Fault Ride Through Capability and Voltage Support in Distribution Grid With Photovoltaic Distributed Generation

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Abstract — **When connected to the power distribution grid, Distributed Generation Photovoltaic (DGPV) systems not only contribute to supply the load demand, but can also assist the grid performance by means of several ancillary services, notably in voltage support after a voltage drop. Main current grid codes and international standards require DGPV units to remain connected even in the event of severe voltage sag. In order to minimize the impacts on the distribution grid, the photovoltaic sources can be used to inject reactive power. This paper discusses the main aspects related to voltage support using DGPV sources and proposes a voltage control architecture, considering the contribution of each DGPV unit and using a distributed communication infrastructure.**

Index Terms — **Distributed Generation, Fault Ride Through Capability, Photovoltaic, Voltage Support**

I. Introduction

The insertion of distributed generation photovoltaic (DGPV) sources in electricity distribution systems is constantly increasing around the world. Reported international experiences present important contributions for the market expansion analysis, gains in production scale and cost savings for investors. According to data from the Solar Power Europe [1], the cumulative global installed capacity of photovoltaic power in 2014 reached 178 GW, with at least 40 GW installed globally in this last year. Europe still leads the global market with over 88 GW installed, representing 50% of the world's capacity, followed by Asia Pacific (40 GW) and China (30 GW). Solar Power Europe Studies indicate a growth for PV generation of approximately 218 GW in a moderate scenario and 362 GW in a political driven scenario at a horizon of 5 years (2015 to 2019).

Changes in the distribution grid caused by DGPV have positive and negative impacts for energy service providers and consumers. The operation of these sources may cause reverse power flow in the network, which has historically been designed in a unidirectional architecture, causing power quality disturbances (over-voltages, loss of frequency stability, harmonics grow, etc.). Additionally, physical and logical configuration changes in grid protection schemes may be required.

Because photovoltaic sources have reached a significant level of penetration on both the local and regional level, it is very important to mitigate the potential impacts caused by the inherent variability of these distributed generators. At the same time, ensuring the continuity of these resources, especially during the occurrence of grid events, can increase system availability.

Specifically, the issues related to voltage support by using distributed photovoltaic generation during occurrence of faults in the grid have been a challenge. Some voltage regulation techniques using reactive power support by PV sources have been tried. These include methods based on local voltage measurements, local power injection measurements or a combination of both [2]-[4]. Moreover, due to the high *R/X* values in LV networks, the effect of reactive power is limited. In this way, local active power curtailment methods are proposed [5],[6].

This paper first analyses the voltage regulation in distribution grids with DGPV sources. Following, the fault ride through capability requirements from different grid codes are mapped. From these requirements, it presents a proposal of a voltage support strategy during grid disturbance using DGPV. Finally, a simulation environment was designed to analyze the voltage support sensibility using photovoltaics sources.

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II. Voltage Regulation in Distribution Grids With DGPV

The connection of PV arrays in the distribution grid can affect the normal power flow conditions on the network and can alter the voltage profile along the feeder, as the network is no longer a passive circuit as in traditional networks.

Fig. 1 shows a representation of a two-node system by its Thevenin equivalent with the presence of a photovoltaic generator connected to the load bus.

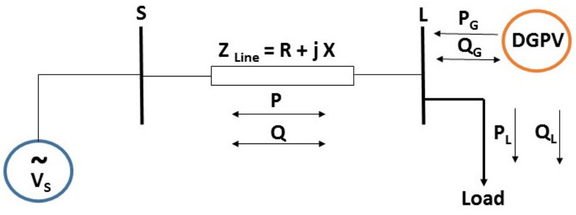


Fig. 1. Two-Node Equivalent Distribution System with DGPV Source

Analysing the diagram shown in Fig. 1, it is possible to predict the electrical grid behaviour with DGPV under different operating conditions. First, assume that the photovoltaic system is not generating power, $P_G = 0$, and that the load is inductive. In this case, the power grid will supply the load, and the current will flow in the forward direction, *i.e.*, from **S** node to **L** node. The current intensity will depend on the P_L and Q_L power demanded by the load. As the power demanded by the load increases, the voltage drop in the line becomes greater. Consequently, the voltage on the **L** node is smaller than the voltage on the **S** node. With the photovoltaic system generating power, the current in the line becomes dependent on the difference between the power generated by the DGPV unit and the power consumed by the load. When the active power generated by DGPV is less than the power consumed by the load, $P_G < P_L$, the line current still flows from **S** node to **L** node. However, because the photovoltaic system partially supplies the load, the current in the line is lower than the current in the scenario without DGPV. In this situation, the voltage on **L** node is higher than the previous case. When active power generated by DGPV is greater than power consumed by the load, $P_G > P_L$, the line current is reversed, flowing from **L** node to **S** node. Consequently, the voltage on the load node V_L becomes higher than the voltage on the supply node V_S, $V_L > V_S$.

In the latter case where $V_L > V_S$, the voltage difference between node **L** and node **S** can be described by (1).

$$\Delta\bar{V} = \bar{V}_L - \bar{V}_S \approx \frac{RP+XQ}{\bar{V}_L} \quad (1)$$

where R, X, P and Q denote, respectively, the line resistance, line reactance and the active and reactive power flow.

Considering that the angle variation between the **L** and **S** nodes is very small and that node **L** is a reference node, *i.e.*, the voltage amplitude is $V_L = 1$, then the voltage variation is summarized in (2):

$$\Delta V = \bar{V}_L - \bar{V}_S \approx RP + XQ \quad (2)$$

where $P = (+P_G - P_L)$ and $Q = (\pm Q_G - Q_L)$

The DGPV exports active power$(+P_G)$ and can export or import reactive power$(\pm Q_G)$, while the load consumes active power$(-P_L)$ and reactive power$(-Q_L)$. According to [7], for an **n-nodes** distribution system, when connecting a DGPV unit in the j^{th} node, the voltage variation $\Delta\bar{V}_{ji}$ at the photovoltaic connection point can be written as (3):

$$\Delta\bar{V}_{ji} \approx \frac{R_{ij}(P_{Gj}-P_{Lj})+X_{ij}(\pm Q_{Gj}-Q_{Lj})}{\bar{V}_j} \quad (3)$$

Considering the case where the power injected by the photovoltaic source is maximum and the load is null (minimum load condition), (3) can be rewritten as (4):

$$\Delta\bar{V}_{ji} \approx R_{ij}(P_{Gj}) + X_{ij}(\pm Q_{Gj}), |\bar{V}_j| = 1 \quad (4)$$

In this way, the voltage variation between two node (ji) will reduce if the second term of (4) takes small positive values or negative values, which depend on the injection or absorption of reactive power by DGPV.

To enable a significant penetration of photovoltaic sources and to minimize the problems related to voltage variation, without the need of large investments to reinforce the distribution grid, it is necessary to adopt grid codes that consider the capacity and flexibility of PV inverters in the ancillary services, to ensure grid stability.

In this context, the following section discusses several voltage regulation strategies, through reactive power compensation techniques using DGPV systems connected to the distribution grid.

III. Fault Ride Through Capability

The occurrence of short circuits in the electrical grid can cause disturbance on the dynamic safety operation of power systems, resulting in grid generator disconnection and, consequently, the loss of significant amounts of energy production necessary to supply the loads.

Until recently, standardization and grid codes adopted by the main countries with intensive use of photovoltaic generation forced the immediate disconnection of DGPV after the occurrence of a voltage disturbance on the distribution grid. However, to avoid improper disconnection of DGPV in cases of voltage sag, some current national grid codes are adapting in order to require the DGPV sources to be resilient during abrupt voltage drops. This under voltage supportability requirement, caused by faults in the electrical grid, is defined as Fault Ride Through Capability (FRTC). The FRTC is described by a characteristic "voltage x time", which indicates a minimum immunity of photovoltaic generators during these disturbances.

For example, according to the German grid code [8], short circuit (phase-ground, phase-to-phase or three-phase) should not cause the disconnection of the DGPV during a period of 150 ms, even to a voltage drop to 0% of rated voltage. According to Fig.2, for any voltage sag values presented above the line, the DGPV must remain connected and contribute to voltage level recovery.

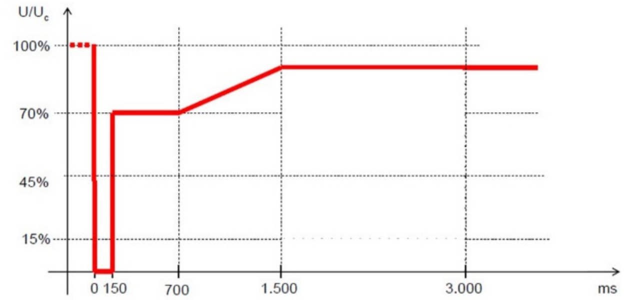


Fig. 2. Fault Ride Though Capability – Germany Grid code [8]

The Brazilian standard ABNT 16149 [9] also requires for DGPV supportability against under voltage, as illustrated in Fig. 3.

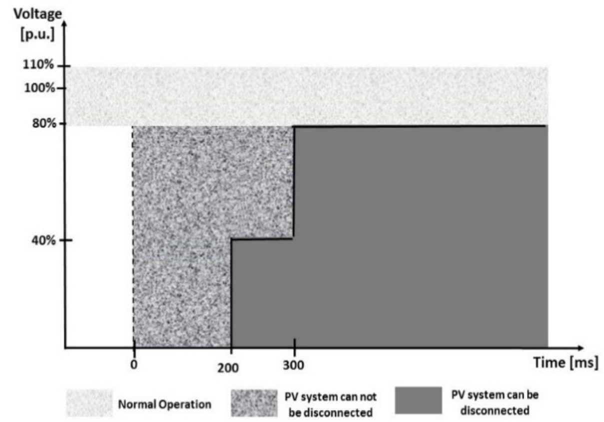


Fig. 3. Fault Ride Though Capability – Brazilian PV Standard [9]

In the hatched area, for voltage sag between 0% and 80% of rated voltage, the PV system cannot disconnect from the grid within 200 ms, but is allowed to cease power supply. If the voltage returns to normal operating range (- 20% to + 10% of rated voltage), the PV system should return to inject active and reactive power with pre-fault values, with a tolerance of ± 10% of the DGPV rated power.

IV. Voltage Support Strategy During Grid Disturbance Using DGPV

A. *Voltage Support Capability*

In order to provide voltage support to the power grid during voltage sags, some grid codes require that DGPV sources increase reactive power generation, by injecting reactive current in their connection point. This functionality is intended to support the electrical grid against steep voltage sags, preventing disconnection of generation sources and loads. Thus, the DGPV sources must combine their resilience to the disturbances and, concomitantly, contribute to the mitigation of voltage sag severity.

The work presented by [10] has compared electric grid codes in different countries The German network code determines that DGPV sources provide additional reactive power to the grid during a power failure, or an extra consumption of reactive power in the case of voltage fluctuation. The voltage control must be applied no later than 20 ms after the fault recognition. According to Spanish grid code, distributed generation sources should stop producing active power in less than 100 ms after a power failure and must be able to inject active power 150 ms after the grid restoration. British grid code procedures specify that DGPV sources should inject the maximum of reactive current as possible, in case of voltage drop caused by disturbances in the network. The Portuguese grid code requires an immediate injection of reactive power with minimum values of 90% of the nominal current when the voltage level drops below 0.5 p.u. After disturbance clearance, the DGPV should return to pre-defined values according to normal operation. In Brazil, although FRTC functionality is required, there is no specific requirement to support voltage control under fault condition in the distribution grid.

B. *Q(U) Method*

The $Q(U)$ is a voltage regulation method used by DGPV sources to establish the voltage regulation in distribution grid with distributed generation. In this method, the calculation of reference reactive power injection for each DGPV unit depends on the voltage magnitude at the connection point. The main advantage of this method is the use of information regarding the local voltage value during the regulation process. The reactive power absorption/injection by each DGPV unit is proportional to the voltage level at the connection point. This method is illustrated in Fig. 4.

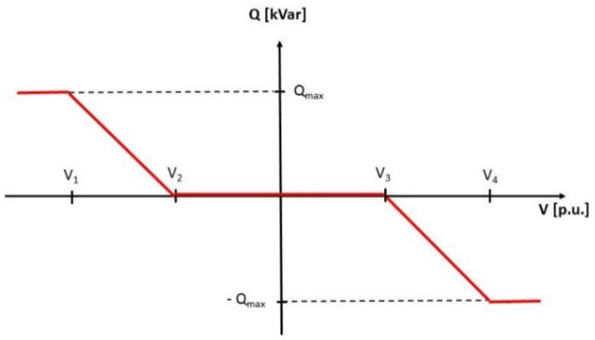


Fig. 4. $\boldsymbol{Q(U)}$ Method – Characteristic Curve

When the voltage measured at the connection point is within a comfortable variation range ($V_2 < V_{measured} < V_3$), no reactive power, Q, is absorbed or generated by DGPV. V_1 and V_4 voltages represent the maximum values of under-voltage and over-voltage tolerated, as determined by the grid code. If $V_{measured} < V_1$ *or* $V_{measured} > V_4$, the maximum injection/absorption of reactive power, $\pm Q_{max}$, in/from the grid is observed. For voltage values measured at the connection point between V_3 and V_4 and between V_2 and V_1, the absorbed or injected reactive power will be a percentage of Q_{max}. Equation 5 summarizes the algorithm for the $Q(U)$ method [11].

$$Q_{ref} = \begin{cases} Q_{max}\,; & V_{meas} < V_1 \\ \dfrac{Q_{max}}{V_1 - V_2}(V_{meas} - V_1) + Q_{max}\,; & V_1 \le V_{meas} \le V_2 \\ 0; & V_2 < V_{meas} \le V_3 \\ \dfrac{Q_{max}}{V_3 - V_4}(V_{meas} - V_3)\,; & V_3 < V_{meas} \le V_4 \\ -Q_{max}\,; & V_{meas} > V_4 \end{cases} \quad (5)$$

V. Voltage Support Simulations and Results

A simulation environment based on PSCAD® and MatLab® computer platforms was designed to analyze voltage support using DGPV, under conditions of fault in the distribution grid. The PSCAD is used to model the power distribution network and simulate the electrical system in the time domain. The power flow calculation is performed in MatLab.

The *Q(U)* method is used to calculate the reactive power injection rate by each DGPV source after voltage disturbance. Fig. 5 shows the distribution network designed for this study.

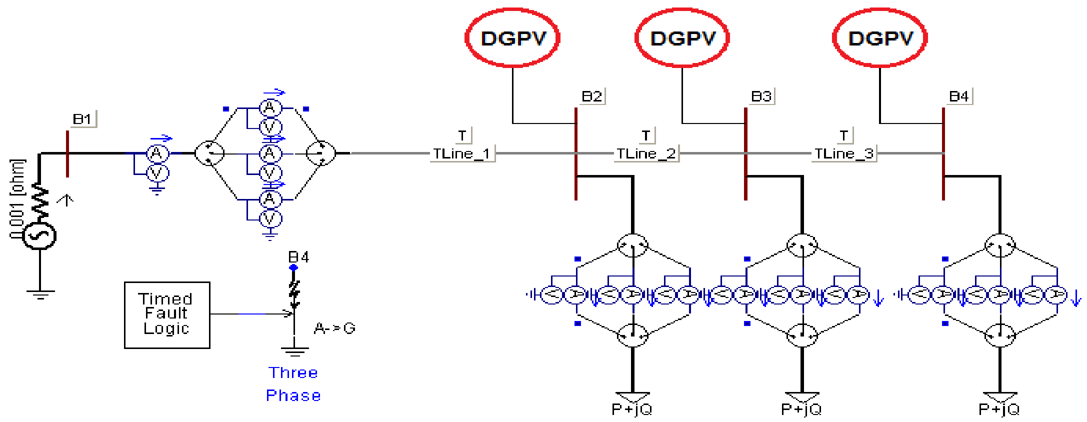


Fig. 5. Distribution Network Modeling for Voltage Regulation Support Simulations

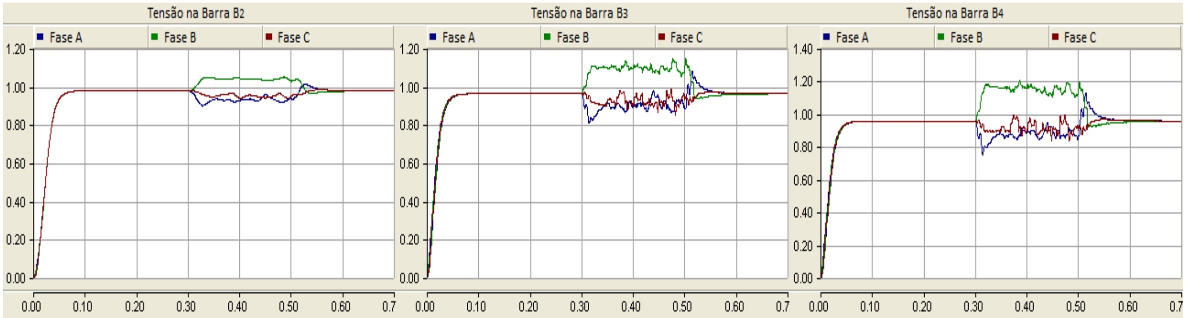
The network is based on a transmission line model available on PSCAD. It consists of a 13.8 kV three-phase voltage source, 3H5 tower and transmission line with 3 chukar type conductors. B_1 is the slack node. DGPV sources of 1 MVA and loads are connected at B_2, B_3 and B_4 nodes. The block "*Timed Fault Logic*" defines the type, the moment and the duration time of the fault applied on the power grid.

Four fault levels have been established for simulation, which parameters are defined in Table I. As the photovoltaic inverters have maximum injection current limit, the reactive power supply capability by DGPV sources will decrease as the intensity of the voltage sag increase.

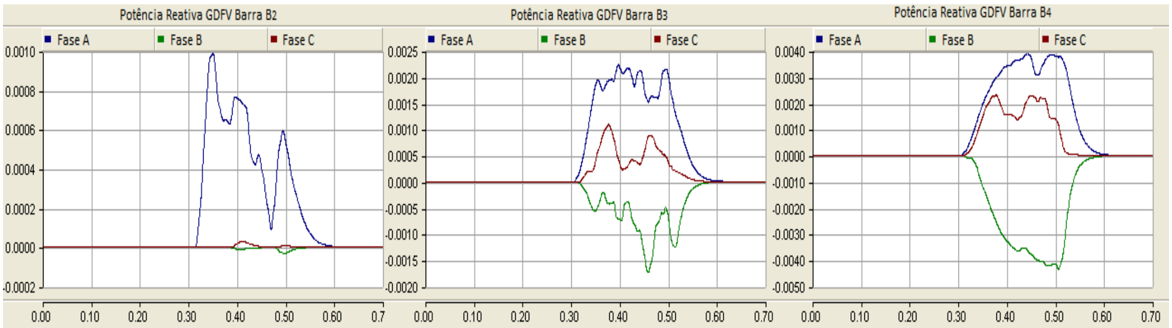
TABLE I
FAULT PARAMETERS

Fault	Characteristic
Type	phase-ground (phase A)
Local	B_4 Node
Occurrence time	300 ms (after simulation start)
Duration	200 ms
Level (% $V_{Nominal}$)	75%, 58%, 38% and 17.5%

As an example of voltage support by DGPV sources, the Fig. 6 shows the results of three-phase voltage variation in B_2, B_3 and B_4 nodes and the reactive power injected/absorbed by respectively DGPV sources during a phase-ground fault to 75% of $V_{nominal}$. Table II presents the values of three-phase voltage and the reactive power injected/absorbed by DGPV sources for all different levels of phase-ground faults.



(a) Three Phase Node Voltages



(b) Three Phase Reactive Power Injection/Absorption

Fig. 6. Three-phase Voltages and Reactive Power Injection/Absorption by DGPV During Phase-Ground Fault Voltage Sag to 75% of $V_{nominal}$

TABLE II
THREE-PHASE NODE VOLTAGES AND REACTIVE POWER FOR DIFFERENT VOLTAGE SAG LEVELS

Voltage SAG		Node Voltages [p.u]								
		Node B_2			Node B_3			Node B_4		
		Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C
17.5%	without DGPV	0.686	1.055	1.45	0.384	1.14	1.108	0.175	1.255	1.19
	with DGPV	0.81	0.98	1.036	0.55	1.13	1.031	0.245	1.24	1.13
38%	without DGPV	0.734	1.066	1.014	0.505	1.155	1.045	0.38	1.27	1.092
	with DGPV	0.806	1.042	0.97	0.62	1.11	1.016	0.54	1.23	1.13
58%	without DGPV	0.8	1.064	0.984	0.651	1.14	0.985	0.576	1.245	0.99
	with DGPV	0.9	1.04	0.93	0.83	0.9	1.11	0.83	1.21	0.926
75%	without DGPV	0.88	1.046	0.963	0.794	1.1	0.935	0.751	1.18	0.914
	with DGPV	0.934	1.028	0.948	0.92	1.076	0.922	0.877	1.12	0,9
Voltage SAG		DGPV Reactive Power Injected / Absorbed [p.u]								
		Node B_2			Node B_3			Node B_4		
		Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C
17.5%		450	0	0	481	-365	-90	236	-314	-314
38%		424	0	0	426	-418	0	432	-256	-432
58%		420	0	0	424	-317	39,3	431	-324	0
75%		98	0	0	222	-172	109	393	-431	230

As observed in Table II, for the most severe voltage sag (17.5% of $V_{nominal}$), the voltage recovery supported by DGPV sources is limited. The voltage increased by only 7% in phase A of B_4 node. In this situation, due to the reactive power limitation, the DGPV sources are incapable of increasing the voltage at connection point to appropriate levels during fault period.

In cases where the voltage sags on phase A of B_4 node reached 38% and 58% of nominal voltage, the reactive power injected by DGPV increased the voltage by 16% and 25%, respectively.

For less severe voltage sag (75% of $V_{nominal}$), the voltage values in most of the nodes is regulated within grid code limits ($0.93\ p.u. \leq V \leq 1.05\ p.u.$). In this case, the DGPV sources do not reach their maximum reactive power injection capacity. The voltage in phase A of the B_4 bar is an exception. Although the voltage increase by 12.6% after the DGPV sources performance, its value remains below the reference limit during the fault period.

The over voltage that occurs in phases not affected by fault is caused due to mutual inductance effect. The DGPV sources also try to adjust these over voltage level by absorbing reactive power during fault period.

V Conclusions

The continuous improvement in efficiency and cost of photovoltaic technology indicates a high penetration scenario of these generation sources in distribution grids. Photovoltaic sources, in addition to supplying the load demands, can be used for ancillary services, including voltage regulation at the connection points.

The FRTC requirements request DGPV units to remain connected even in the occasion of severe faults in the electric grid. The photovoltaic sources can contribute to voltage support after occurrence of a disturbance, but it is necessary that they operate with a very fast response time (<20 ms). Considering the potential contribution of other units distributed along the feeder, a dynamic and integrated coordination is only possible using a communication infrastructure that enables the interaction of these sources with the supervisory and control system.

This work contributes with a co-simulation of distribution and communication network, performed with a special arrangement using PSCAD, for electric grid, and MATLAB, for communication system. The simulations showed that DGPV sources can support voltage regulation in less severe voltage sag scenarios in distribution grids.

Acknowledgment

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