International Conference on Renewable Energies and Power Quality (ICREPQ'18)
Salamanca (Spain), 21th to 23th March, 2018
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.16 April 2018

A study of voltage rise in distribution grids with high concentration of power generators

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Abstract. The growing demand for electric power together with the environmental agencies pressure for decreasing polluting gases emission are the main causes of the big expansion that Distributed Generation systems have been undergoing lately. This kind of electric generation system allows to produce parts of the electricity power nearby the costumers making energy costs cheaper for final consumer and improving the share of clean sources on the energy matrix. Despite Germany's great experience with photovoltaic plants, Distributed Generation systems are not well widespread around the world. Most governmental regulations about the theme are recent and sometimes do not cover all the specificities, so it has been continuously rewritten. Although Brazilian market has a small concentration of sources connected to the distribution grids, the annual relative growth is significant. High concentration of sources nearby the costumers may cause problems in the operation and in the stability of electric quantities. Some of these problems are voltage rises, harmonics and general damages to electrical equipment. This paper presents the voltage rise effect in distribution grids with high concentration of generators; it also suggests mitigation techniques for this outcome. It becomes clear that is possible to reverse power flow without voltage rise beyond legal limits.

Key words

Distributed Generation, Voltage Rise, Distribution Grids, Photovoltaic Generation, Power Quality.

1. Introduction

The regulation concerning distributed generation in Brazil is mainly composed by the normative resolutions REN 482/2012 and REN 687/2015 written by ANEEL (Electric Energy National Agency) and by the section 3.7, module #3 of PRODIST (National Electric System's Distribution Proceedings). These legislations are responsible for describing and controlling distributed generation (DG) on Brazilian electric system, furthermore it establishes charging criteria for the electric power distribution companies.

Distributed Generation is a recent subject in Brazil and, despite the growing amount of connections, they still represent an insignificant share of national energetic matrix. Although, other countries such as Germany are more developed adopting DGs and alternative renewable electric power sources. According to Stetz et al. [1] on January 2012 Germany had at least 978 thousand implemented photovoltaic plants, this county had developed accelerated growth on its photovoltaic capacity between 2008 and 2012, but there was noticed a slower rhythm after 2012. International experiences about DGs have been contributing to elaborate bibliographies about the side effects of distribution grids with distributed generation connections. These known side effects together with the growth expectancy for the connection amounts motivate the national agencies and power companies to elaborate guidelines for generators connection and grid operation in this new reality.

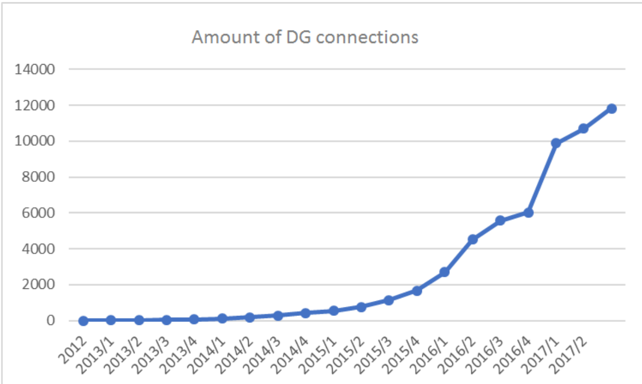

Fig. 1. Amount of DG connections in Brazil [2]

Considering these facts, this paper seeks to present the main problems caused in distribution grids by high concentration of generator connections. Voltage rise is the effect chosen to be shown a more complete approach, with simulations of different scenarios of DGs connected to a trustingly parameterized distribution grid.

2. Side Effects of High Concentration of generator connections in distribution Power Grids

Nowadays Brazilian reality does not present a high concentration of power generators connected to distribution grids. However, the amount of these sources and its installed power are on a stage of increased growth. Then, the side effects provided by the increasing of power feeding in distribution grids must be studied.

The German case of power generators high penetration together with researches about the subject being made around the world evidence the occurring of some effects such as voltage rises and sags, phase unbalance, damage at transformers due to increased number of tap changings, power factor (PF) changing and another side effects [3].

A. Voltage Rise

This is the most noticeable effect of high power generators penetration on a distribution grid. It occurs when active power coming from the distributed generators is greater than the instant load on the same grid and it is not significant when the active power provided by the generators is less or equal than the load on the same grid. Rising the voltage on the Point of Common Coupling (PCC) there is a situation where voltage drop along the grid is reduced and it may result on power flow reversing. This is an unusual operation mode when power flows from the load to the electrical substation and may cause damages on existent equipment [3].

Nowadays, this side effect is largely studied on academic and industrial field, it is important to stablish a grid PV penetration capacity. The study presented on [4] states that voltage rise problem limits the maximum PV penetration in a network, due the stablished voltage limits, it also presents the effect occurring from a simplified electric model. Another study [5], presents a simulation of a grid with PV penetration varying from 20% to 100%, the simulation was able to prove the effect occurring.

Considering a simplified model, shown on Fig. 2, where the distribution grid is represented by an impedance Z; U_N is the voltage at the substation; dU is the voltage rise or sag; and I is the current from the power generator. It is possible to obtain the value of voltage rise or sag from the value of generator's apparent power, as presented by Stetz et al. [1].

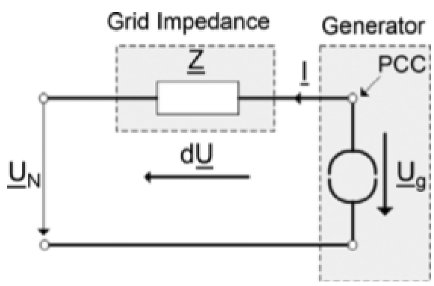

Fig. 2. Simplified model of a generator on a distribution grid [1]

Then,

$$\frac{dU}{|U_N|} = \frac{Z \cdot I}{|U_N|} \quad (1)$$

The current I, from the generator is given by

$$I = \left(\frac{S_{PV}}{|U_N|}\right)^* = \left(\frac{P}{|U_N|} - j\frac{Q}{|U_N|}\right) \quad (2)$$

$$Z = R + jX \quad (3)$$

in which S_{PV}, P and Q are the apparent, active and reactive power injections. R and X describe the resistive and reactive portions of grid impedance.

Replacing (2) and (3) in equation (1), this one can be rewritten as:

$$\frac{dU}{|U_N|} = \left(\frac{(P \cdot R) + (\pm Q \cdot X)}{|U_N|^2} + j\frac{(P \cdot X) - (\pm Q \cdot R)}{|U_N|^2}\right) = dU_D + jdU_Q \quad (4)$$

in which dU_D is the real value of voltage rise or sag and dU_Q is the imaginary value.

However, the major part of the generators in distribution grids with distributed generation is photovoltaic, so the imaginary value will be insignificant in PCC voltage, therefore, the dip or sag $\frac{dU}{|U_N|}$ can be written as in (5).

$$\frac{dU}{|U_N|} = \frac{(P \cdot R) + (\pm Q \cdot X)}{|U_N|^2} \quad (5)$$

Therefore, voltage rises will occur when distributed generators are injecting active and reactive power, or when there is simply an injection of active power on the grid. The reactive consumption may cause voltage sags at low values of PF.

B. Other Impacts

Despite of Voltage Rise being the focus of this paper and the most noticeable impact of high concentration of power generators on a distribution grid, other impacts may come together and must be considered.

Patil et al. [3] paper lists some impacts caused by high penetration of photovoltaic generators on a distribution grid. Few of them such as improvements in transformers life cycle and isolation can be considerate positive. Some others such as phase unbalance, harmonics, DC bias, PF changings, voltage flicker, increased fault current, protection issues and system islanding.

C. Strategies to reduce negative impacts of Distributed Generation in distribution grids

Table I. Implementation status of mitigation strategies for DG impacts on German distribution grids

Strategy	**Implementation status**
Distribution grids reinforcement	Measures and reinforcements such as transformers and conductor exchanges are common practice in Germany
Limitation of active power feeding to 70% of installed capacity	Since 2012, in Germany, it is required to all photovoltaic generators with less than 30 kWp of capacity and without the capability of being remotely controlled.

Voltage limitation by energy buffer	It is not commercially available yet
Reactive power feeding	Since 2012 German power companies can demand reactive power from their customers with generators connected to low voltage distribution grids.
Voltage limitation by automatic active power control	It is not commercially available yet
Voltage limitation by automatic active and reactive power control	It is not commercially available yet
Distribution transformers with on load tap changing (OLTC)	Only first prototypes are developed yet

Stetz et al. [1] and Cappelle et al. [6] suggests in their papers some convenient strategies seeking to reduce voltage rise on grids with high penetration of DGs. These strategies are shown on Table I together with their respective implementation status.

The simulations presented in this paper seeks to demonstrate some of these strategies: Limitation of active power feeding; Reactive Power Feeding (by customers and by energy company); Voltage Regulators in the place of the OLTC prototypical solution.

3. Simulation

The simulation was made with OpenDSS and Matlab, using programs developed by Castro [7] and Oliveira [8] with some modifications seeking to acquire the results shown on this paper.

The grid of this simulation is parametrized from a distribution grid of a medium-sized Brazilian city, with majorly residential and commercial customers. It was adopted 4 consumption profiles, a commercial one and 3 residential profiles, each one with a different consumption time plot. Electric and geographic data were in a .kmz file.

OpenDSS does not support bars as a code input, then it demanded creating distribution lines, informing which bars were between them. Each transformer of the simulated system refers to a time plot of these 4 consumption profiles. Also, there is a Vθ bar, set in 1,05 pu voltage guaranteeing that far located customers do not receive voltage measures out of Brazilian legislation limits. Transformers and generators were input on the code as devices connected to the bars previously created from the distribution lines. Monitors were situated to measure simulated electrical quantities on each bar, the data were stored in .csv files and read with Matlab to present the charts.

A. No Distributed Generation scenario

There are no generators connected to the distribution grid in this first simulating scenario. This scenario is a previous analysis and allows to being made comparatives with the next ones.

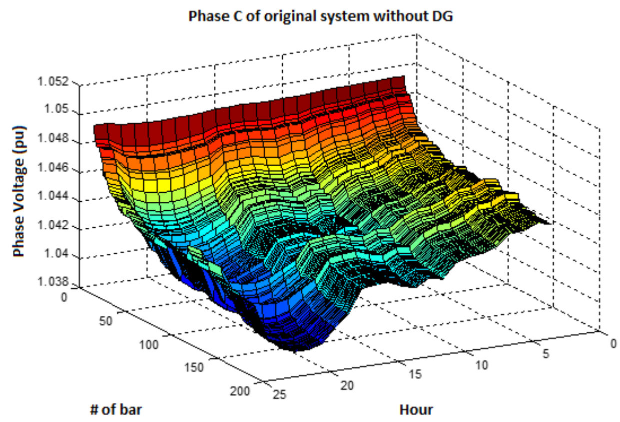

Fig. 3. Voltage profile on the original distribution grid

From Fig. 3 and Fig. 4 it is characterized the normal working condition of the simulated system, from the substation to the last bar and during a complete day.

The identification number of each bar grows as the distance from the electrical substation increases. Therefore, knowing that:

$$P_{km} = \frac{V_k V_m}{x_{km}} \sin(\theta_k - \theta_m) \quad \textbf{(7)}$$

in which P is active power, V is voltage, x is line impedance, θ is voltage angle and k and m are the bars. As expected, power flows from the electric substation to the grid ending in this scenario.

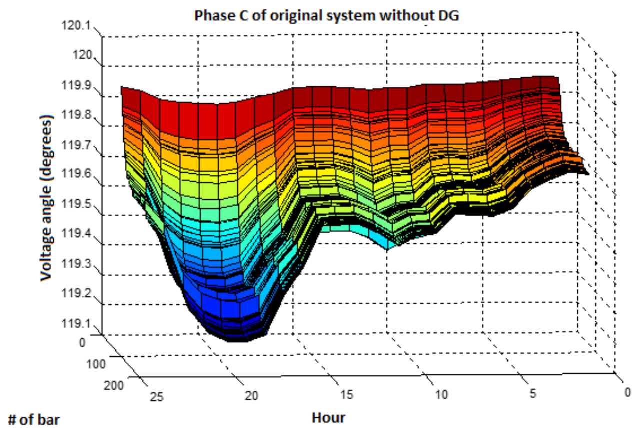

Fig. 4. Voltage angle profile on the original distribution grid

B. Scenario with Distributed Generation

DG was implemented by 4 different simulations, present at 75% and at 100% of the customers, also, there were made a scenario which generators were feeding power with a capacity equal to 100% of the load capacity and another one with 120% of the load capacity. Fig. 5 presents the most extreme possibility, when there is DG at 100% of the customers and all of them are feeding power with 120% of the load capacity. The voltage peak around 12 p.m. occurs due to the photovoltaic generation peak that is unsynchronized with the power demand peak.

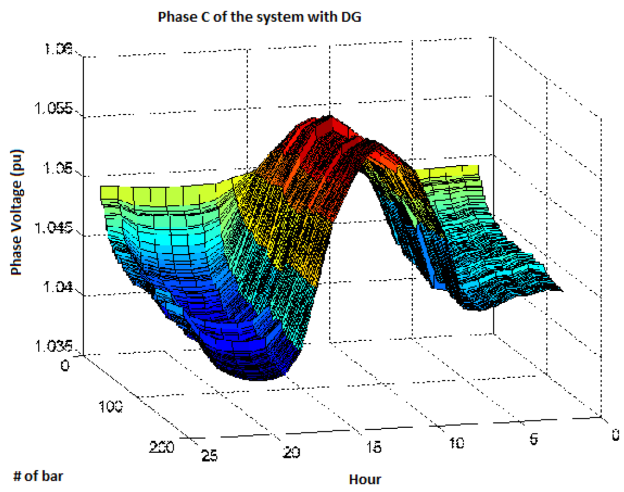

Fig. 5. Voltage profile on the original distribution grid

Fig. 6 presents the reverse power flow, between the substation (bar #1) to the grid (bar #2) that occurs around 12 p.m.

The results shown in Table II allows to acknowledge the direct ratio between voltage rises and active power feeding. The maximum rise was seen at bar #161, the farthest from the substation.

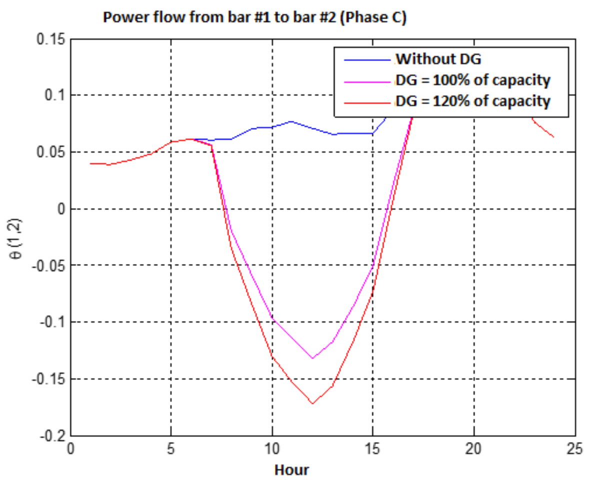

Fig. 6. Reverse power flow between bars #1 and #2

Table II. Summary of Scenarios (Phase C)

Scenario	75% DG; 100% capacity	75% DG; 120% capacity	100% DG; 100% capacity	100% DG; 120% capacity
Bar	#161	#161	#161	#161
V (pu)	1.0514	1.0533	1.0548	1.0573
Angle (degrees)	120.547	120.744	120.907	121.174

4. Mitigation strategies implementation

A. Limitation of active power feeding

This simulation was made stablishing a generation limit at 70% of the load capacity. Is was able to bring voltage levels under legal limits (1.05 pu), as shown in Fig. 7, but there were smaller voltage rises along the grid due to the unsynchronized consumption and generation plots.

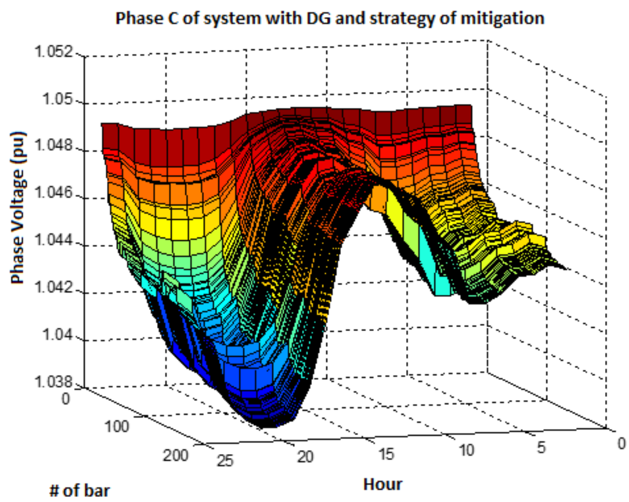

Fig. 7. Voltage time plot with strategy A

B. Reactive Power Feeding by customers

This simulation was made changing the Power Factor of generator units, this way the reactive feeding time plot will be the same as the active feeding one.

It must be acknowledged that most photovoltaic currently produced and already working are not able to generate reactive power. Although, German regulation allows energy companies to demand reactive power from DGs. The most common compensators cannot be continuous controlled as in this simulation without a complex control system.

The found results show that DGs feeding active and reactive power is an effective strategy limiting voltage rises as shown in Fig. 8.

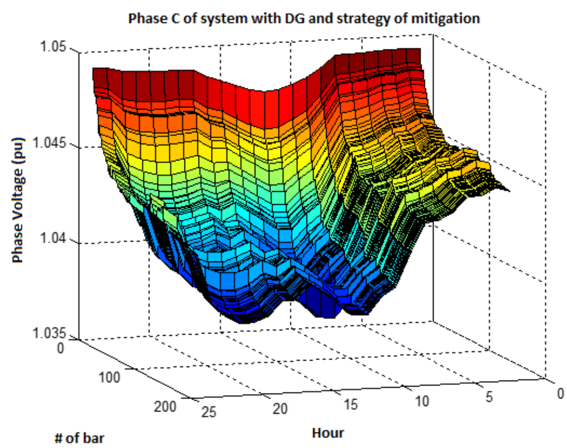

Fig. 8. Voltage time plot with strategy B

C. Reactive Power Feeding by energy company

This strategy, despite feeding reactive power from each DG unit, it feeds from one or few bigger compensators located along the grid. In this simulation there was set a compensator nearby the bar with the biggest voltage rise, this compensator is an ideal inductance and works with a binary time plot, feeding reactive power only in hours of high solar incidence. This were also effective reducing voltage levels under 1.05 pu as seen in Fig. 9.

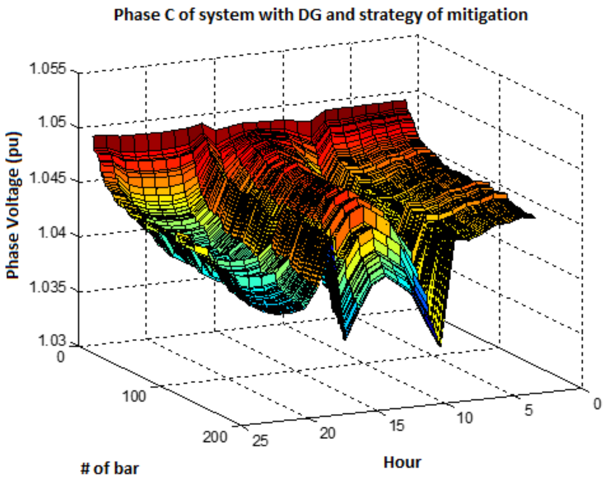

Fig. 9. Voltage time plot with strategy A

D. Voltage Regulators

The simulation was made considering the implementation of 3 voltage regulators along the grid, nearby regions with higher voltage rises. It was also an effective strategy to bring voltage levels under the legal limits as shown in Fig. 10.

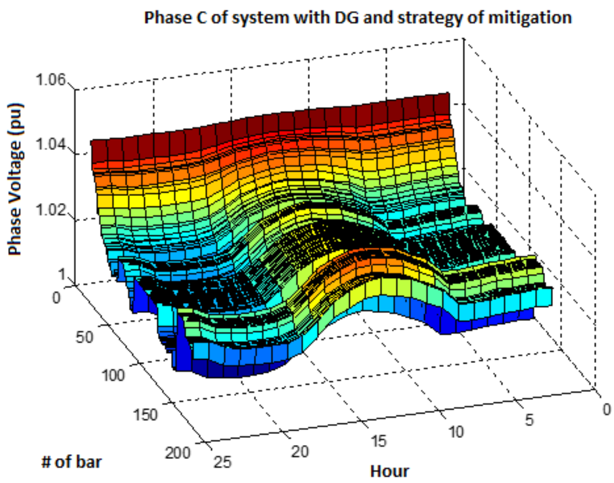

Fig. 10. Voltage time plot with strategy D

5. Conclusion

The four strategies simulated have shown themselves capable to work effectively reducing voltage rises caused by high concentration of DGs.

Therefore, it is possible to conclude that voltage levels are controllable to values compatible with the legislations. This control could be made with low effort strategies such as limiting power feeding or with more complex ones, such as reactive compensators with the same time plot as active power feeding.

All of these strategies that have been simulated were able to reduce voltage rises, but the active power flow is still going from DGs to substation in all of them. It means that DGs were still feeding the substation after solving voltage rise problem.

Technical and economic aspects should be considered choosing the most appropriate strategy for each circumstance. Limiting the active power feeding may harm customers in systems where high DG penetration is already real. Although, demanding reactive power from the customers may increase the costs of DG setting. Bigger compensators, set by energy companies together with another grid reinforcement costs could be dilute between costumers with DGs connections, making them more satisfied, since there are no individual requirements. Then, this choice should be made considering pros and cons, together with the opportunity cost of the deprecated options.

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