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## Article

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# Aspects to Consider in the Evaluation of Photovoltaic System Projects to Avoid Problems in Power Systems and Electric Motors

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## ABSTRACT

This paper analyzes the problems in electrical power systems with high penetration of photovoltaic systems, which must be considered in evaluating new projects with these generation sources. The study analyzes the characteristics of photovoltaic systems, their generated effects, and proposals for technological improvements. The features of electric motors and their affectation when they are fed from networks with power quality problems are also described. As a result, the variability in energy production, the difficulties in frequency regulation, the increase in harmonics, and the instability in generating reactive power, are the main problems caused by the massive use of photovoltaic systems. Regarding electric motors, it is shown that harmonics and voltage regulation are the power quality problems that most affect their operation. None of the studies conducted analyzes the direct influence that photovoltaic systems can have on the process of electric motors. Considering the growth prospects for using photovoltaic systems and the importance of electric motors, it is suggested that the scientific community develop research focused on this problem.

**Keywords:** Electric Motors, Electrical Systems, Photovoltaic Systems, Power Quality, Project Evaluation

**JEL Classifications:** Q2, Q4

## 1. INTRODUCTION

In recent years, the use of renewable energy sources (RES) has increased as one of the main strategies for compliance with the Paris 2015 agreement. This agreement aims to reduce greenhouse gas emissions and combat their effects on climate change (UNFCCC, 2015). From 1990 to the present, RES has had an average annual growth of 2% within the global energy supply. Figure 1 shows the most significant increase in using photovoltaic solar energy at 37.3% and wind power at 23.6%. The other energy source with significant growth is biogas at 12.3%, solar thermal at 11.5%, and liquid biofuels at 10% (IEA, 2018).

The generation of electricity has had an annual growth of 2.9% since 1990. In this same period, generating electricity using RES has grown slightly, with 3.7%. RES is the second largest contributor to electricity production, with 23.8%, behind coal,

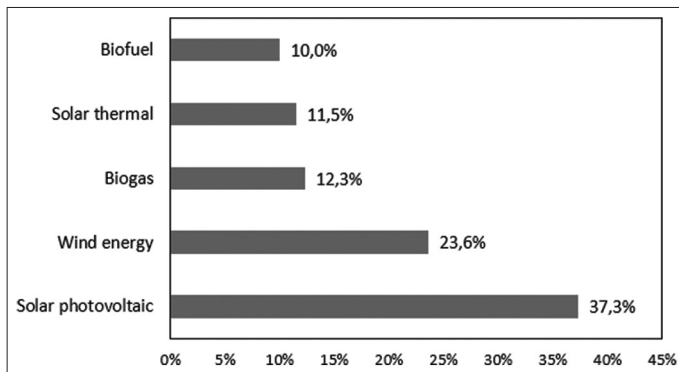
representing 39.2%. The other contributors to generating electrical energy, as shown in Figure 2, are gas at 23.6%, nuclear energy at 10.6%, and oil at 3.8% (IEA, 2018).

In Colombia, as shown in Figure 3, the electric power generation matrix comprises 78% hydroelectric plants, 10% thermoelectric plants that operate with gas and coal, respectively, and 8% with other energy sources (Ministerio minas y energia and UPME, 2016).

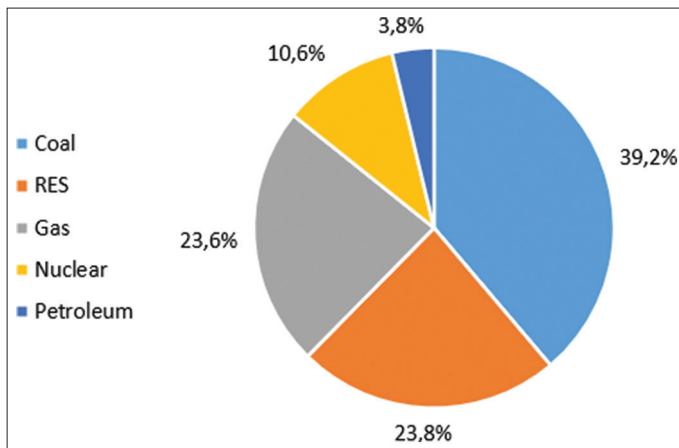
Although clean energy generation predominates in Colombia, there are risks to energy security due to the possible absence of rain, which has led to the projection of the diversification of the matrix with non-conventional RES (FERNC), mainly from photovoltaic generation (UPME, 2015).

Based on the regulatory framework of Law 1715 of 2014 (Congreso de Colombia, 2014) and Resolution 030 of 2018

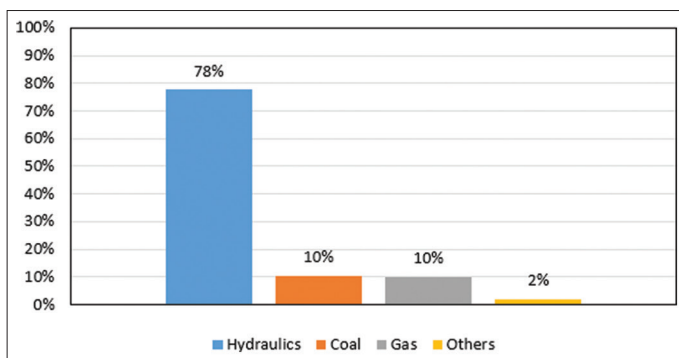
**Figure 1:** Annual growth of energy supply from RES



**Figure 2:** Contribution of energy sources to electricity generation



**Figure 3:** Contribution of energy sources to electricity generation in Colombia



(Ministerio de Minas y Energía, 2018) and research that demonstrates the energy potential of FERNC, it is expected that the development of electricity generation from alternative sources will be promoted in Colombia. The expectations of growth in the penetration of FERNC, specifically of photovoltaic systems (PS), although it is a good alternative for the current energy and environmental scenario, imply new challenges for the operation of the electrical system. Among the challenges implied by the widespread use of FERNC, particularly PS, are the variability of energy availability and production depending on weather behavior (Rönneberg and Bollen, 2016), the bi-directionality of energy transfer (Azzouz et al., 2017), frequency regulation (Ye et al., 2019), design and selection of protection schemes (Brahma and

Girgis, 2004), deterioration in power quality (Liang and Andalib-Bin-Karim, 2018), and instability of reactive power generation (Sarkar et al., 2018).

On the other hand, among the primary energy consumers of the electrical system are electric motors (EM). These loads are estimated to consume between 43 and 46% globally and between 60 and 70% in the industrial sector (Gómez et al., 2022). EM, since their invention, have been designed to operate with balanced sinusoidal voltages close to their nominal value; therefore, any deviation from this condition affects their operation, increasing losses and reducing energy efficiency (Sousa Santos et al., 2019).

The studies presented by (Rocha et al., 2022) and (Rocha et al., 2022) show that in Colombia, there is great energy potential from generation from photovoltaic systems and present the challenges that the country would have for the massive implementation of this source of energy. Although these studies evaluate regulatory, social, economic, and technological aspects that must be considered in evaluating this type of project, they do not consider the affectations that may occur in the electrical power system and in electric motors due to quality problems of energy.

Considering the growth prospects of electric power generation from PS and the importance of EM as one of the primary consumers, this article analyzes the challenges that generation with PS implies for the operation of electrical systems and of the EM. The paper analyzes the characteristics of the PS, the problems associated with intensive generation from these systems, and proposals for technological improvements developed. In addition, the features of the EM and their affectation when they are fed from networks with power quality problems are described. As a result of this study, it is proposed that these aspects be considered in developing new generation projects with photovoltaic systems, specifically in Colombia.

## 2. SF CHARACTERISTICS

As shown in Figure 4, the PS mainly comprises solar panels, regulators, converters, and batteries that can be complemented with control systems to improve efficiency (Mohanty et al., 2016).

The photovoltaic solar cell (PSC) is the base element of the SF. This device works from the photoelectric effect that occurs in semiconductor materials when energy is transferred from the photon of sunlight to the free electrons of the semiconductors. The number of electrons that can move and generate energy in semiconductors depends on several factors, such as temperature, composition, electric field, and magnetic field (Pierret, 1983). The main characteristic of the PSC for its application is the current-voltage (IV) characteristic curve under lighting conditions. Within this curve, the most critical parameters are the short circuit current, the open circuit voltage, the current and voltage of the maximum power point, and the form factor or fill factor. The efficiency of the PSC has been improved through several parallel layers that allow better capture of photons, prevent light from being reflected, and guide it to penetrate inside the cell. With this alternative, recombination is also avoided, the series resistance

is minimized, and parallel resistance is increased (Tiwari and Dubey, 2010).

In an SF, in addition to the PSC, which is the energy generating element, the converter is the essential equipment since it is the one that delivers energy to the end user, controls the SF, and allows synchronization with the grid.

As shown in Figure 5, these systems can be classified as stand-alone photovoltaic systems (SPS) and grid-connected photovoltaic systems (CPS) (Hernández-Callejo et al., 2019).

The SPS can be used without batteries and directly coupled to the load or using batteries with DC self-regulation or with a charge controller with an AC system. The SPS also operate with a hybrid SF that includes the possible use of wind turbines, hydro

turbines, fuel cells, or diesel generator, among others. The SFRs, can be made up of a bimodal SF with a storage system or directly connected to the user without a storage system.

### 3. CHALLENGES OF A MASSIVE PENETRATION OF PS

The main change implied by the increasing use of PS is in the modes of electric power production, which would go from being generated from large units under the control of a network operator to small units connected to the distribution network, whose availability and production It is highly variable depending on the behavior of the weather (Rönneberg and Bollen, 2016). The main challenges that electrical power systems must face due to the massive use of PS are described below.

Figure 4: Components of a photovoltaic system

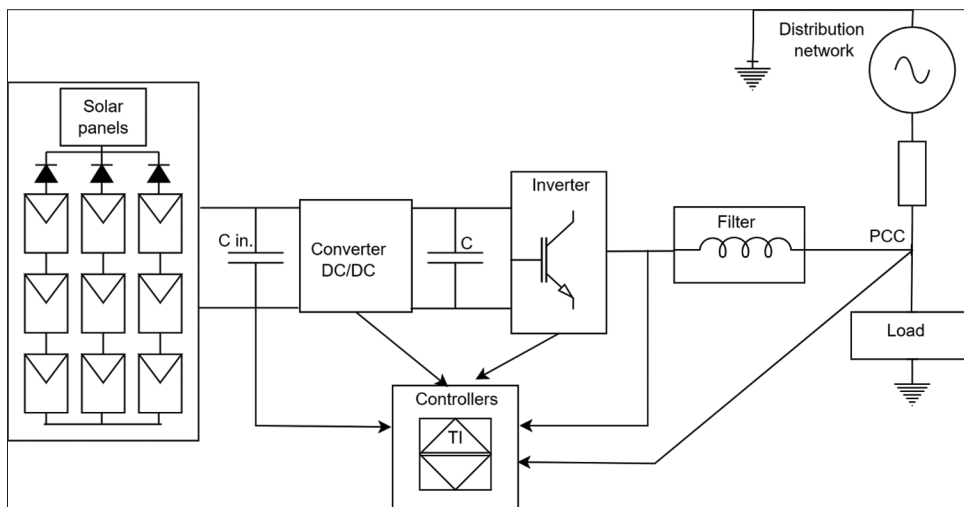
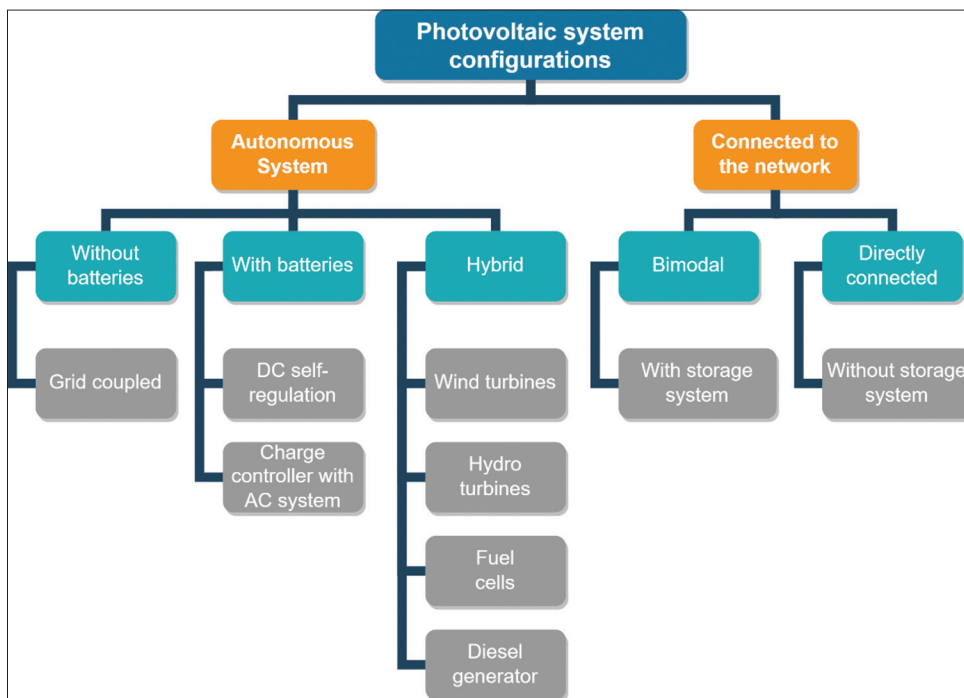


Figure 5: Configurations of photovoltaic systems



The problem of the intermittency of generation from PS is a matter of concern that has been studied, proposing solutions based on hybrid systems that include the storage of pumped hydroelectric energy (Basu, 2019; Pérez-Díaz and Jiménez, 2016). Another problem of distribution networks with RES is that, unlike conventional networks, they have a bidirectional power flow that generates voltage regulation problems. Controlled voltage regulation schemes stand out among the methods developed to mitigate this problem (Dib et al., 2019).

Frequency regulation is another challenge in electrical power systems with high penetration of PS due to the variability in their generation. These problems are analyzed in studies where new load frequency control methods are proposed based on artificial intelligence methods that seek faster responses to variations in generation from PS (Tungadio and Sun, 2019).

With the penetration of PS, new challenges have arisen for designing and selecting protection schemes in electrical systems because the fault level changes and the power supply is intermittent. In addition, the unwanted tripping of the overcurrent relays in the distribution feeders can be increased, and their impact can reach the distance relays of the transmission system (Telukunta et al., 2018).

The massive use of PS has also caused the deterioration of power quality, specifically the increase in harmonics in the points of common coupling (PCC) produced by electronic devices (converters), generating harmonic instability problems for transmission operator networks. Various studies have worked on new analysis models and control mechanisms to mitigate these harmful effects (Liang and Andalib-Bin-Karim, 2018).

Reactive power is another parameter that has been affected, with the consequent affectation on voltage regulation and dynamic and transient stability. Concerning this other problem, research has been conducted on developing new technologies that allow reactive power to be supplied from the same electronic devices used in the PS (Sarkar et al., 2018).

#### 4. EFFECTS OF PS ON THE POWER QUALITY OF ELECTRICAL SYSTEMS

Power quality refers to various electromagnetic phenomena that characterize the voltage and current during a particular time in a specific place of the power system. The quality of the energy is affected by electromagnetic distortions that alter the operation of a device, a mechanism, or a system, reducing its useful life. Among the main phenomena causing electromagnetic distortions at low frequencies are (IEEE Std 1159, 2019):

- Harmonics and Interharmonics.
- Voltage fluctuations.
- Voltage variations and interruptions of short and long duration.
- Voltage imbalance.
- Frequency variation.
- Low frequency-induced voltages.
- Direct current signals in alternating current networks.

Photovoltaic power plants must comply with the requirements of the network to which they are connected, including the established limits of power quality. Among the factors that affect the disturbance of photovoltaic energy is the size of the photovoltaic plant, the connection voltage, the short-circuit power at the interconnection point, and the degree of system penetration (Ortega et al., 2013).

In the case of photovoltaic power plants, the main power quality problems are harmonic content, flicker, voltage variations, and harmonic resonance (Chidurala et al., 2016). Harmonics, defined as sinusoidal voltages or currents with frequencies that are integer multiples of the system's fundamental frequency, are among the problems of most concern. Harmonic currents increase energy losses in EM, overheat the neutral conductor and transformers, and can cause protective devices to malfunction (Vita et al., 2016).

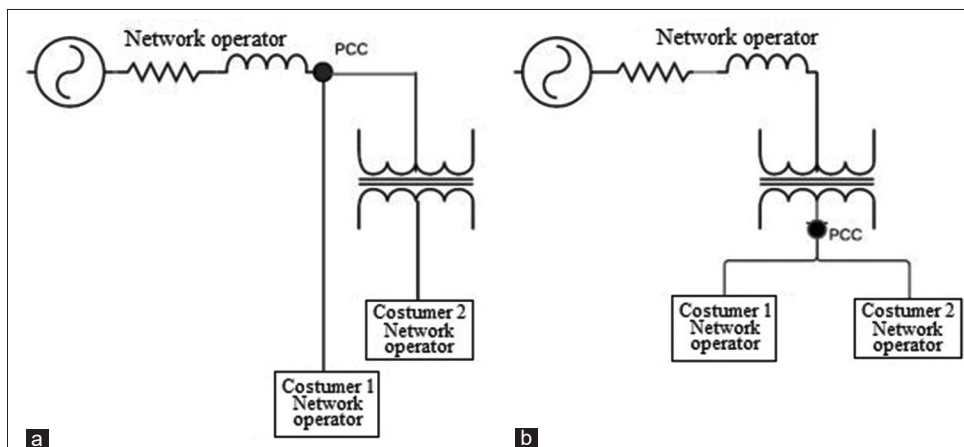
According to the IEEE-519 standard (IEEE, 2014) and IEEE-1159 (IEEE Std 1159, 2019), verifying that the harmonics generated by the PS do not exceed the established limits must be done in the PCC. As can be seen in Figure 6, the PCC can be in the primary or secondary of the transformer, depending on the connection points of other customers.

Another characteristic that must be considered with the massive insertion of PS is that the harmonic currents flow from the non-linear loads (harmonic sources) towards the lowest impedance, generally the primary source. As shown in Figure 7, although the impedance of these sources is typically much lower than the impedances of the parallel paths of the loads, the harmonic current is divided according to impedance ratios. Higher harmonics will flow to capacitors with low impedance at high frequencies IEEE-519 (IEEE, 2014). The interaction between the harmonics generated by the PS and the non-linear loads can produce resonance phenomena that are very detrimental to the operation of the electrical system (Chidurala et al., 2016).

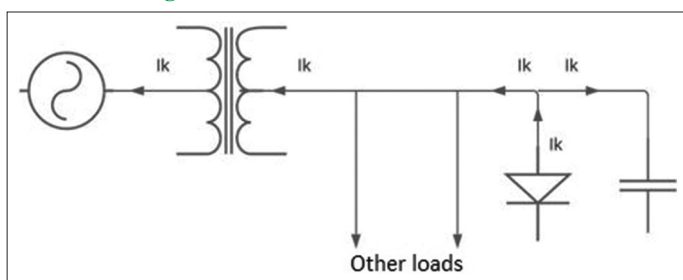
The magnitude and order of the harmonics that photovoltaic units can introduce into the grid will depend to a large extent on the power converter technology. Therefore, these components have been studied to improve their performance. Recent designs have been based on Insulated Gate Bipolar Transistors (IGBTs) with Pulse Width Modulation (PWM) technology, as they have been shown to produce less harmonic content than thyristor-based converters. In a study where five different converters were evaluated during clear and partly cloudy days, it was possible to demonstrate the influence of the capacity of the converters on the harmonic distortion that can be produced (Chicco et al., 2009; Langella et al., 2016).

In another study where a methodology to measure and evaluate the power quality in PS based on IEC standards is applied to a large power plant connected to a medium voltage feeder, it was possible to demonstrate that at low power intervals, the harmonic emission is high (IEEE, 2014). Interharmonics are also a growing concern. Their leading cause is the non-synchronous behavior of electronically connected electrical subsystems: the DC side of the drive and the AC side. Some studies have analyzed inter-

**Figure 6:** Position of the PCC (a) in the transformer’s primary, (b) in the secondary



**Figure 7:** The Flow of Harmonic Currents



harmonics emission in a photovoltaic converter, pointing to control with maximum power point tracking (MPPT) as a possible cause for frequencies below 100 Hz. It is also shown that at more than 100 Hz, distorted high-frequency harmonics can have a significant impact.

A study conducted in a 96-house distribution system with high SF penetration in the Netherlands could identify a high harmonic distortion in the PCC. In this distribution system, the harmonics were produced due to many PS, the typical electronic charges, and the interaction that had the resonance phenomenon (Benhabib et al., 2007).

In another study in an Australian network, the impact of harmonics injected from a network with high SF penetrations was analyzed, which caused an increase in the k-factor of the transformers, causing the overloading and heating of this equipment (Chidurala et al., 2016).

## 5. TECHNOLOGICAL IMPROVEMENTS IN PS TO AVOID POWER QUALITY ISSUES

Studies on the incidence of PS in the operation of electrical power systems focus on improving the operation of their components and reducing the harmful effects of power quality problems in the electrical system. Among the parts of the PS, the power converters are the ones that have received the most attention in various studies that have presented new technological and control strategies that have allowed the improvement of the performance of the PS.

One of the control strategies that have been developed is based on status feedback to a DC-DC converter applied for SF regulation purposes. The SF output voltage level is determined by a maximum power point tracking (MPPT) algorithm. This control technology provides a suitable duty cycle for switching the DC-DC converter to improve its dynamics concerning the reference voltage generation supplied by the MPPT algorithm. The proposed method is tested using computational simulations in the Matlab/Simulink environment. In addition, an experimental device was used to emulate the simulated results and corroborate the technique’s efficacy (Fernandes et al., 2017).

A technological solution that has shown excellent reliability against faults is the development of an H-bridge cascade converter applicable to medium voltage and high power. The proposed converter can maintain balanced three-phase network currents during uneven power generation caused by irregular solar irradiation and by different temperatures of each module (Yu et al., 2015).

Another variant that has given good results is the development of a parallel-input, series-output boost converter with dual coupled inductors and a voltage multiplier module. In this technology, the primary windings of two coupled inductors are connected in parallel to share the input current and reduce current ripple. In addition, the converter uses interleaved series connected output capacitors, which enable high voltage gain, reduced output ripple, and reduced switch voltage stress (Hu and Gong, 2015).

The configuration of a multilevel power converter for grid-connected PS has been an effective technology for delivering good quality power. This technology has a modular design and is reusable and scalable. In addition, the converter adds a voltage stabilizer for each module to be installed (Duman et al., 2017). The analysis of the principles of classical operation of the converters characterizes the presentation and validation of new designs. Another feature of validation is the use of numerical simulations or implementation in novel prototypes.

In addition to generation, the operation of an SF is supported by other processes such as monitoring, control, simulation,

optimization, fault diagnosis, production stoppage, production start-up, and the operation of all these elements (Zhao et al., 2000). To estimate photovoltaic production, it is necessary to anticipate the value of the existing resource, which is irradiance. In forecasting, using Artificial Neural Networks (ANN) is widespread. Recent research has focused on obtaining short-term forecast models for predicting generation with PS due to the intermittency of solar radiation (Gómez Rodríguez et al., 2021).

One of the problems that have caused the increase in the installation of photovoltaic solar farms is the increase in voltage in the PCC due to the reverse power flow. To regulate the voltage in the PCC, public service companies use the most technology as the voltage source converter with the devices or flexible alternating current transmission systems (FACTS), aiming to compensate reactive power when there is no generation on the farm (Dib et al., 2019).

The implementation approach of adaptive PS with MPPT has allowed the optimal operation of microgrids in island mode. This strategy enables efficient coordination between all its elements: V<sub>f</sub> and PQ converter control, MPPT control, and storage control. It can also be complemented by maintaining the battery unit's state of charge (SOC) (Rajesh et al., 2017).

Hybrid systems composed of PS and a diesel generator have also been studied to minimize costs associated with the consumption of fossil fuels while guaranteeing good energy quality. In a model developed for this purpose, the energy production was programmed through optimization and control techniques to minimize the generator's fuel costs during operation. The control of the hybrid system was evaluated in two scenarios. In the first, the "continuous" operation control of the generator was analyzed, and in the second, through "on/off" sequences. As analysis criteria, it was considered to minimize the cost of operation of the hybrid system while maintaining the optimal flow of energy, considering the intermittency of energy in the SF, the SOC of the battery, and the charging demand. The study's results demonstrated significant operating savings in this type of system (Kusakana, 2015).

Another alternative to using converters that have proven to have good results is the development of a self-balancing multistage DC-DC boost converter for photovoltaic applications (Bhaskar et al., 2017). With this topology, unidirectional energy transfer is guaranteed in scenarios where it is required to increase the voltage without magnetic components (without transformer and inductor).

In this case, the output voltage from renewable sources is low and must be expanded using a DC-DC converter for photovoltaic applications. Among the advantages of this topology stands out the fact that they are free of magnetic components (without transformer and inductor); the use of continuous input current, capacitors, and low voltage semiconductor devices; modulation capacity; the facility to add a more significant number of levels to increase the voltage gain and the use of only two control switches with alternating operation and simple control.

## 6. EFFECTS OF POWER QUALITY ON EM

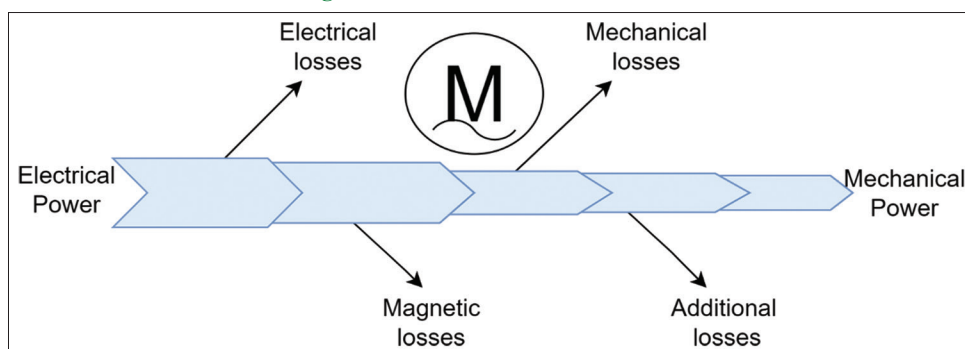
EM are machines that convert electrical energy into mechanics to drive applications such as pumps, fans, compressors, and conveyors. In EM, losses inevitably arise during electromechanical conversion, when a certain amount of energy is irreversibly transformed into heat. Figure 8 shows that these are divided into electrical, magnetic, mechanical, and additional losses.

Electrical losses depend on electrical current squared, so it increases rapidly with increasing load. Magnetic losses occur in the steel sheets in the stator and rotor due to hysteresis and eddy current phenomena and vary with flux density and frequency. Mechanical losses are due to machine bearings and ventilation system friction. In contrast, additional losses occur mainly due to stray flow, non-uniformity in current distribution, mechanical imperfections in the air gap, and irregular air gap flux density (Sousa Santos et al., 2019).

Harmonics and their associated problems in the operation of EM have been of interest since the 1920s. In 1929, this phenomenon was addressed as unnecessary noise in electrical devices. In the 1950s, researchers began to address the severe problem of induction machine losses caused by harmonics due to the increasing number of induction machine applications with power supplies based on static frequency converters (Rawcliffe and Menon, 1952). In the 1960s, additional magnetic power losses in MES due to voltage waves with harmonic frequencies were evaluated (Jainy, 1964).

Studies have shown that each harmonic voltage order has its effects that can be divided into three general categories: (1) insulation voltage; (2) thermal stress; and (3) interruption (Gnaciński et al., 2019). Regarding the voltage variation, the NEMA MG-1 standard

Figure 8: Power flow in electric motors



(Motors and Generators, 2016) establishes that the EM will operate correctly under operating conditions with a voltage variation of  $\pm 10\%$  and a frequency variation of  $\pm 5\%$ . For its part, IEC 600034-1 standard (International Electrotechnical Commission, 2014) allows two different operating ranges: a  $\pm 5\%$  variation for continuous operations and a  $\pm 10\%$  variation for intermittent operations. The tolerance in the standards is due to the voltage variation's influence on the operation and efficiency of the EM.

The voltage variation and frequency variation directly influence the magnetic losses of the induction EM (Saidur, 2010), which, in turn, represent around 15% of the total losses of the motor operating at full load (Bonnett et al., 2016). The worst operating condition of the EM is when it is powered at low voltage at a load greater than 70% since the steady state current increases, and consequently, the operating temperature increases. Instead, some overvoltage (less than 5%) can decrease EM heating as slip falls, and as a result, efficiency can improve, even though the power factor decreases and starting current increases.

The voltage variation also directly influences the torque/speed characteristic of the EM, such that, with the increase in voltage, the torque and speed also increase, and vice versa (Mehazzem et al., 2017). The variable nature of generation in PS and the use of electronic devices in their operation cause power quality problems such as harmonic distortion and voltage deviation that directly affect the operation of EM. Due to the high incidence that EM have, as one of the primary consumers of the electrical system, PS's influence on their operation should be included.

## 7. CONCLUSION

The analysis based on state-of-the-art shows the challenges that the massive penetration of PS implies for electric power systems and EM. The studies demonstrate the affectation that PS has produced in the operation of distribution circuits, mainly due to the variability in the availability and production of energy, the problems of frequency regulation, the generation of harmonics, and the instability of reactive power generation.

The article showed how companies in the energy sector and various research centers had directed their efforts toward the technological improvement of PS components to mitigate the problems indicated. The power converter is the most studied component for its crucial function in controlling and synchronizing the energy generated by the SF when coupled with the electrical networks.

Studies were presented that evaluate the affectation in the operation of the EM when it is fed from networks with power quality problems, demonstrating that harmonics and voltage regulation are the power quality problems that most affect their operation.

None of the studies presented analyzes the direct influence that PS can have on the operation of EM. Considering the importance of these charges and the reduction in the energy that can be derived from the PS, this work intends to call the scientific community's attention to develop research focused on this problem. It is also

proposed that the aspects analyzed be considered in developing new generation projects with photovoltaic systems.

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