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An Enhancement of Low-Voltage Distributed Photovoltaic Systems Oriented to Fault Ride through Capability

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Abstract

According to grid guidelines the photovoltaic inverter is required to maintain the running status even the grid voltage drops and needs to have the ability to contribute towards the stability of the power grid and support the grid voltage ride through. A distributed generation photovoltaic (DG-PV) systems on low-voltage distribution networks has brought up many problems regarding their performance in case of network transients. The analysis was conducted to critically review the literature on expected technical problems related to high penetration levels of grid tied PV systems. A sudden stoppage of one or more PV systems due to transient phenomena may contribute to grid disturbances. The standards of PV systems are increasing services under the transients also. The future PV systems have to provide a full range of services same as the conventional power plants. A low-voltage ride-through (LVRT) concept is under grid faults and grid support service. The design principles that DG-PV units must integrate in order to meet the requirements of the low - voltage ride through capability (LVRTC) are examined through detailed theoretical analysis and calculations. The analysis shows that over-sizing of interfaced inverters of DG-PV and appropriate selection of the equivalent interconnecting reactance XDG, in conjunction with high penetration levels, can lead to agreement of LVRTC demands without violating the protection limits of the network. Moreover the consequence of uniform dispersion along the distribution lines is proving rather favorable concerning the demand of LVRTC for voltage selectivity. Finally, considering the derived outcomes, a methodology of optimum design about LVRTC is proposed within the structure of reasonable constraints, which can be applied to any low-voltage distribution network.

Keywords: DG-PV, LVRTC, Reactance X_{DG} ,Optimum design of PV.

I. INTRODUCTION

Research of grid connected photovoltaic systems (PV Systems) has gained great interest in the recent years. Due to this, new guidelines have been set up for connection of PV Systems including guidelines for fault tide through or low voltage ride through (LVRT) capability. The PV systems are larger share of supply portfolio, they are required to stay operational and not disconnect from the grid supporting the grid with reactive power during and after voltage sags. Such requirements are known as Fault Ride-Through (FRT) or Low Voltage Ride-Through (LVRT) capability. Low voltage ride-through is a condition required to the PV Systems when the voltage in the grid is temporarily reduced due to a fault or large load change in the grid. The required low voltage ride-through (LVRT) behavior is defined in grid codes. In this paper, a survey on recent LVRT solutions for PV Systems is discussed. LVRT capability must be provide to PV Systems as high penetration level of power to grid. In this paper, the necessary inverter over-sizing is thoroughly investigated in order to meet LVRTC requirements. The effects of LVRTC application on LVDG-PV(Low Voltage Distributed Photovoltaic systems) systems are discussed in this paper, focusing especially on the case of high PL. In this paper, the inverter design is taken into account and the investigation of PL parameter is extended in terms of meeting the current LVRTC requirements. Moreover, the necessary adjustments that these units have to incorporate are emphasized in order to fulfill these new operational demands, improving so distribution network during disturbances. General LVDG-PV design guidelines are presented, through a detailed theoretical analysis. Finally, an optimum design is proposed regarding the selection of XDG and the higher possible PL achievement, in order to come up effectively against the emerging problems of LVRTC application at the low-voltage network.

II. TERMINOLOGY

PL	penetration level (%)
PV	photovoltaic generator
DGk	distributed generator connected to k-bus

ZLK	the equivalent single-phase load impedance at k-bus (k=1,2,….n) (pu)
ZLVk	the equivalent single-phase line impedance between k-1 and k-bus (pu)
X_{DGk}	the equivalent single-phase series reactance of LVDG-PV generation at k- bus (pu)
Zs	the equivalent single-phase upstream network impedance calculated at low voltage (LV) Side of medium or low transformer (pu)
eDGk	the equivalent single-phase AC voltage source time function of LV-DG generation at k-bus
i	the short circuit bus(i=0,1,…n)
Zk,L,SCi	the equivalent single –phase impedance at k-bus because of the upstream network in case of three-phase short circuit at i-bus (pu)
ZkR,,sci	the equivalent single –phase impedance at k-bus because of the downstream network in case of three-phase short circuit at i-bus (pu)
Zk,sci	the equivalent single –phase impedance at k-bus because of the total network in case of three-phase short circuit at i-bus (pu)
EDGk	the vector representation of eDGK (pu)
PDGk	the nominal active power injection of DGk at k-bus (pu)
IDGK	the rms nominal phase current of DGk at steady state (pu)
IDGk,SCi	the contribution to fault current vector of DGk at steady state (pu)
Vk	the nominal phase to ground voltage at k-bus (pu)
δK	the power angle between EDGk and Vk (rad)
Vk,sci	the voltage vector at k-bus in case of a three-phase short circuit at i-bus (pu)
Vk→k,sci	the voltage contribution vector of DGk at k-bus in case of three-phase short circuit at i- bus(pu)
Isc(t)	the short circuit current waveform in case of three-phase short circuit at i-bus(pu)
∑PDG	the total generated active power of DG-PV units (W)
∑SLOAD	the total load demand of the distribution network (kVA)
VjLVk	the rms-voltage value at jLVk-bus (j=1,2,….,6)
Sc_1LVi	(k=1,2,…6 in case of a three-phase short circuit at i-bus (i=1,2,…6)(pu)
IDGk-tr	the maximum transient current capability of DGk converter during disturbance,equal to 2.8 times the IDGk(pu)
dk	the ratio of DGk converter over-dimensioning (OD) in relation to IDGK

ODk	the necessary over-dimensioning percentage of DGk
ODlimit	the optimization constraint value of OD factor (%)
Isc	the ratio of the bus short-circuit current in the examined network to the short circuit current if there is not any installed DG in network (pu)

III. LVDG-PV DESIGN GUIDELINES ACCORDING TO LVRTC

Low voltage ride through (LVRT) means that the time when the grid voltage drops, the PV system can maintain to connect the grid .The PV generation system can even deliver certain reactive power to support the grid recovery until the grid comes back to normal, so as to pass through this low voltage time. PV inverters are required to stay connected with the grid when the grid voltage low .Fig. 1 shows typical example of LVRTC standards.

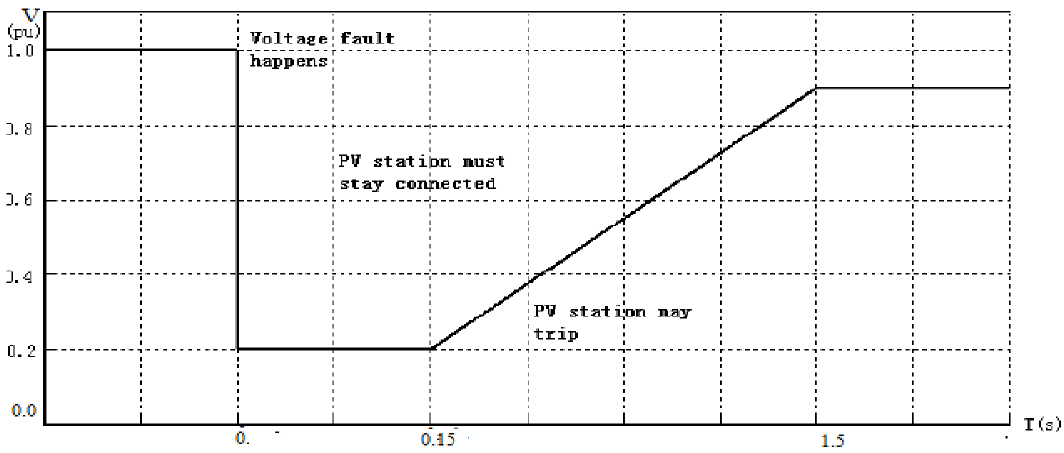

Fig. 1: Typical low voltage ride through requirement

According to Fig.1 is to avoid the unnecessary simultaneous breakdown of multiple generation sources during a network disturbance. In detail generation sources have to stay connected to the low-voltage network for time duration which is a function of their 'electrical distance' from the faulty part of network. The electrical distance is stated by the voltage drop at DG's PCC, and hence the term of voltage selectivity is cleared. In cases of short duration faults, generation loss is limited to the ones being adjacent to the faulty network part. This characteristic is important for the growth of DG-PVs in the direction of high PL realization [1].

The above features imply that the DG units have to obtain the performance of the synchronous generator during a disturbance. By adjusting like a operational behavior of conventional synchronous generators to LVRTC terms, the DG units have to withstand short-circuit currents higher than their nomina current values, since they shall be disconnected after at least 0.15 s (according to Fig. 1), reaching to steady-

state faulty conditions. Hence, it is desirable for the LVDG-PV systems to behave as voltage sources during disturbances instead of acting as constant current sources (given a little amount of more than their nominal AC currents value during disturbances). On the other hand, the LVDG-PV units can be suitably controlled in order to decrease the significant deviation between transient and steady-state currents.
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The LVDG-PV units have to behave as a voltage source in series with a reactance. This means that voltage source inverters are more likely to this type of operational behavior. The current fast response during disturbances, the serious issue in case of a high PL value is a suitable response so as to meet the desired voltage the inverter control signal recollects its pre-disturbance value in order to avoid unnecessary generation divergences in case of short-term disturbances. The equivalent voltage source of the LVDG-PV unit is remains close to its steady-state value (same as conventional generators). Though, if the disturbance duration is longer, the inverter controller is triggered either to moderate the current within safe limits or trip the LVDG-PV unit if the time limit (defined by LVRTC scheme) is exceeded. The inverter control signal maintains its pre-disturbance value in order to avoid unnecessary generation losses in case of short-term disturbances. Hence, the equivalent voltage source of the LVDG-PV unit remains close to its steady-state value (same as conventional generators). If duration disturbance is longer, the inverter controller is triggered either to moderate the current within safe limits or trip the LVDG-PV unit if the time limit (defined by LVRTC scheme) is exceeded.

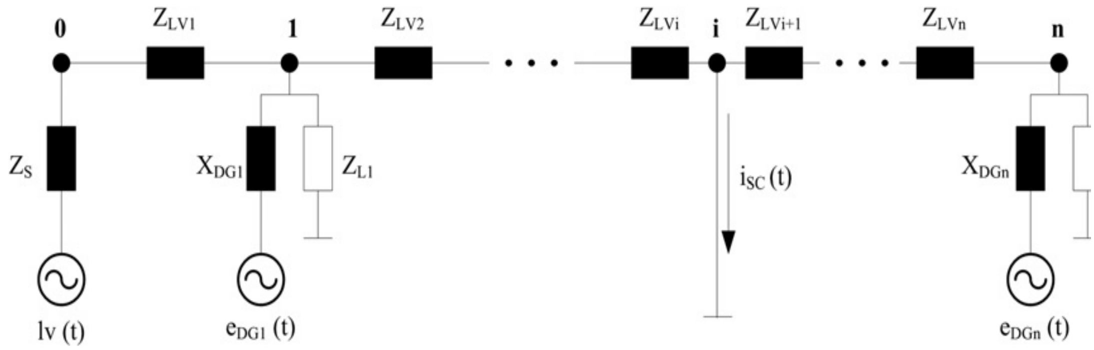

Fig.2 Single-phase equivalent circuit of LV distribution network line with DG-PV units

The design guide lines will be presented based on the general low voltage network form taking into account that all connected LVDG-PV units act as conventional AC voltage sources under faulty conditions (according to the above study). A three-phase low-voltage network with DG-PVs, operating under unity power factor in steady state is considered. If a three-phase short circuit fault occurs at the i-bus, then the single-phase equivalent circuit of Fig. 2 stands. The three-phase short circuit fault is used for dimensioning the network's protection equipment, so the worst case is incorporated[2].

Considering a three-phase short circuit at the i-bus in Fig. 2, the voltage at k-bus is derived from the sum of contributions from all sources. Particularly, for k<i it can be calculated as follows

$$v_{k\to k,SCi\backslash k<i} = v_{k\to k,SCi} + v_{lv\to k,SCi} + \sum_{j=1}^{k-1} v_{j\to k,SCi} + \sum_{j=k+1}^{i-1} v_{j\to k,SCi} \quad (1)$$

for the buses that are on the right side of the short-circuited bus (k > i), the following expression stands

$$v_{k\to k,SCi\backslash k>i} = v_{k\to k,SCi} + v_{lv\to k,SCi} + \sum_{j=i+1}^{k-1} v_{j\to k,SCi} + \sum_{j=k+1}^{n} v_{j\to k,SCi} \quad (2)$$

The calculation of the individual terms in (1) and (2) arises from the superposition principle of source

For k < i

$$v_{k\to k,SCi\backslash k<i} = E_{DGK} \frac{1}{1+(\frac{jX_{DGk}}{Z_{kiSCi}})} \quad (3)$$

$$v_{k\to k,SCi\backslash k<i} = LV \frac{1}{1+\frac{Z_s}{Z_{0,SCi}}} \prod_{j=0}^{k-1} \frac{Z_{j,R,SCi} - Z_{LVj+1}}{Z_{j,R,SCi}} \quad (4)$$

$$v_{k\to k,SCi\backslash j<k<i} = E_{DGj} \frac{1}{1+(jX_{DGj}/Z_{j,SCi})} \prod_{p=1}^{k-1} \frac{Z_{p,R,SCi} - Z_{LVp+1}}{Z_{p,R,SCi}} \quad (5)$$

$$v_{k\to k,SCi\backslash k<j<i} = E_{DGj} \frac{1}{1+(jX_{DGj}/Z_{j,SCi})} \prod_{p=k+1}^{j} \frac{Z_{p,L,SCi} - Z_{LVp}}{Z_{p,R,SCi}} \quad (6)$$

For k > i

$$v_{k\to k,SCi\backslash k>i} = E_{DGk} \frac{1}{1+(jX_{DGk}/Z_{k,SCi})} \quad (7)$$

$$v_{lv\to k,SCi\backslash k>i} = 0 \quad (8)$$

$$v_{j\to k,SCi\backslash i<j<k} = E_{DGj} \frac{1}{1+(jX_{DGj}/Z_{j,SCi})} \prod_{p=1}^{k-1} \frac{Z_{p,R,SCi} - Z_{LVp+1}}{Z_{p,R,SCi}} \quad (9)$$

$$v_{j\to k,SCi\backslash i<k<j} = E_{DGj} \frac{1}{1+\left(\frac{jX_{DGj}}{Z_{j,SCi}}\right)} \quad (10)$$

$$Z_{k,SCi} = Z_{k,L,SCi} // Z_{k,R,SCi} // Z_{Lk} \quad (11)$$

It is worth mentioning that if there is no generation or load at k-bus, from the equations (1) and (2) stand if E_{DGk} becomes zero and X_{DGk} and Z_{Lk} become infinite, for the specific k-bus. Considering that the DG-PVs supply only active power in steady state, the internal voltage of a DG connected to the k-bus is modeled as follows

$$P_{DGk} = \frac{|E_{DGk}| * v_k * \sin \delta_k}{X_{DGk}} \quad (12)$$

The DGs operate under unity power factor, the following equations stand

$$P_{DGk} = V_k * I_{DGk} \quad (13)$$

$$\tan \delta_k = \frac{X_{DGk} * I_{DGk}}{V_k} \tag{14}$$

Combining (14) and (15) the following expressions can be given

$$\tan \delta_k = \frac{X_{DGk} * I_{DGk}}{V_k^2} \tag{15}$$

Finally, from (12) to (15) the E_{DGk} can be extracted as

$$E_{DGk} = \frac{P_{DGk} * X_{DGk}}{V_k * \sin\left(\tan^{-1}\left(\frac{X_{DGk} * P_{DGk}}{V_k{}^2}\right)\right)} \angle \tan^{-1}\left(\frac{X_{DGk} * P_{DGk}}{V_k{}^2}\right) \tag{16}$$

Equation (16) shows that the internal voltage of DG units depends on steady-state parameters at their PCC, that is, the bus voltage and the DG active power.

Finally, taking into account (1)–(16), the DG contribution to a fault current in case of a DG connected to the k-bus is given by

$$I_{DGk,SCi} = \frac{E_{DGk} - V_{k,sci}}{jX_{DGk}} \tag{17}$$

The above calculation set (1) to(17) can be used as a simplified tool for the estimation of the necessary series inductance as well as of the equivalent AC voltage source for each LVDG-PV unit, so as to accomplish the desired voltage drop selectivity. It is clear that generation units that are on the left side of the short-circuit location are in a more appropriate situation, because the voltage at these buses has an additional component because of the upstream network (Vlv→k,SCi).

Therefore the worst case is a short circuit at n −1 bus, since it leads n-bus to its smallest possible voltage level (excluding the short circuit at n-bus itself). For the above worst case, equation set (1)–(11) defines the root-mean-square (rms) voltage at the terminal bus as follows (assuming that |ZLn|≫|ZLVn|).

$$V_{n,SCn-1} = V_{n\to n,SCn-1} = E_{DGn} \frac{1}{1+(jX_{DGn}/Z_{LVn})} \tag{18}$$

Considering that the internal rms-voltage of LVDG-PV unit is approximately1 pu (in order to generate power under unity or marginally leading power factor), we come up with the marginal minimum rms-voltage at a 'healthy' bus.

$$V_{min,rms}(pu) = \frac{1}{d_{min}},\ d_{min} = \left|1 + \frac{jX_{DGn}}{Z_{LVn}}\right| \tag{19}$$

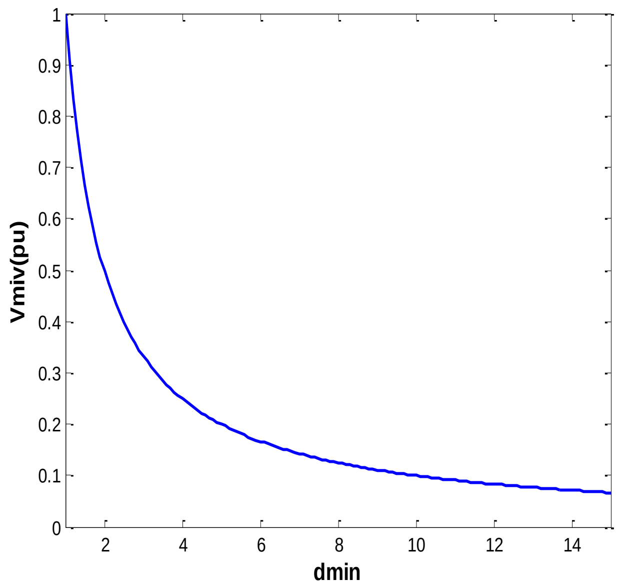

Fig.3. Example of the proposed LVDG-PV design concept for high PL values

Fig. 3 Vmin,rms as a function of dmin in the perspective of a design example, considering a specific LVRTC scheme As it can be observed, by setting dmin value, a minimum voltage level can be achieved in case of a three-phase short circuit at the adjacent bus. More specifically, according to the example of Fig. 3, the selection of dmin below 6.5 guarantees that voltage at 'healthy' buses (even at the neighboring ones) shall always be >0.15 pu and so they have to stay connected for at least 0,625 ms (more than 30 line cycles in 50 Hz systems). In this way, the idea of LVRTC is served and so impermanent faulty conditions would have limited impact on the available DG-PV power production. Of course, the exact definition of dmin has to take into account the corresponding LVDG-PV unit short-circuit level [4].

IV. OPTIMUM DESIGN OF LVDG-PV SYSTEMS

The possibility of DGs' design optimization process is the suitable selection of XDG and PL values in the direction of buses voltages' maintained in the highest possible levels (under faulty conditions). This requirement restricts the impact of the potential temporarily disturbances on the DG-PV power production. It has to be noted that the proposed optimization process is conducted at a given network with equal DG-PV units (same as that in Fig. 4), but it can be simply applied at any distribution network with increased DG-PV penetration. The first step in optimization problems is the definition of an objective function with one or more variables. Through the maximization or minimization (depending on the case) of the objective function, the optimum values for these variables are extracted.

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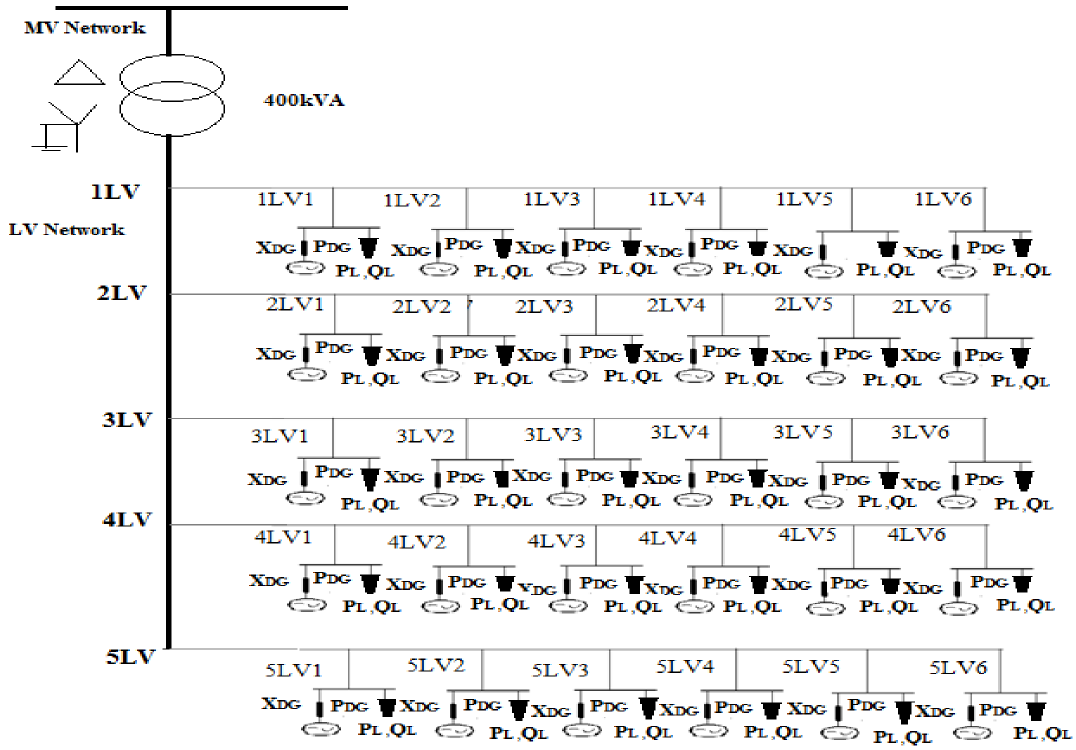

Fig.4. Layout of distribution network with DG-PV units

Concerning the typical distribution network presented in Fig. 4, the objective function consists of the sum of buses' voltages after a fault in line 1. Moreover, the transformer installed power is 400 kVA and the grid loading is set to 68% with a typical power factor equal to 0.85. The parameters of the optimization function are the XDG reactance and the PL value. In this paper, the definition of PL is based on the total load demand and is given by the following equation

$$PL(\%)=\frac{\Sigma P_{DG}}{\Sigma S_{LOAD}} \times 100\% \tag{20}$$

Nowadays, the commercial inverters are able to supply an overcurrent upto 2.8 times the IDG for several milliseconds during disturbance intervals. Moreover, considering that this policy has been recently applied for power quality improvement on autonomous LV–PV systems the factor ODk at k-bus is defined as follows

$$OD(\%) = \left(\frac{d_k * I_{DGk}}{I_{DGk-tr}} - 1\right) \times 100\% \tag{21}$$

The above factor denotes the percentage of DG-PV inverter necessary OD in order to meet the LVRTC requirements.

Table 1. Objective function and constraints of optimization

Objective function	$f\,(X_{DG}, PL) = \left[\sum_{i=1}^{6} \sum_{j=1}^{6} \sum_{k=1}^{6} \mathbf{V}jLk, sc\_1Lvi\right](X_{DG}, PL)$
Constraints	$OD_k < OD_{limit}$ at k-bus

The objective function is its maximization, that is, the maximization of bus voltages in order to satisfy the LVRTC demands respecting the DG-PV units' OD constraint ODlimit and the network short-circuit current protection limits I_{SC}. The optimization process has been conducted for different ODlimit values. It is noted that the actual PV inverter design and control, according to the current standards does not allow contribution to fault currents higher than 120% of the nominal value.

Fig. 5 presents the optimum XDG value as a function of PL, for different ODlimits.It is clear that the higher ODlimit makes possible the achievement of voltage selectivity under a wider range of PL values. For example, if ODlimit is set equal to 100%, high-voltage selectivity may be achieved under any PL value between the approved ranges.

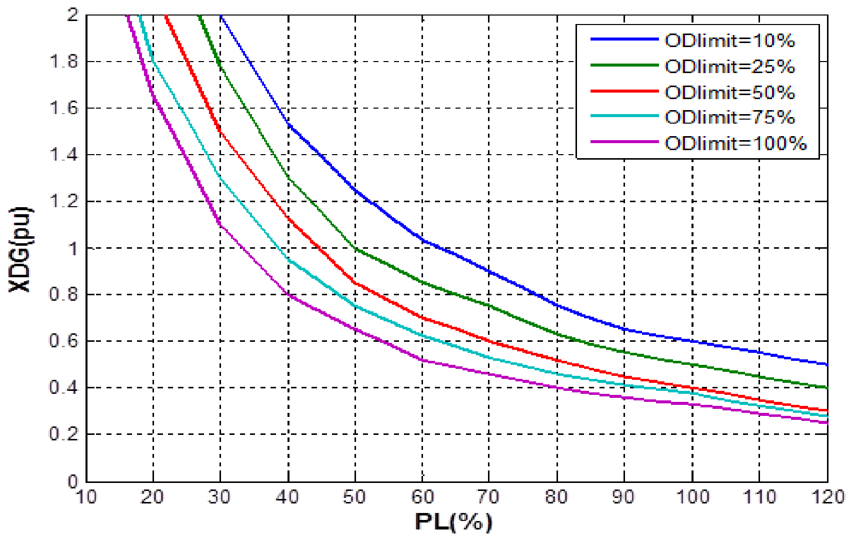

Fig. 5 XDG optimum value as a function of PL for different ODlimits

Fig. 6 presents the percentage of buses with voltage greater than 0.1 pu as a function of PL, with ODlimit being a parameter, in case of a short circuit at 1LV1 bus. It has to be noted that Fig. 6 refers to a short circuit at 1LV1 bus, which is the worst case about the voltage levels. The results in Fig. 6 agree with the ones in Fig. 5, highlighting the fact that more buses may preserve sufficiently high-voltage levels as ODlimit increases. Assuming that this disturbance is temporary, the selection of ODlimit and the respective optimum XDG value can be set so as to preserve a critical amount of

DG-PVs in operation, particularly for high PL values. Evidently, under smaller PL values (e.g. 30 or 40%) the DG-PV generation is less critical and so there is no point trying to preserve considerable generation capacity under the worst faulty conditions.

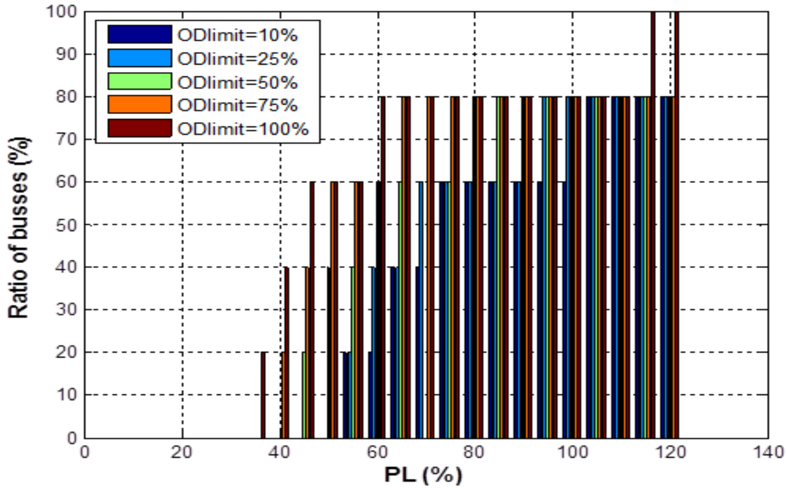

Fig. 6 Percentage of buses with voltage higher than 0.1 pu as a function of PL, with ODlimit being a parameter, in case of a short circuit at 1LV1 bus.

An important result of this optimization process is that the above-mentioned results, regarding the X_{DG} optimum value, do not remarkably violate the protective limits of the distribution network. This is shown in Fig. 7, where the ratio of 1LV5 bus short-circuits current is presented as a function of the PL value, with OD_{limit} being a parameter. Particularly, the I_{SC} varies between 1 and 1.35 Mostly, for a accurate choice of ODlimit lower than 20%, the I_{SC} value comes below 1.2 pu. Therefore the proposed design of DG-PV units can be implemented with minimum reconfigurations in the network protection scheme. Meanwhile, it can be realized that the restriction of $I_{SC} < 1.2$ pu still permits the achievement of voltage selectivity under a wide PL range, as long as ODlimit is higher than 25% [3].

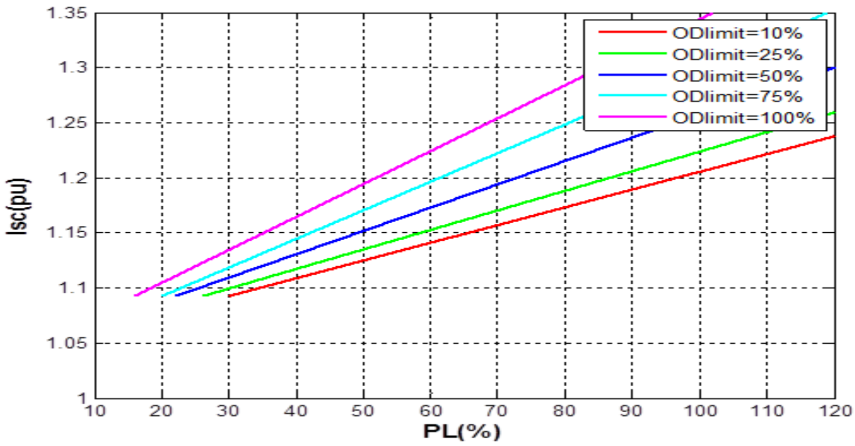

Fig.7 Impact of optimum XDG and PL values on the ratio of bus short circuit currents in line 1, in case of a three-phase short circuit at 1LV4 bus.

The above optimization results has been established that the achievement of PL levels, in the low-voltage distribution level, considerably higher than the current ones is an accurate target, taking for granted that DG-PV units will be designed and controlled in a way that they can operate similar to that of conventional synchronous generators. The main design modification that this concept raises is the OD for any individual DG-PV unit, in order to comply with the current LVRTC scheme.

CONCLUSION

The design aspects of low-voltage DG-PV units were considered in order to comply with LVRTC requirements. By integrating the LVRTC guide lines and Oversizing of inverter we can able to get benefits like, continual operation of DG-PV systems, loss of energy reduced. The design features of low-voltage DG-PV units were investigated in order to comply with LVRTC requirements. The theoretical analysis showed how the impedance of the DG units affects the bus voltages of the distribution network after a fault occurrence. Moreover, the concept of voltage selectivity is defined. Surely, the DG-PV over-sizing has to be limited (up to 75 or 100%) so as to avoid an exaggerated power converter size and cost. In this direction, an optimum design for DG-PV units was proposed, concerning the maintenance of bus voltages of the low-voltage distribution network at the highest possible levels in case of a disturbance.

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