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Original Research Article

Fault ride through concept in low voltage distributed photovoltaic generators for various dispersion and penetration scenarios

I.I. Perpinias [a,*], N.P. Papanikolaou [b,1], E.C. Tatakis [a,2]

[a] *University of Patras, Department of Electrical and Computer Engineering, Laboratory of Electromechanical Energy Conversion, 26504 Rio, Patras, Greece*
[b] *Democritus University of Thrace, Department of Electrical and Computer Engineering, Laboratory of Electric Machines, 67100 Xanthi, Greece*

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ABSTRACT

The Distributed Generation expansion and its smooth integration in distribution networks have gained much interest over the last years. Particularly, the photovoltaic systems connected to the low voltage distribution networks, present noteworthy benefits for the energy markets and customers. Meanwhile, aiming to high penetration level, many issues emerge regarding their behavior under grid disturbances. In this paper, the concept of Fault Ride Through Capability (FRTC) is applied to low voltage distributed photovoltaic generators (DG-PV), aiming mostly to the coordinated design and control of their interfacing inverters, so as to successfully address the FRTC requirements. These design alterations are examined in combination with an appropriate control concept that improves the FRT behavior of the DG-PV units. In order to apply the proposed control, an energy storage system is deemed indispensable. Through load flow analysis, the impact of the DG-PV interfaced reactance value X_{DG} is thoroughly investigated for various dispersion and penetration levels scenarios. Therefore, by applying the above control concept, a suitable selection of X_{DG} can be reached, achieving so compliance with FRT limits without leading to extremely inverter overloading (during faults). Finally, it is shown that the wider dispersion of DG-PV units enhances their FRT compatibility.

Introduction

The continuously decreasing reserves of fossil resources (carbon, petroleum and natural gas), their harmful impact on the natural environment, and considering also the increasing energy demands, have led energy markets in alternative energy sources [1]. Renewable Energy Sources (RES) have a widespread deployment and an intense activity is conducted in research level for their optimal integration and coexistence with the traditional energy systems [2–4]. Additionally, various regulations and standards have been introduced by international organizations and energy markets [5–7].

Initially, RES are introduced as centralized production systems in high and medium voltage levels. However, a trend towards the expansion of RES in distribution networks is recently appeared, called Distributed Generation (DG) [8]. DG introduces noteworthy advantages, such as transmission losses reduction and improvement of reliability and quality of the entire power system. On the other hand, the DG integration in the distribution network calls for a proper design and investigation of DG behavior in order to operate normally with the rest of the system without unsettling it. For the above reasons, the research community has already conducted a lot of studies [9–14] regarding the optimum allocation, size, penetration and control of DG units aiming to their smooth integration to the rest of the grid.

A very attractive RES application in distribution networks are the grid connected DG-PVs, because of their notable benefits such as the easy installation and low maintenance cost [15]. Therefore, there is a significant activity in photovoltaic installations either as small parks or as building integrated on roofs [16]. Especially, DG-PVs connected to the low voltage distribution network (LVDN) are of great interest since they can be easily dispersed at domestic houses achieving high penetration level (*PL*) values without affecting the urban environment [17,18].

However, the expansion of DG-PV in a large scale faces many difficulties by the distribution operators. Particularly, the *PL* of DG-PV in relation to the installed power is limited to 20–30%, in order to minimize its effect on the distribution grid [19,20]. It is noted that according to existing standards [21], in case of grid disturbances the DG-PVs have to trip almost immediately (in few line

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[*] Corresponding author. Tel.: +30 2610 996412; fax: +30 2610 997362.
E-mail addresses: jperpinias@ece.upatras.gr (I.I. Perpinias), npapanik@ee.duth.gr (N.P. Papanikolaou), e.c.tatakis@ece.upatras.gr (E.C. Tatakis).
[1] Tel.: +30 25410 79739; fax: +30 25410 79015.
[2] Tel.: +30 2610 996412; fax: +30 2610 997362.

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Nomenclature

DG	Distributed Generator
FRTC	Fault Ride Through Capability
PV	photovoltaic generator
PL	penetration level (%)
RES	Renewable Energy Sources
DG-PV	distributed photovoltaic generator
LVDN	low voltage distribution network
PCC	point of common coupling
SC	short circuit
S_{tr}	transformer installed power (kVA)
u_k	transformer short circuit reactance (%)
$\sum P_{DG}$	the total active power of DG-PV units (W)
$\sum s_{LOAD}$	the total load demand of the distribution network (kVA)
iLVj	the *j*-bus of *i*-line of distribution network under study ($j = 1, 2, \ldots 6$), ($i = 1, 2, \ldots 5$)
emf	the equivalent electromotive force
$V_{BUS,PF}$	the rms pre-fault bus voltage of the distribution network under study (pu)
$I_{DG,PF}$	the rms DG-PV unit pre-fault current of the distribution network under study (pu)
$P_{DG,PF}$	the pre-fault active power per DG-PV unit (pu)
P_{DG}	the injected active power per DG-PV unit in case of a fault (pu)
Q_{DG}	the injected reactive power per DG-PV unit in case of a fault (pu)
δ_{PF}	the power angle between E_{DG} and the vector of $V_{BUS,PF}$
δ	the power angle between E_{DG} and the vector of V_{BUS}
$V_{BUS,NOM}$	the rms nominal bus voltage of the distribution network under study (pu)
$I_{DG,NOM}$	the rms DG-PV unit nominal current of the distribution network under study (pu)
V_{BUS}	the rms bus voltage in case of a three phase short circuit at the distribution network under study (pu)
I_{DG}	the rms DG-PV contribution to the fault current in case of a three phase short circuit at the distribution network under study (pu)
X_{DG}	the equivalent single phase series reactance of DG-PV (pu)
E_{DG}	the vector representation of the equivalent single phase nominal AC voltage of DG-PV generation at PCC (pu)
$E_{DG,rms}$	the equivalent rms single phase nominal AC voltage of DG-PV generation at PCC (pu)
$V_{BUS}/V_{BUS,NOM}$	the ratio of V_{BUS} to $V_{BUS,NOM}$
$I_{DG}/I_{DG,NOM}$	the ratio of I_{DG} to $I_{DG,NOM}$
Q_{XDG}	the reactive power of X_{DG} in case of a three phase short circuit at the distribution network under study (pu)
P_{MV1}	the active power injected from the slack node MV1 (the primary of MV/LV transformer) in case of a three phase short circuit at the distribution network under study (pu)
Q_{MV1}	the reactive power injected from the slack node MV1 (the primary of MV/LV transformer) in case of a three phase short circuit at the distribution network under study (pu)
I_{SC}	the bus short circuit current rms value in line 1 in case of a three phase short circuit at the distribution network under study (pu)
$I_{SC,NO\text{-}DG}$	The bus short circuit current rms value in line 1 without the presence of any DG-PV unit, in case of a three phase short circuit at the distribution network under study (pu)
$I_{SC}/I_{SC\_NO\text{-}DG}$	the ratio of I_{SC} to $I_{SC\_NO\text{-}DG}$

cycles) for protecting their electronic part and not causing additional voltage stability problems to the rest of the grid. It is obvious that for low *PL* values this policy is reasonable, but simultaneously it constitutes a suspending factor for further DG-PV development.

Regarding the behavior of DGs during disturbances and especially in voltage dips, new regulations have been imposed by energy markets only for high and medium voltage level networks. Specifically, the FRTC standard has been adopted by several grid operators [22–24] as it can be seen in Fig. 1. However, until today, there is not a common FRTC standard for all energy markets. Hence, the issue of a suitable DG response in cases of abnormal grid conditions is still an open research issue for the academia and the standards committees.

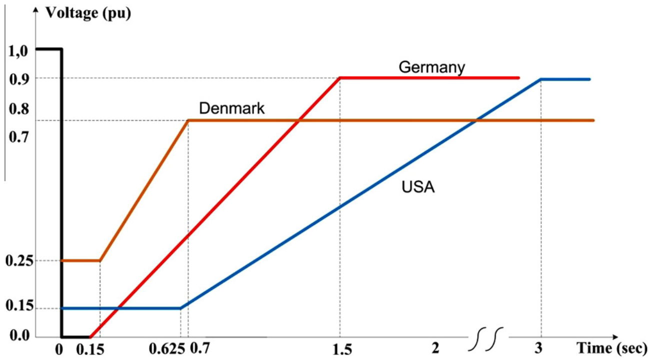

Fig. 1. FRTC schemes of several energy markets.

FRTC standard imposes to large Wind and DG-PV systems new operational characteristics, similar to those of conventional generators, so as to support the grid during a fault for a predetermined time interval. According to Fig. 1, this interval is a function of the voltage dip at the PCC. As the voltage dip becomes more severe the time interval lessens. So, if the disturbance is temporary the RES units return to their pre-fault state reestablishing their generation, otherwise they owe to trip for their safety. The FRTC was initially applied to large scale wind farms because of their significance for the system normal operation [25,26]. However, this trend has been expanded in PV parks due to their increasing market share and technical improvement [27].

Regarding the operation of DG in LVDNs, the FRTC standard is in contradiction in relation to already applied regulations [21]. However, the substantial development of DGs (and especially DG-PV) has led the research community to introduce alternative policies and revisions of the existing standards. Particularly, the majority of these studies refer to various control methods of DG-PV's amount of reactive power supply during a disturbance, according to the FRTC standard of various energy markets [28–29]. Nowadays, this trend has started to expand in LVDN, because the DG-PV concept in power level of 1–100 kW is deemed a very attractive perspective for high *PL* achievement, due to their easy and flexible installation at public and domestic roofs [30]. Furthermore, the FRTC standard has been recently applied at low voltage PV inverters topologies creating a new promising field of research [31–34]. Nevertheless, little progress has been made on the way of coordinated design of the DG-PV units' interconnection to the LVDNs [35], which is the main subject of the present work.

In this paper, the impact of FRTC adoption for DG-PVs connected to the LVDN is investigated from the power electronics'