Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Special Issue: Energy in Agriculture

Scientific Paper

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43nepe20220156/2023

VOLTAGE REGULATION IN RURAL NETWORKS WITH DISTRIBUTED GENERATION

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KEYWORDS

electric power systems, voltage control, power quality.

ABSTRACT

The increase in distributed generation (DG) interferes with the energy distribution system, which may present low voltages due to voltage drops and high voltages due to the insertion of distributed generation, resulting from renewable energy sources in rural areas. These voltage levels must be controlled to comply with the limits imposed by the distribution rules and procedures (PRODIST). This study aims to evaluate the voltage rise caused by DG, simulating three DG insertion scenarios, as well as simulate strategies to correct these voltage levels, such as the limitation of the active power supply, the reactive supply by the consumer and the utility, and the installation of on-load tap changers. The simulations were performed using the MATLAB® program, more specifically the PSAT toolbox. Correction techniques were simulated using the active power supply limitation method, the reactive power supply method by consumers, and the voltage regulator process once the voltage rise effect was identified. The first two proved to be ineffective in this case, while the last one meets the voltage levels required by the National Electric Energy Agency.

INTRODUCTION

Electric power systems (EPSs) are divided into three main parts: generation, transmission, and distribution. Generation converts other types of energy into electrical energy and injects it into the transmission grid, which transports this power to locations where it is needed and delivers it to the distribution grid, which distributes the energy to consumers. However, part of this energy is lost during this path, generating a voltage drop. It occurs because the lines have a certain characteristic impedance, which is intrinsic to the material used in the construction and size of the line. Voltage in some places at the ends of distribution lines can reach critical levels, especially in rural areas, as they are far from substations. Another factor that contributes to this phenomenon is the radial predominance of distribution networks, with no interconnections with other distribution systems, as occurs in ring systems (Rawa, 2018).

In Brazil, the National Electric Energy Agency – ANEEL is responsible for regulating and inspecting the electricity sector, and created rules and procedures for the electricity distribution system – PRODIST (Machado et al., 2020). Module 8 refers to the quality of electrical energy, showing the parameters that must be controlled by the utilities to guarantee the quality of energy, one of them consisting of the steady-state voltage level of the distribution system (Silva et al., 2021). The ways used to solve this problem of voltage regulation are the installation of voltage regulators and capacitor banks (Zhou et al., 2019). Switched capacitor banks serve to compensate for the inductive reactive energy present in the system (Xue et al., 2017). The large concentration of new generators with the growth in the use of distributed generation, mainly with the rise of renewable energy sources, will produce an increase in voltage, which may exceed the minimum levels required by PRODITST (Almeida et al., 2015).

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Area Editor: Juliana Lobo Paes
Received in: 8-31-2022
Accepted in: 1-5-2023

The Ministry of Mines and Energy (MME) of Brazil estimates that renewable energies represented 84.8% of the total electricity production in the country in 2021, with the wind source representing 8.8% and the solar source 1.7 %, being expected to reach 13% and 4%, respectively, by 2030 (Marchetti & Rego, 2022). The high concentration of generators can cause problems such as overvoltages, phase unbalance, as well as protection and stability problems (Hossain et al., 2018). Brazil still does not have a significant portion of distributed generators, but it is a future trend, and studying the effects that a high concentration of generators causes on the network is important so that problems that have occurred in other countries that already experience this reality can be anticipated when this becomes a reality in Brazil (Almeida & Jota, 2018).

The PSAT toolbox of the MATLAB® program was used to investigate this problem. The simulated scenarios serve as test models to evaluate the insertion of distributed generation in the buses of distribution systems, showing the voltage levels of the system in each case (Deshmukh & Ahuja, 2022). These simulations also aim to verify the effect of changing the bus voltage of a substation (SE), an effect that is commonly used in the regulation of voltage levels (Weigert et al., 2019). Corrective actions for voltage rises are applied to this same system and a comparative analysis will show how effective each of these compensation strategies is to ensure an adequate voltage level for consumers in the presence of distributed generation. The proposed strategies (reactive handling, voltage drop at the substation and along the line, installation of on-load tap changer (OLTC), and limitation of active power supply) can show how effective they are to mitigate voltage rise.

MATERIAL AND METHODS

The transmission system, which transports the largest amount of energy, is assembled in a grid, thus ensuring that, in the event of a failure in one of the lines, the others can be fed, without interrupting the supply of energy to consumers. The distribution system, both primary and secondary, is usually a radial system (Nweke & Adamu, 2020).

The voltage drop equation for a balanced three-phase distribution network can be obtained by analyzing the single-line diagram in Figure 1.

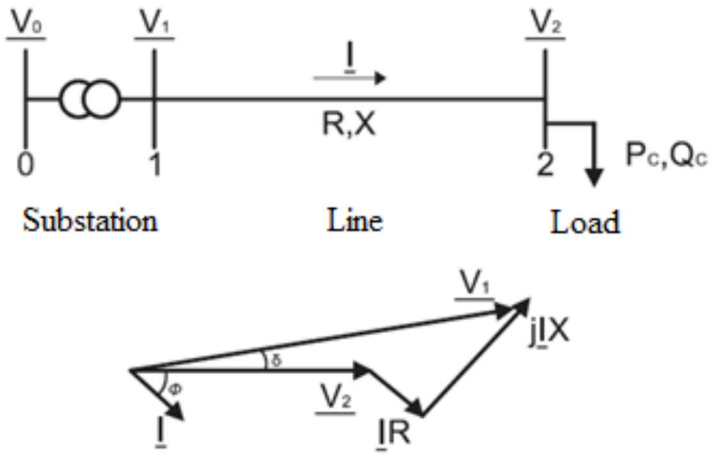

FIGURE 1. Single-line and phasor diagram to illustrate the voltage drop in the distribution system. Source: Mastromauro et al. (2009).

The current phasor (I) and the voltage drop phasor due to resistance influence (RI) are in phase in the phasor diagram, whereas the voltage drop phasor due to line reactance (jX) is ahead by 90° relative to the current. The voltage drop that occurs on the line is given by the difference in voltages at buses 1 and 2 (Shayeghi & Alilou, 2021).

$$\Delta V = |V_1 - V_2| = |I(R + jX)| \quad (1)$$

$$I = \frac{S_C^*}{V_2^*} = \frac{P_C - jQ_C}{V_2^*} \quad (2)$$

Where S_C is the apparent power in volt-ampere of the load, V_2 is the load bus voltage in volts, P_C is the active power in watts of the load, and Q_C is the reactive power in reactive volt-ampere of the load. Substituting [eq. (2)] in [eq. (1)], we have:

$$\Delta V = \left| \frac{(RP_C + XQ_C) - (XP_C - RQ_C)}{V_2} \right| \quad (3)$$

In which R is the line resistance in ohms and X is the line reactance in ohms. Considering a distribution network and its typical power flow, the angle δ between voltages V_1 and V_2 is very small. Therefore, the voltage drop ΔV is approximately equal to the real part of [eq. (3)] (Mastromauro et al., 2009), as described by [eq. (4)]:

$$\Delta V = \frac{(RP_C + XQ_C)}{V_2} \quad (4)$$

The steady-state voltage level must remain within the limits established by technical standards. Table 1 shows the limits of the primary distribution network. Table 2 shows the limits for the secondary network.

TABLE 1. Steady-state voltage classification range for the primary distribution network (1–69 kV).

Distributed voltage (DV)	Reading voltage (RV) variation range relative to the reference voltage (R)
Adequate	0.93R≤RV≤1.05R
Poor	0.90R≤RV≤0.93R
Critical	RV<0.90R or RV>1.05R

TABLE 2. Steady-state voltage classification range for the secondary distribution network (220/127V).

Distributed voltage (DV)	Reading voltage (RV) variation range
Adequate	(202≤RV≤231)/(117≤RV≤133)
Poor	(191≤RV≤202 or 231<RV≤233)/ (110≤RV<117 or 133<RV≤135)
Critical	(RV<191 or RV>233)/(RV<110 or RV>135)

Voltage stability is related to the operational and construction characteristics of the line. Equations (3) and (4) show that each and every load connected to the system causes a voltage drop in conventional distribution systems, leading the voltage profile to drop to the end of the line.

The equipment used to fulfill this function, considering that the power flow only flows in one direction and the voltage decreases downstream of the substation, consisted of on-load tap changers – OLTCs – and shunt capacitors (Castro et al., 2022).

Considering that in Figure 1 a bank of capacitors was injecting reactive energy $Q_{Capacitor}$ in the load bus, the voltage drop can be approximated by [eq. (5)].

$$\Delta V = \frac{\left(RP_C + XQ_{Load} - Q_{Capacitor}\right)}{V_2} \tag{5}$$

The connection of distributed generation (DG) in the system requires to be evaluated, as this system was not originally designed for such a function, which causes concern for utilities, as it may cause damage to their own equipment and that of their customers (Castro et al., 2022).

The value of the voltage deviation due to the insertion of a generator in the distribution network is given by:

$$\frac{dU}{|U_N|} = \frac{(P * R) + (\pm Q * X)}{|U_N|^2} \tag{6}$$

Where:

P and Q are the generator active and reactive power,

R and X are the network resistance and reactance,

U_N is the voltage supplied by the SE bus, and

dU is the voltage deviation of the connected generator.

Equation (6) shows that the active power will always contribute to raising the voltage module, and the higher the resistive portion of the network impedance, the higher this contribution will be. On the other hand, the reactive power can either increase or reduce the voltage module.

The presence of a DG leads to an increase in the voltage level, which can cause the voltage at this point to become higher than the substation voltage, thus inducing a reverse flow to the connection point with the medium voltage electrical network (Torres & Tiba, 2019).

The system voltage level increases when the power level generated and injected by DG into the distribution network is higher than the power consumed by the load (Hasheminamin et al., 2015). Transformers try to correct this phenomenon by switching their TAPs.

Reactive supply is also a strategy, which allows power distributors to require generators to supply reactive power to the distribution network (Li et al. 2021). Sources belonging to utilities or large consumers, such as dynamic reactive compensation devices, static compensators, and even capacitor banks are traditionally used when reactive power is needed. This need to generate reactives is not only for controlling the voltage level. This power is required in the system for the operation of motors and transformers.

Simulations of the behavior of the electrical system were carried out through the insertion of distributed generation along a radial distribution system to analyze the phenomenon. Three insertion scenarios were simulated, seeking to understand how the penetration level of distributed generation can affect the voltage levels of a system. The MATLAB® software was used in the simulations through a toolbox called PSAT.

The IEEE 33-bus model, which is usually used in simulations of radial power distribution systems to study voltage stability (Alayi et al., 2020), was used.

Three different scenarios for insertion of distributed generation were considered, and these generators were randomly distributed, namely:

a) Without DG.

b) DG in 75% of the system buses.

c) DG in 100% of the system buses.

The most common types of DG nowadays are photovoltaics. Photovoltaic systems for maximum production are designed to supply and even exceed the consumed load so that credits are left to the user. These consumers become generators at this time and can be called prosumers, following international standards. They inject power into the system instead of consuming it. Taking this into account, the simulations considered that each load where there is a DG at the moment of maximum production starts to inject a value 20% above the consumed power.

Mitigation strategies were implemented in this system to analyze the relationship with the original system and compare all strategies, thus allowing evaluation of the effectiveness of each one.

No generator is present in the distribution system in the first simulation. Therefore, all buses in the system only consume electrical power. This scenario is the basis for comparison in situations in which distributed generation is present.

At first, the voltage on the substation bus (Bus 1) is considered 1.00 pu but a voltage of 1.05 pu was also considered on the substation bus, which is a usual value and ensures that the consumers that are farthest from the substation also receive an adequate voltage value.

Figure 2 shows the system voltage profile without distributed generation and its natural voltage drop along the branch, with substation bus voltages of 1.00 pu and 1.05 pu, respectively.

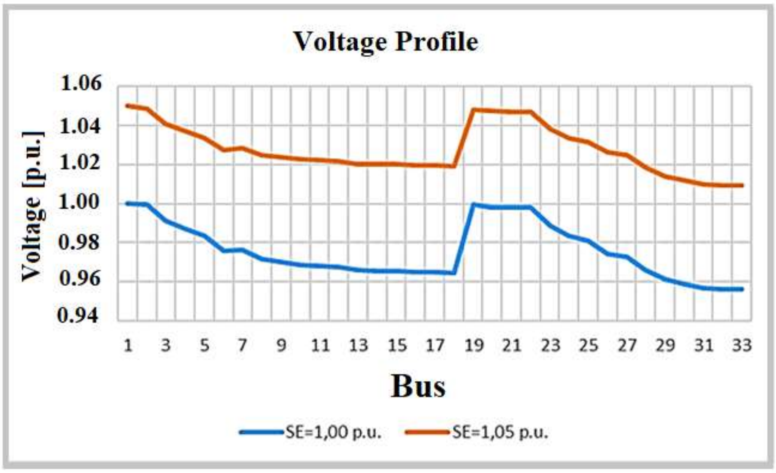

FIGURE 2. System voltage profile without distributed generation.

Figure 3 shows the three-dimensional heat graph with the voltage magnitudes in the system, demonstrating that the connection of generators to the system can cause voltage increases and reach limits above those established.

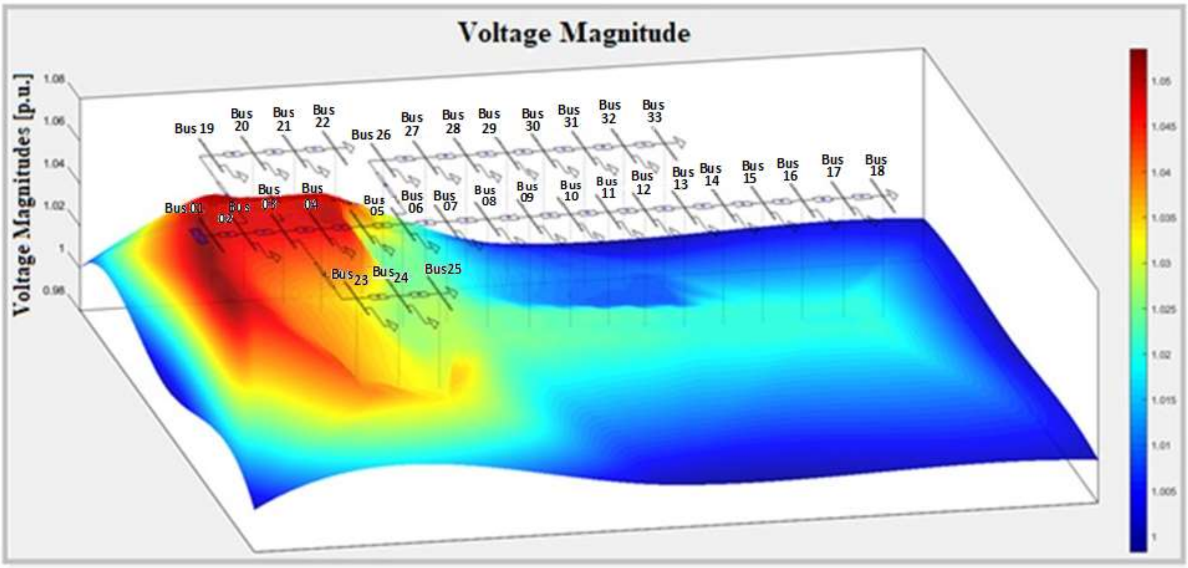

FIGURE 3. Heat graph of voltage magnitudes on the substation bus equal to 1.05 pu.

RESULTS AND DISCUSSION

For a generation scenario in 75% of the system buses, which is a high concentration of distributed generation, 75% of the system buses was considered to have generators connected, producing 20% more active power than the load consumed at their peak hours.

Figure 4 shows that the system does not exceed the tolerance of 1.05 pu in the scenario in which the substation voltage is 1.00 pu even with a high concentration of distributed generation. However, voltage values exceed the maximum limit required by standards when the substation voltage is adjusted to 1.05 pu, reaching up to 1.0999 pu at bus 18.

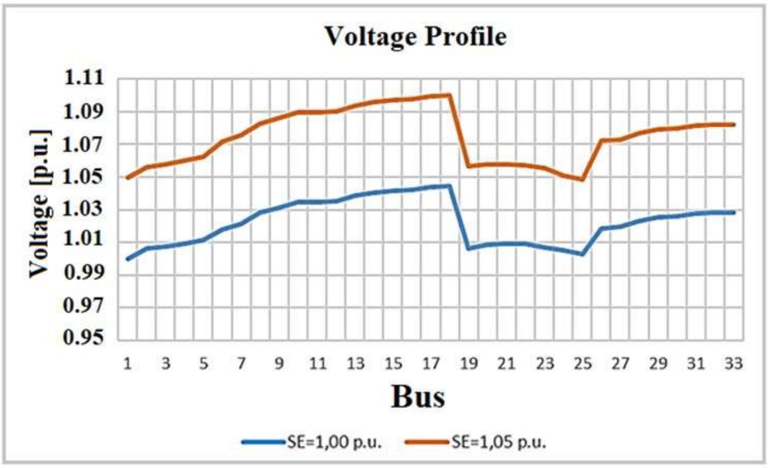

FIGURE 4. System voltage profile with 75% DG.

Figure 5 shows that all system bus voltages are limited to 1.05 pu violated. In the scenario with generation at 100% of the system buses, all system buses have generators installed and the system only supplies energy to the SE transformer and does not consume it. Figures 6 and 7 show the two SE voltage levels considered in the previous scenarios.

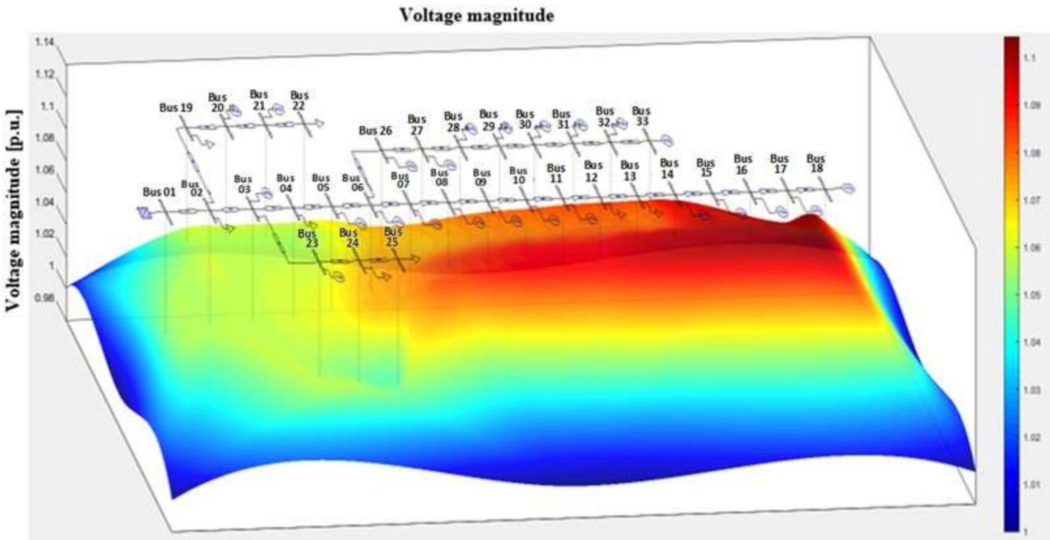

FIGURE 5. Graph of equipotential lines with 75% DG and voltage on the substation bus equal to 1.05 pu.

Thus, in both scenarios shown in Figure 6, the voltage rise caused by the insertion of distributed generation exceeded the voltage limit of 1.05 pu. The higher the injection of active power into the network, the higher the voltage levels. Again, bus 18 showed the highest voltage levels in the system, reaching 1.0615 pu when the SE voltage is 1.00 pu and 1.1135 pu when the SE voltage is 1.05 pu.

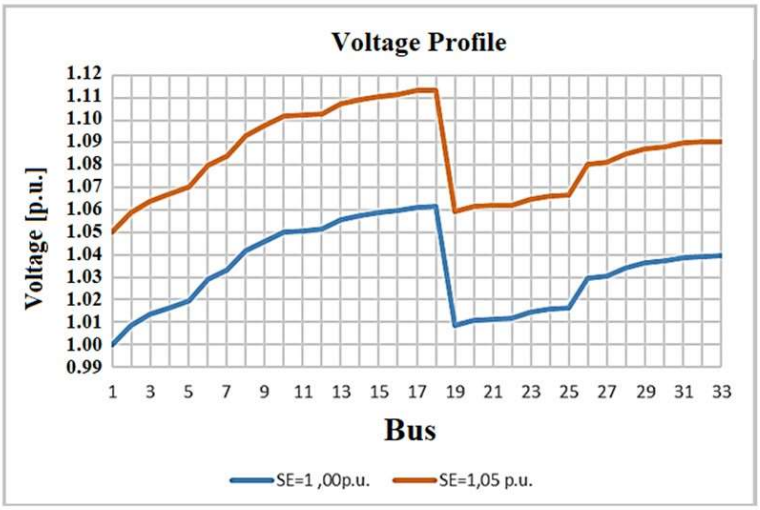

FIGURE 6. System voltage profile with 100% DG.

Figure 7 shows the comparison between the simulation scenarios using the SE voltage of 1.05 pu. The generators make a big difference in the voltage level of the system and mitigating the effects of this voltage rise is necessary to expand the Brazilian energy matrix.

Four simulations are tested to verify which ones represent the solutions for the voltage rise. The used scenario is based on 100% insertion of DG into the system with an SE voltage of 1.00 pu.

The first simulation uses the active power supply limitation method. Generators are used in 100% of the buses in this scenario, with the substation voltage at 1.00 pu and power supplied by each generating unit limited to 70%.

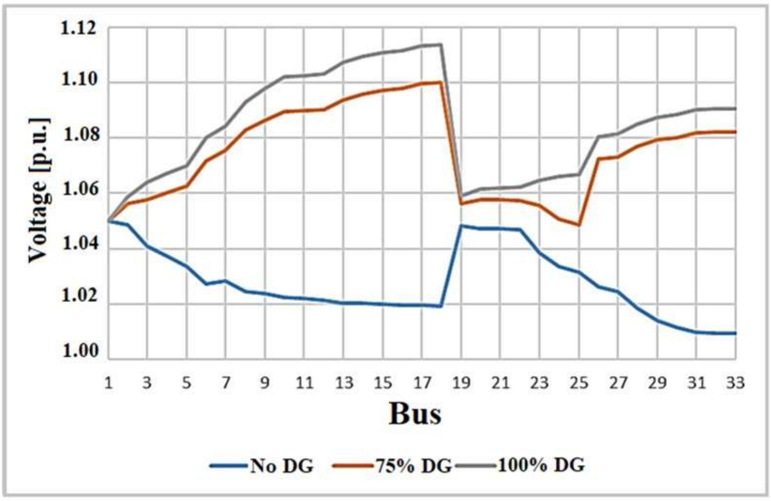

FIGURE 7. Comparison of system profiles.

Figure 8 shows the system voltage level in the scenario described above, with and without the limitation of active power injection by distributed generators. The voltage level presents a slight improvement but this technique acting alone in this system is not capable of maintaining the voltage at the appropriate levels.

The second scenario tests the reactive power supply method by consumers. In this case, reactive power is injected by each generator aiming at an improvement in voltage levels. It happens by changing the power factor of the generating units.

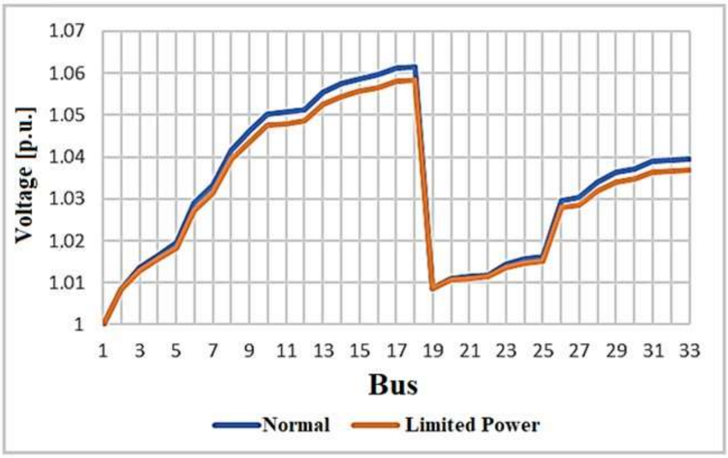

FIGURE 8. Normal and power-limited system voltage profile.

The curve shown in Figure 7 was used in this case to define the operating point of the generators. The chosen power factor was 0.6 for all generators.

Figure 9 shows a significant improvement in the voltage profile when this technique is used. However, the limit of 1.05 pu is still violated in some buses.

The third scenario simulates the supply of reactive energy by the utility.

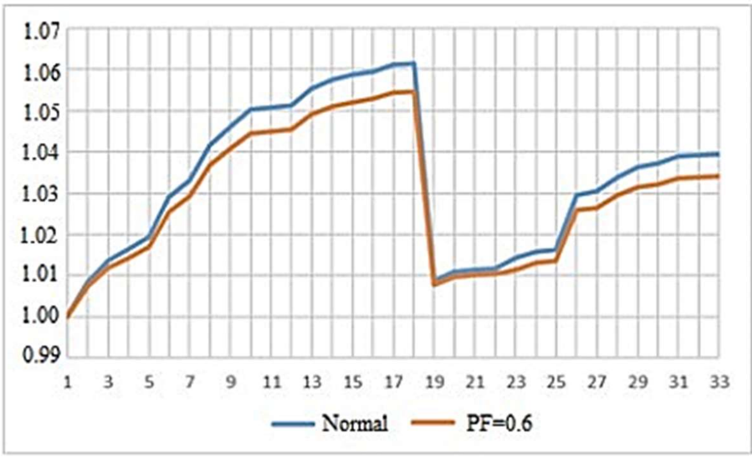

FIGURE 9: Voltage profile with generators with (Power Factor) PF=0.6.

This strategy takes place through the implementation of compensators along the network, coming into operation at the peak hours of active power supply from the generators.

In this case, an inductive reactive compensator with a nominal power of 5 MVA was introduced at bus 10 of the system, as shown in Figure 10.

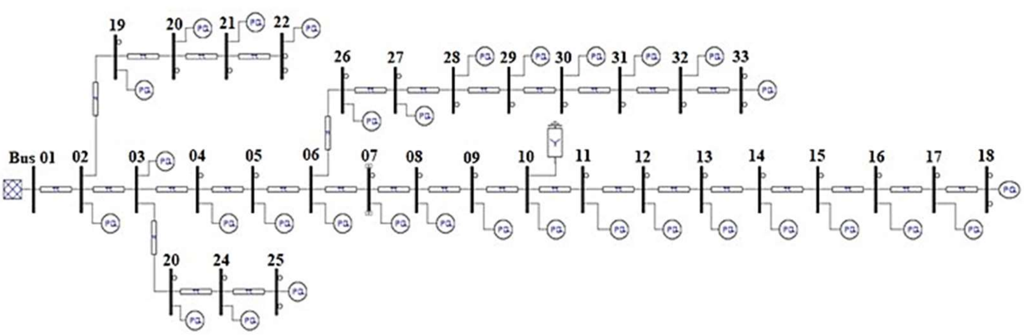

FIGURE 10. Model with reactive compensator allocation.

Figure 11 shows a very significant improvement in the voltage levels of the system. The reactive compensator brought the voltage level down, making the limit of 1.05 pu not be extrapolated on the system buses.

Importantly, this compensator works only at certain times of the day, which can generate some implementation difficulties, as it will be necessary to configure a timed relay or controller. Another problem occurs on cloudy days because the generation does not behave as expected. Therefore, a finer control should be implemented to inject reactive power into the network in power steps and not in a binary way as it was performed.

The third simulated scenario uses the OLTC voltage regulator process. In this case, a voltage regulator was allocated between buses 9 and 10 of the system, where the voltage rose to levels higher than those allowed.

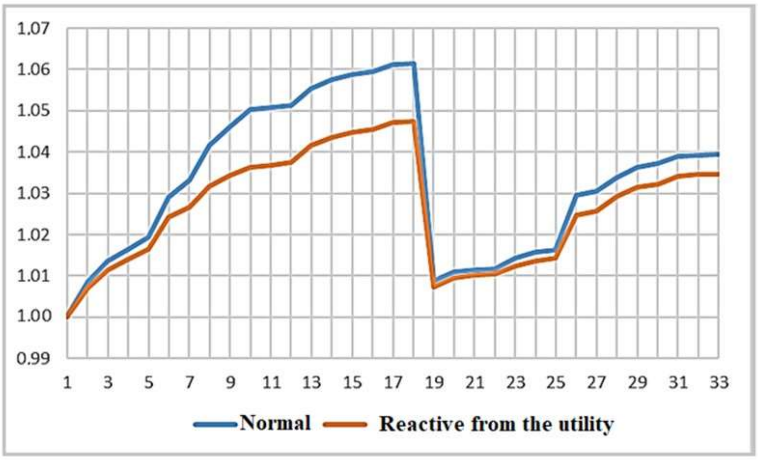

FIGURE 11. Voltage profile with reactive injection by the utility.

Figure 12 shows the voltage profile with an OLTC installed. The 1.05 pu value was not extrapolated at the buses, showing the effectiveness of this method in mitigating the voltage rise. Importantly, the voltage regulator operates continuously, always maintaining the appropriate secondary voltage level for consumption.

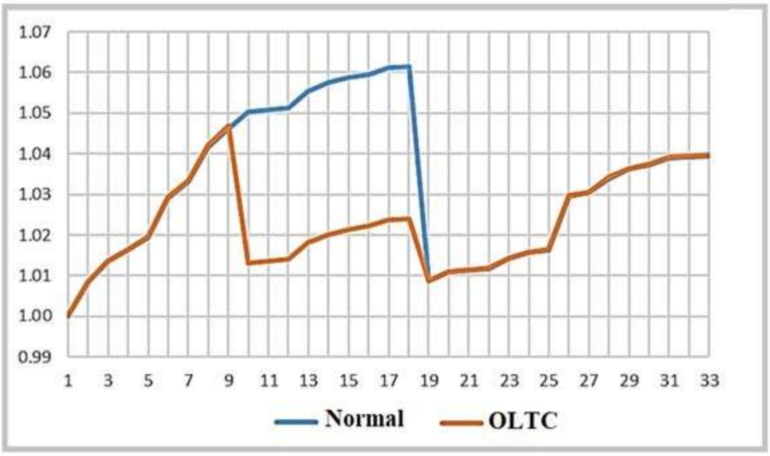

FIGURE 12. Voltage profile with OLTC.

Figure 13 shows the comparison between all strategies for mitigating voltage rise in the system before the insertion of distributed generators. The four strategies combat the problem of voltage rise.

In this case, limiting the injection of active power was not effective because the insertion of generators is already very high. However, this is a strategy that has a low degree of complexity and would work perfectly in scenarios that have less DG insertion.

The choice of the best correction technique must consider technical and economic aspects. Limiting active power injection would cause a lot of loss to the consumer. Making consumers have to inject reactors would also impede new generator connections. The implementation of reactive regulators and compensators does not result in direct costs to the consumer, but it has a higher degree of complexity in its implementation. Thus, the choice of which strategy should be used must consider the pros and cons of each strategy and be implemented jointly if necessary.

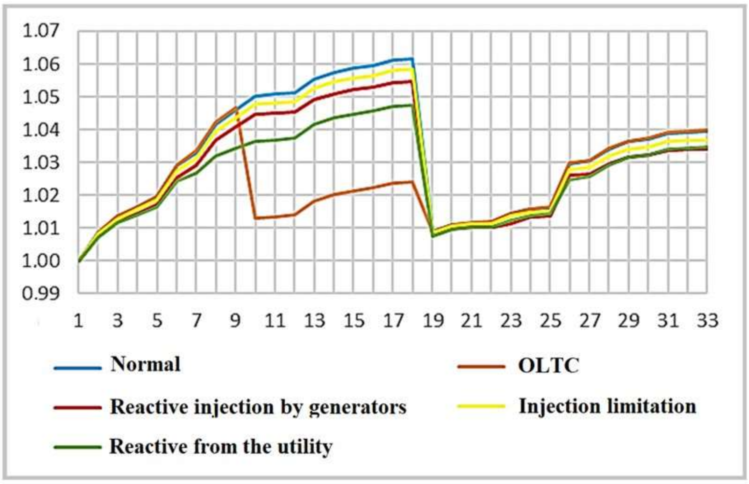

FIGURE 13. Comparison between voltage elevation correction strategies.

CONCLUSIONS

The use of MATLAB® software and the PSAT toolbox allowed simulations of the power flow of a system to be performed simply, being necessary to assemble a model in SIMULINK and upload it in the GUI interface of the toolbox. In addition, bar graphs of the variables resulting from the power flow were generated.

The IEEE 33-bus system, which can be used in voltage regulation studies, was chosen for the simulations. Three simulation scenarios were considered, and the substation voltage was also varied in each of them. The observed voltage rise provided by the insertion of distributed generation can cause the voltage level at certain points of the system to exceed the permitted limits when it is at high concentrations.

The four strategies showed the possibility to reduce the voltage levels but some of them are not effective in the simulated system. Each of these strategies presents its particularities of economic cost and technical complexity to be executed. Economic, political, technical, and customer satisfaction factors must be considered when choosing the appropriate technique.

The trend is that this type of generation will grow a lot in the coming years in Brazil and this study allows us to foresee problems that may occur shortly if this scenario becomes a reality.

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