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Integration of PV and EVs in unbalanced residential LV networks and implications for the smart grid and advanced metering infrastructure deployment

Andrea Rodriguez-Calvo *, Rafael Cossent, Pablo Frías

Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, C/Santa Cruz de Marcenado 26, 28015 Madrid, Spain

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ABSTRACT

Voltage unbalance is a relevant problem that causes a less efficient operation of the system due to higher energy losses and lower hosting capacity. Unbalance has often been neglected by distribution system operators due to the lack of monitoring data in the low voltage (LV) grid. However, the massive deployment of smart metering in recent years in many countries provides very valuable information to detect unbalance. Moreover, in the current context of increasing presence of single-phase distributed energy resources connected to LV networks, such as electric vehicles (EVs) and photovoltaic (PV) generation, unbalance is bound to increase.

This article investigates the technical impact of future integration of EV and PV in LV unbalanced networks. This paper has assessed the daily energy losses and voltage problems as load unbalance gradually increases, based on load flow analysis on an hourly basis, considering residential demand and homogeneously distributed EV and PV. The analysis has been carried out for several rural and semi-rural LV networks and various scenarios of demand level and penetration degree of EV and PV. The three-phase load flow analysis is computed using the forward-backward sweep algorithm.

Furthermore, this work discusses the implications for the deployment of supervision and monitoring solutions based on advanced metering infrastructure (AMI). Their implementation should be prioritized in more loaded and longer networks where high integration of distributed energy resources is expected so that unbalance can be detected and corrective actions can be applied.

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1. Introduction

As the smart grid gradually turns into a reality, new solutions have become available to increase the observability and controllability of distribution networks [1,2]. Smart metering has already been implemented in several countries across Europe such as Italy, Finland, and Sweden, and is currently on-going in many other (e.g.: Spain, the Netherlands, UK, Ireland). Actually, it is expected that by 2020 around 70% of European consumers will have a smart meter [3]. Smart meters can register real-time energy consumption including voltage, phase angle and frequency measures. Thus, Automatic Meter Infrastructure (AMI) systems can be used to create a distributed monitoring system of the low voltage (LV) grid [4]. Monitoring provides very valuable information that may be used by distribution companies to perform power quality and fault analysis and detect issues such as non-technical losses and voltage unbalance [5].

Voltage unbalance is actually a relevant problem that results in higher energy losses, higher neutral currents (which in turns contributes to voltage drop), a less efficient utilization of network assets (a highly unbalanced grid reaches its hosting capacity limit much sooner than a balanced grid so that network reinforcement costs are moved forward in time [6]) and possible damage to electric equipment [7] (overheating and vibrations in motors[1]) [8].

Voltage unbalance is mainly caused by the difference between the single-phase loads connected to each phase. In higher voltage levels both generation and demand are typically three-phase and

[1] For every 10 °C a motor is operated over its rated temperature, its insulation life (and therefore motor life) decreases by half. NEMA motor standards recommend a maximum voltage unbalance of 1% without derating the motor.

* Corresponding author.
E-mail address: andrea.rodriguez@iit.comillas.edu (A. Rodriguez-Calvo).

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balanced[2]. Unbalance is especially relevant in LV networks, where most consumers are single-phase loads. Originally, at the time of connection, single-phase loads are assigned to the three phases in a balanced manner, but the loads are asymmetrical and vary differently in time. Furthermore, when new consumers are connected to the grid, the phase allocation may not be optimal. In practice, high values of current unbalances are observed. Moreover, the presence of single-phase distributed energy resources (DER), such as electric vehicles (EVs) and photovoltaic (PV) generation connected to LV networks is bound to increase further unbalance.

Unbalance has often been neglected by distribution system operators (DSOs) due precisely to the lack of monitoring data in the LV grid [9,10]. The work of [10] develops a methodology to estimate unbalance using probability based on historical data for the MV network. However, the use of AMI and smart meters to detect unbalance is already proposed and discussed by several authors [8,11,12]. Furthermore, unbalance has often been neglected in the operation of the system, assuming a fully balanced system when carrying out one-phase power flow analysis for voltage control. Some works acknowledge the impact of unbalance and thus propose to use three-phase power flow analysis to determine optimal operation of distribution networks [13,14]. Another example is the algorithm proposed in [15] for voltage control which explicitly incorporates the restriction of unbalance limits.

The increasing presence of DER has further motivated the explicit consideration of unbalance in voltage control. In the case of the EV, the work of [16] analyzes the impact of EV on distribution networks and compares the results obtained in balanced and unbalanced systems. The authors of [17] determine smart charging strategies for EVs adding regulatory unbalance limits as constraints in the three-phase optimal power flow analysis. Similarly, [18] include unbalance in their proposal to determine the charging strategy of minimal cost based on a multi-period, rolling optimization technique with the updated information on demand and EV connection for an unbalanced three-phase load flow analysis. The participation of PV in voltage control has been addressed by [19], which proposes a multi-objective optimal power flow that explicitly considers the restriction of unbalance within acceptable limits. Further work on the interaction of PV integration and unbalance in LV grids includes [20], which investigates the effect of PV units of different capacity connected at different nodes in a residential LV network on voltage unbalance along the line, and the assessment of voltage unbalance sensitivity to set the requirements of maximum capacity of PV units to be connected in LV networks [21].

In order to mitigate unbalance, different solutions have been proposed in the literature. The reconnection or re-phasing of loads is discussed in [8,22–24], and different algorithms have been proposed to optimize the load assigned to each phase, such as ant colony optimization in [8]. However, DSOs may not be able to afford too many phase moves due to the limitation imposed by the architecture of the LV grid, cost of manual re-connection, interference and potential service interruption of consumers, etc. More recent works propose to make use of automation to perform reconfiguration for re-phasing [8,23,24]. The work of [25] shows that an ideal reactive source can control positive sequence magnitude and cancel any negative phase sequence terms and propose the use of thyristor-switched capacitors (TSCs) for this purpose. The work of [20] discusses the increase of feeder cross-section, installing capacitors at phases with lower voltage and controlling PV converters to reduce unbalance in LV residential networks with PV. The authors then propose in [26] the application of series (DVR) and parallel (DSTATCOM) custom power devices. The use of Battery Energy Storage Systems (BESS) for load levelling across the three phases has also been proposed and tested. Single-phase BESS in combination with PV units have been addressed by [27]. The work presented in [13] studied a three-phase BESS connected to the LV distribution grid through a three-phase inverter and [28] proposed a day-ahead dispatch of BESS for peak load shaving and load levelling using Characteristic Daily Load Profiles (CDLPs) in each phase.

In the future, as higher volumes of DER are integrated in the LV grid, it will be of the utmost importance to prioritize monitoring in those areas where the hosting capacity of the network is more limited and problems are more likely to arise. Rural networks are usually more sensitive to unbalance in loads, since in more densely populated urban areas LV networks are typically much shorter and loads tend to be more balanced. Therefore, the objective of this paper is to assess the effect of unbalance on DER integration in rural LV networks. For this purpose, analyses are conducted to determine energy losses and voltage profiles in several rural and semi-rural LV networks under different degrees of unbalance in the system and varying penetration degrees of distributed generation (DG) in the form of PV panels and EV in the form of slow charging connections. Accordingly, the reminder of the paper is structured as follows: Section 2 defines the methodology applied to carry out the analyses. Then, Section 3 describes the case study and Section 4 discusses the results obtained, together with the implications for the use of AMI and LV supervision solutions for monitoring. Finally, Section 5 concludes with the final remarks.

2. Methodology

This section describes the methodology applied for the study of the integration of EVs and PV in unbalanced LV networks, based on three-phase unbalanced power flow analyses.

2.1. Measuring unbalance in the LV network

Unbalance can be quantified following different approaches. Most commonly, regulation uses the percentage voltage unbalance factor (VUF), defined by the International Electrotechnical Commission (IEC) as the coefficient between the negative and the positive component of voltage. Other indices include the phase voltage unbalance rate (PVUR) defined by Institute of Electrical and Electronics Engineers (IEEE) and the line voltage unbalance rate (LVUR) defined by the National Equipment Manufacturer's Association (NEMA). An exhaustive comparison and assessment of the suitability of different indices for voltage unbalance may be found in [29].

The European Standard EN 50160 states that the 95% of the 10 min average voltage unbalance must not exceed a value of 2%, or up to 3% for some specific locations, over a one-week period [30]. Other countries impose even stricter limits to unbalance, such as the UK or Malaysia, where the statutory limit for voltage unbalance is 1.3% and 1%, respectively. However, these standards are usually not enforced since voltage unbalances are hardly ever measured in practice.

For the sake of simplicity, this work follows the PVUR approach to measure voltage (and current) unbalance u_U, defined as the maximum deviation from the mean, according to (1), where U_m is the mean of the RMS values of voltage (current) of the three phases and U_j is the RMS value of the voltage (current) at each phase.

$$u_U = \frac{\max\limits_{j}(U_j - U_m)}{U_m} \cdot 100\% \tag{1}$$

Load unbalance will be directly translated into current unbalance, as voltage variations in each node due to load unbalance

[2] It must be noted that distribution networks in Europe are generally based on secondary substations with three-phase MV/LV transformers (as opposed to the USA, where MV networks frequently feature single-phase or two-phase systems in lateral branches) [40].

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