduced flow (60%) in response to a torque step of 0.3 p.u.

As mentioned earlier, there are several methods for varying the motor current based on changes in active power consumption until the point of minimum losses is reached, thereby achieving a balance between copper and iron losses; for this reason, they are called minimum-search methods or algorithms (Bonnett, 2008).

Control techniques based on measuring active power consumption

The basic idea behind this type of controller (Boglietti, 2008) is to minimize the active power of the drive, which is physically measured at some point in the system. To do this, one of the drive's control variables—such as slip frequency, rotor magnetizing current, or stator voltage—is varied, and then a search algorithm is used to find the point where losses are minimized (Fig. 8). Search controllers are very accurate; however, they are highly sensitive to load variations. Another problem they present is the occurrence of disturbances in the electromagnetic torque due to step changes in one of the drive variables. In high-dynamic-performance control schemes used in industrial applications, such as Field-Oriented Control (FOC) and Direct Torque Control (DTC), the flux is usually maintained at a constant nominal value. In this situation, efficiency is maximized only when the system operates at its rated operating point. Below this point, the excessive storage of energy in the windings necessarily reduces the machine's efficiency.

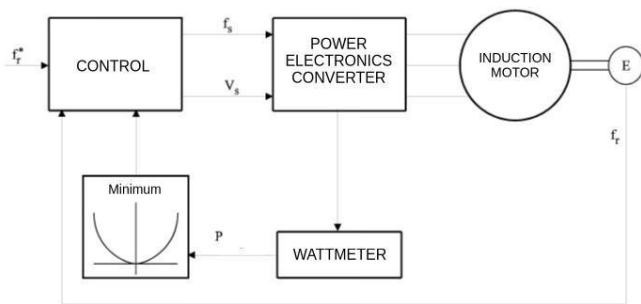


Fig. 8. General diagram of the optimization approach based on measuring the active power consumed by the drive.

To apply the algorithms for finding the minimum-loss point, a disturbance must be introduced into the system; that is, the process begins at an operating point with a specific flow rate (generally the nominal flow rate), and the active power consumed is measured. Next, a flow disturbance is applied—typically a reduction in flow of about 10% of the nominal flow—and the active power consumption is measured again. Once two initial operating points are established, the optimal flow search algorithm is applied; this algorithm will vary the motor's flow while measuring new active power consumption values until the flow that results in the lowest active power consumption is found. Fig. 9 shows a schematic diagram of the iFOC's operation along with the iterative search methods used to simultaneously achieve speed control and optimization of the active power consumed by the induction motor. This provides a clearer idea of how this combined power controller and optimizer is implemented. This is just one example of how various search techniques for minimizing active power consumption can be combined with a well-known control technique for induction motors.

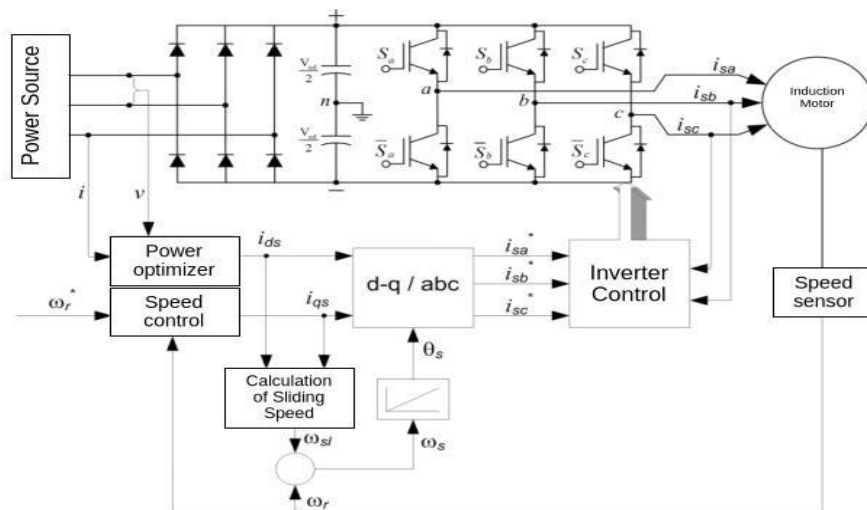


Fig. 9. Schematic diagram of the combination of iFOC with search methods.

Direct Torque Control (DTC)

There have been some contributions regarding modifications to the FOC to account for optimizing motor performance based on the connected load; however, very little has been reported regarding modifications to the DTC, and even the existing work is based on the operation of the conventional DTC (Noguchi, 1985; Moustafa, 2002) and then modifies it from an energy efficiency perspective. The contribution of this work focuses on implementing the modifications proposed in (Kaboli, et al., 2004) to account for improved motor efficiency when controlled using the conventional DTC technique, while also enhancing the control's performance to address intrinsic issues in its operation using the techniques proposed in (Toh, et al., 2005). In addition, various elements are added to the control to enhance its robustness and improve its performance, based on the contributions made by (Calzada Lara, 2005).

Essentially, this method uses the system's input power as the objective function and adjusts the reference flux to minimize that input power, thereby increasing efficiency. An example of deriving the objective function is shown in Fig. 10, in which the components of both the current and voltage vectors in the stator are multiplied; once the function is obtained, the flux is varied in steps until the minimum of the function is found (Kaboli, et al., 2004).

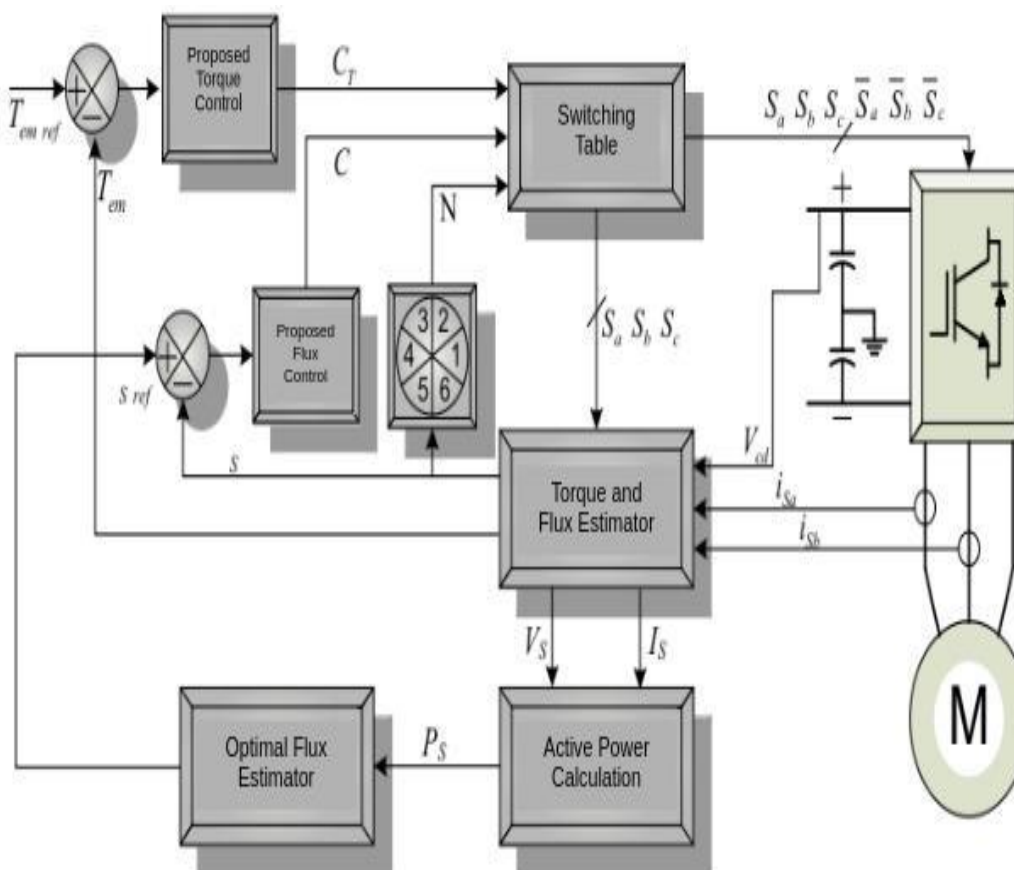


Fig. 10. Modification of the DTC to vary the reference flow with respect to the input power.

SIMULATION RESULTS

Simulations have been performed for both the power supply system and the load operation under different operating conditions. As shown in Fig. 11, the entire system—from the power supply to the motor load—has been successfully simulated. The results shown in Fig. 12 were obtained by simulating the operation of an induction motor for water pumping, where a soft start is intended, as can be seen in the speed graph, until reaching a steady-state setpoint speed. Also shown is the line-to-line voltage produced by the inverter that powers the induction motor; the currents in the three phases are represented in the second graph.

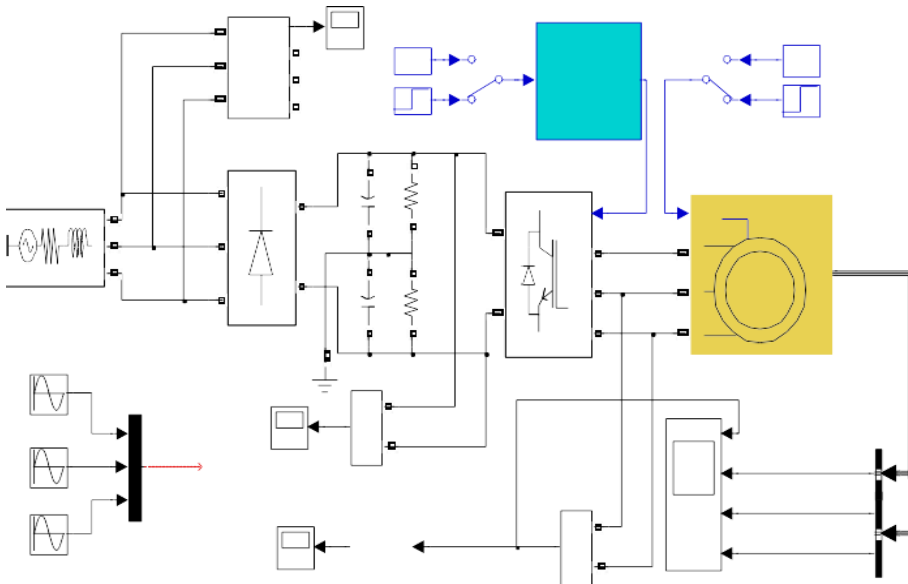


Fig. 11. Schematic diagram for the simulation.

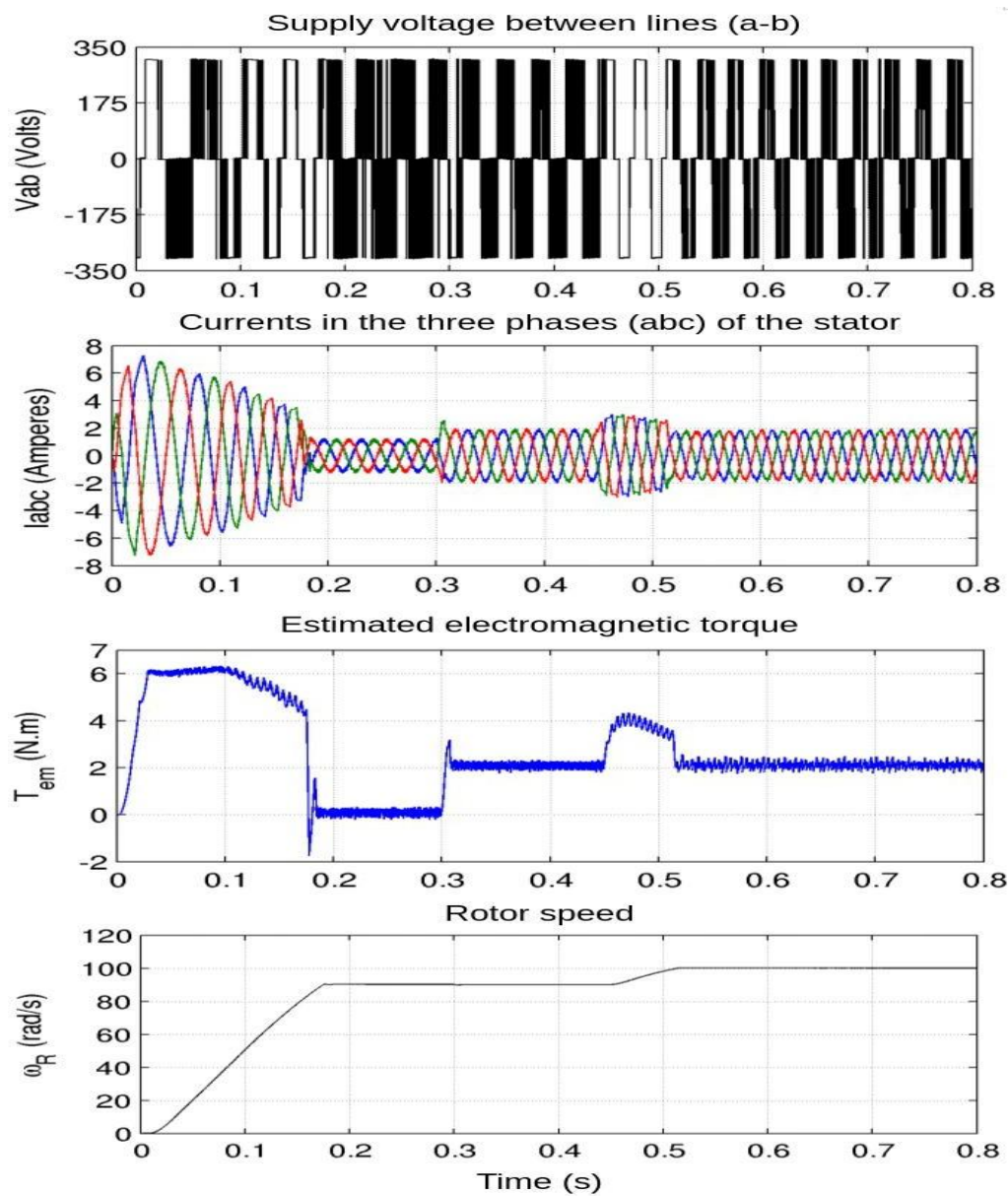


Fig. 12. Simulation results.

EXPERIMENTAL RESULTS

Figure 13 shows the power and control boards. An STM32-Nucleo-F031K6 board (32-bit microcontroller) is also used; it handles the control strategy and sends the pulses needed to activate each of the inverter's IGBTs.

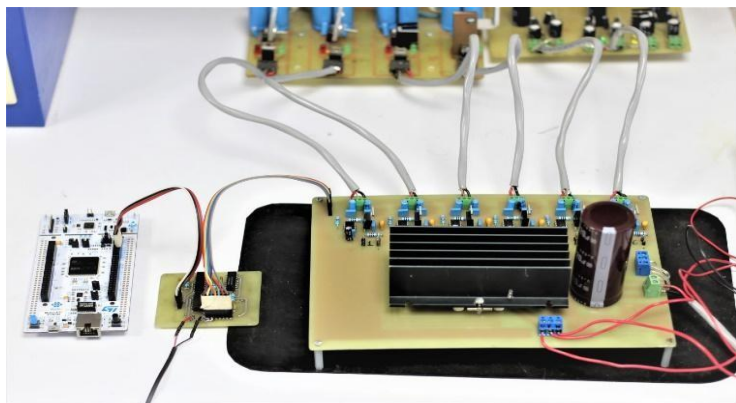


Fig. 13. Three-phase inverter and its control board.

Finally, the following figures show preliminary experimental results of the converters operating in conjunction with the induction motor using scalar control to maintain a constant ratio between voltage and frequency. Fig. 14 shows a screenshot of the oscilloscope when the inverter's output voltage is at nominal conditions.

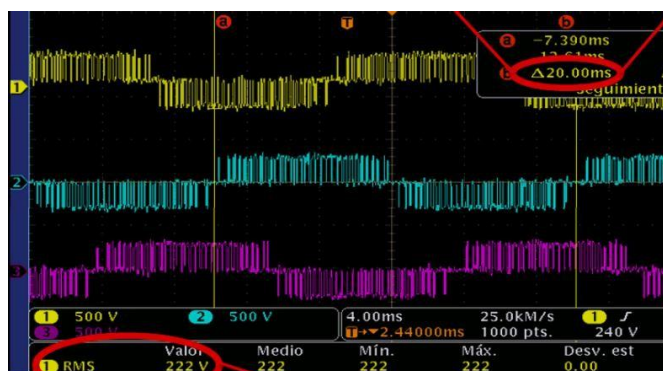


Fig.14. Output voltage of the three-phase inverter.

Fig. 15 shows different combinations of voltage and frequency of the modulating signal used to test the scalar control (which causes speed steps). The results of applying scalar control to the induction motor are shown in Fig. 16, which presents measurements of the motor currents affected by the speed steps resulting from changes in frequency and voltage at the inverter output (note that this initial test uses a very simple compensation scheme that will be improved over time).

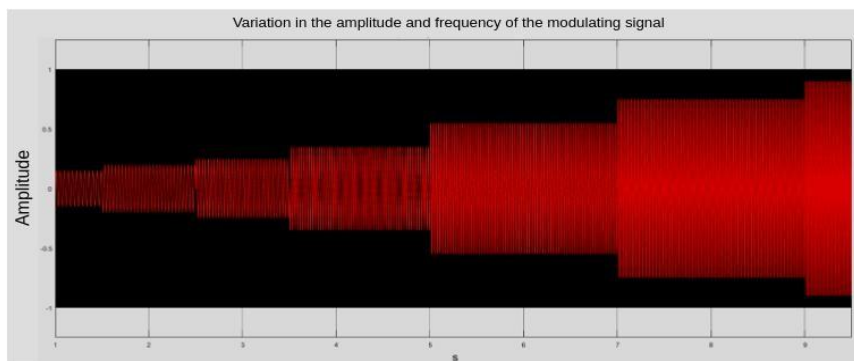


Fig. 15. Modulation of the sinusoidal signal to obtain variable voltage and frequency at the inverter output.

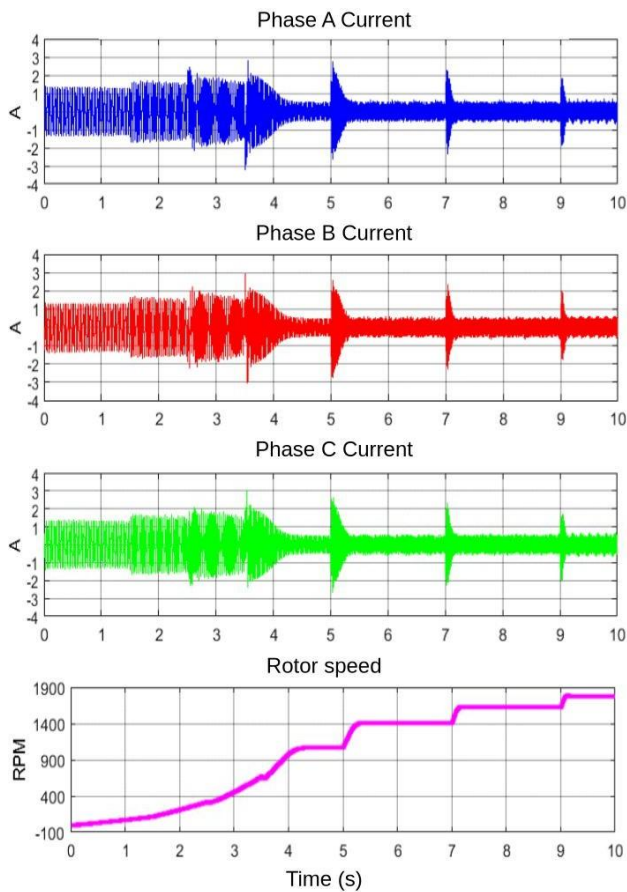


Fig. 16. Current consumption and actual motor speed.

CONCLUSION

Based on the premises studied and their validation through simulation and experimentation, it can be concluded that it is possible to build an electronic power converter that meets the desired characteristics to function as a high-efficiency power supply in both urban and rural settings; this converter could be used in a wide range of applications. The construction of the prototype is the result of combining multiple fields of science related to control, such as power electronics, photovoltaic systems, electrical machines, digital signal processing, instrumentation, and programming.

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