Electric Power Systems Research 131 (2016) 264–274

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Coordinated voltage control of a decoupled three-phase on-load tap changer transformer and photovoltaic inverters for managing unbalanced networks

Junjie Hu [a], Mattia Marinelli [a,*], Massimiliano Coppo [b], Antonio Zecchino [a], Henrik W. Bindner [a]

[a] Center for Electric Power and Energy, Technical University of Denmark, DTU Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] Department of Industrial Engineering, University of Padova, Via Gradenigo 6/A, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form
24 September 2015
Accepted 21 October 2015

Keywords:
On-load tap changer
Photovoltaic system
Power transformer
Voltage control

ABSTRACT

The increasing penetration of fluctuating photovoltaic (PV) generation brings operational challenges for distribution system operators, such as introducing the voltage rise problem. The situation is made worse in the presence of single-phase generation being unevenly connected to the different phases. To address this problem, distribution transformers with single-phase tapping capability, together with reactive power provision of PV systems, are under investigation. This paper presents modeling and analysis of the benefits of coordinated voltage control of a decoupled three-phase on-load tap changer (OLTC) and photovoltaic inverters in a distribution system, for accommodating a greater number of photovoltaic generators in the grid. A 24 h root-mean-square simulation study is performed in the DigSilent PowerFactory with a 1 s time step using 10 min resolution consumption and production profiles on a real Danish distribution grid, as well as the developed dynamic photovoltaic generation and load models. The simulations show that the joint action of the power distribution transformer with OLTC control on each phase, and the reactive power provision of photovoltaic inverters, significantly improves the PV hosting capacity in the analyzed unbalanced scenarios without side effects, such as additional power losses, or significant neutral voltage rises.

1. Introduction

Network operators nowadays need to face the challenge of ensuring a stable supply voltage in the low-voltage grid, at the same time integrating an increasing number of nonprogrammable distributed energy resources, such as photovoltaic generation, which might raise the risk of violating the permitted voltage band [1–4]. Network operators are being forced into expensive expansion investments, even though the capacities of their grid are far from used up.

Alternatively, as listed in [5] and [6], several solutions have been suggested to deal with the overvoltage phenomena in the presence of a high level of PV generator penetration in low-voltage grids. These methods include: 1) voltage control using reactive power generation from PV inverters [7,8]; 2) voltage control at the LV side of the MV/LV transformer by on-load tap changers (OLTC) [9]; 3) active power derating of PV production in the case of overvoltage conditions [10]; and 4) battery storage/energy buffer at PV generators and MV distribution levels [11]. Each solution is currently investigated by different stakeholders and their feasibility is described in report [6]. In practice, several national standard bodies, such as CEI in Italy [12] and VDE in Germany [13] have updated the connection rules to enable reactive power provision by the inverters interfacing static generators such as PV units, even at low-voltage levels. Different reactive power control methods have been set, most of them relying on local measures on the busbar voltage or the produced active power; they can be summarized as: fixed cosφ, cosφ(P) characteristics, fixed Q, Q(U) droop function, and remote set values method.

Coordinated volt/var control has been widely proposed and studied in the literature. In [9], the DG DemoNet project is introduced, the project objective being to develop and test an intelligent voltage control method in an active distribution grid. The

Abbreviations: DG, distributed generation; DSO, distribution system operator; MV/LV, medium voltage/low voltage; OLTC, on-load tap changer; PV, photovoltaic; VUF, voltage unbalance factor; One-phase OLTC, decoupled single-phase OLTC that has the possibility of tapping each phase independently.; Three-phases OLTC, the controller changes the taps on 3 phases simultaneously; Q_{reg}, reactive power provision of photovoltaic inverter.

* Corresponding author. Tel.: +45 20124369.
E-mail address: matm@elektro.dtu.dk (M. Marinelli).

http://dx.doi.org/10.1016/j.epsr.2015.10.025
0378-7796/

voltage control method involves the coordination of OLTC operation and reactive power exchange between the distribution system operator and the PV inverter. Several articles [14–17] have been published regarding this project. In [18], a coordinated strategy for voltage control in distribution networks is investigated, where the automatic voltage controller installed at the primary substation cooperates with the DG controllers in setting the active and reactive power set points for generators. In [19], the authors discuss the voltage control with on-load tap changers in medium voltage feeders in the presence of distributed generation. Concerning the OLTC, two kinds of controls are discussed for the conventional distribution grid: the first is based on the local voltage measurement, while the second is intended for remote voltage regulation through line drop compensation (LDC). With the provided background, the authors in [19] studied the effect of both the controls on a distribution network in the presence of DG. Their analysis showed that OLTC and OLTC with LDC are robust against DG, whereas DG can negatively affect the voltage regulation provided by LDC, therefore a proper coordination between DG and LDC is needed to ensure voltage regulation, while enhancing the integration of DG. In [20], the authors presented a proposal for active management of the distribution system that makes use of an innovative controller that coordinates the on-load tap changer action with the regulation of reactive exchanges between DG plants and feeders in MV networks. A similar approach is also presented in [21], where the application of the OLTC control is considered for MV/LV transformers, along with the reactive power control for DG units.

All the aforementioned research activities described, deal with the OLTC's applications on voltage control in three-phase balanced systems, using a synchronized tap changer on the three phases. Other studies [9,14–17,19,20] do not take into account the voltage unbalance effect in low-voltage networks due to the users' single-phase connections, as it usually happens to the PV inverters typically for domestic installations. This kind of connection of the PV could exacerbate the power flow unbalance already existing in these systems due to the unbalanced load connections.

The novelty of this work consists of addressing the voltage control problem through an OLTC capable of operating on the single phases independently; the objective is to evaluate the hosting capacity of a distribution network characterized by high PV penetrations. This study is a further extension of the work presented in [22] in which only the passive network with no PV connections is considered. Highlights of this study include: 1) a coordinated voltage control of a decoupled three-phase on-load tap changer transformer and photovoltaic inverters is proposed for the first time to address the voltage problems of unbalanced distribution networks that are characterized by high PV generations; and 2) details regarding the modeling and control algorithms of OLTC are presented.

The rest of the paper is organized as follows: in Section 2, a general working principle of OLTC in the presence of distributed generation is discussed. Section 3 presents the modeling assumptions and methods for the elements of the distribution system. In Section 4, a Danish low-voltage network adopted as a case study is presented. Simulations are shown in Section 5 to illustrate the performance of the proposed method. In addition, future work on experimental validation of the one-phase OLTC transformer is also described. Finally, conclusions are given in Section 6.

2. On-load tap changer working principle in the presence of distributed generation

According to European standard EN 50160, the range of variation of the root-mean-square magnitude of the supply voltage, whether line to neutral, U_n, or line to line, U_c, is $U_n \pm 10\%$ or $U_c \pm 10\%$ for at least 95% of the week. As illustrated in Fig. 1, in practice, a maximum voltage rise of 3–5% is available to renewable energies in the low-voltage grid, since the rest is reserved for the medium-voltage grid, considering voltage drops and setting imprecisions.

By using an OLTC transformer instead, the network operator can increase the grid capabilities by dynamically adapting the voltage that decouples the voltages of low- and medium-voltage grids. Referring to the example made in Fig. 1, this may result in an 11% rather than a 3% voltage rise being available in the low-voltage grid for feed-in from renewable energies, which is shown in Fig. 2. This kind of action helps to improve the hosting capacity without expensive grid expansion investments.

The transformer is provided with a certain number of taps along one of the windings in order to adjust the turns ratio between the primary and secondary sides. A tap changing device that makes the physical change in the tap position during on-load operation is

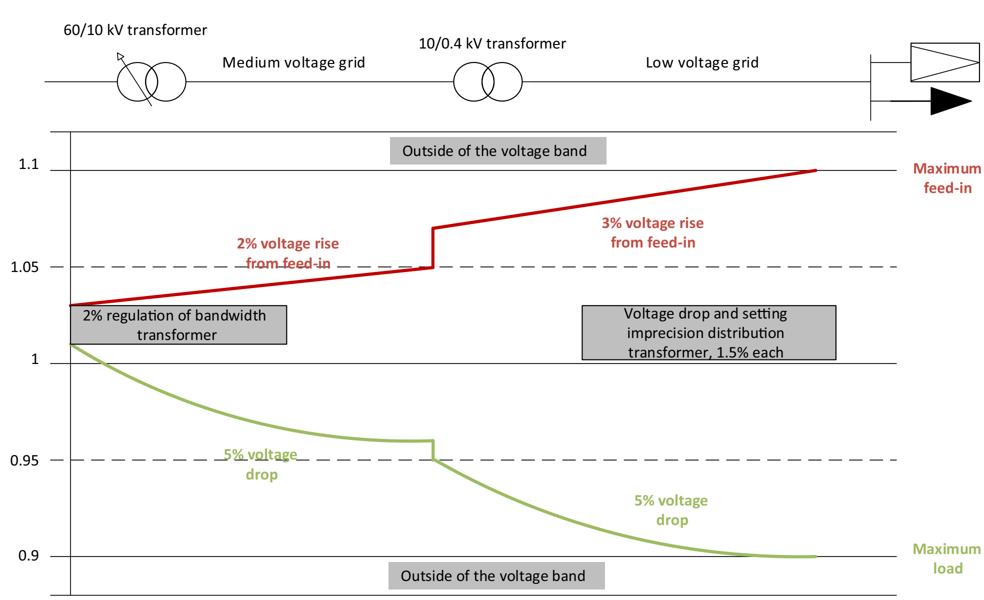

Fig. 1. Potential problems faced by the network operator without OLTC.