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Impacts of microgrids with renewables on secondary distribution networks ☆

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HIGHLIGHTS

- Low voltage distribution networks are severely affected from high DG penetrations.
- High-resolution and stochastic supply and demand profiles provide valuable insight.
- Determination of DG capacity depending on the worst-case scenarios is limiting.
- The voltage increases and line losses do not reach extreme levels.

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ABSTRACT

High penetration of distributed generation (DG) in secondary (low-voltage) distribution networks (SDN) is one of the primary challenges of network operators. Particularly in radial LV networks, renewable intermittency and bidirectional power flow may cause critical problems such as under/over voltages, line overloads and high energy losses. System operators usually consider the worst-case scenarios for the assessment of the impacts of new integrations and usually they prefer passive methods to mitigate the negative effects. However, analysis of daily operation with high resolution, stochastic DG supply and residential demand profiles can reveal both the occurrence rates and the severities of the critical events, while paving the way for the development of active mitigation methods. This study is focused on detailed daily operation analysis of SDNs with renewable-based microgrids. Seasonal DG output and residential demand profiles throughout a day were simulated using a virtual test bed to investigate the critical cases.

1. Introduction

The concept of distributed generation grows in popularity throughout the world [1]. There are numerous technical, financial and environmental advantages that foster its development [2,3]. Contrarily, high penetration of renewable-based DG into existing power systems can breed new issues. The prominent challenges are increasing volatility in daily net load profiles (which is named as duck curve) [4–6], extreme surplus supply from DGs [7] and bidirectional power flows [8]. These stimulate the use of high cost/low efficient peaking plants, cause periodical avoidance of renewables [9] and limit the penetration of DGs in generation mix [10,11].

Low voltage (LV) radial distribution networks with high R/X ratios are more severely affected by DG penetration than the distribution and transmission networks with higher voltage levels. While bidirectional power flows in a radial network may cause overvoltage and line overloading problems, they can also increase the system losses. In addition to the point of connection, neighboring busses are also being affected [8]. Since distribution networks are not designed for bidirectional power flow, impact analysis is a vital assessment prior to new DG integrations into existing distribution networks.

There are plenty of studies in the literature that concentrate on DG impact on LV networks. The studies are focused on the analysis of technical challenges [12], evaluation of hosting capacity [13], investigation of negative impact mitigation options [14,15] and

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sizing of the devices that will be used for mitigation [16]. It is stated in [8,17,18] that the most severely affected bus in a LV distribution system was the furthermost one to the substation, while the negative impact on the closest bus was very minor. Doumbia et al. focused on the voltage variation in a small scale network for three critical cases; namely, minimum generation-maximum demand, maximum generation minimum demand and maximum generation-maximum demand [19]. Conventionally, distribution network operators consider the most threatening operating conditions to scale the capacity of new DG installations. However, determination of tolerable DG capacity depending solely on the worst-case scenarios is very constraining for the utilities [20,21]. Wind turbines generally operate at a level less than their rated capacities, because of variation in wind speed. The highest output from wind turbines is generally provided in a couple of hours after midnight, while photovoltaic (PV) panels reach their peaks during midday just for a short period of time [22]. Therefore, peak outputs of wind generation and photovoltaic generation rarely coincides. Moreover, recent developments in distributed storage facilities provide more uniform generating profiles and more effective utilization of renewable generation. Besides, common load factors for buildings are approximately 40% [23] which reduces the occurrence possibility of extreme (minimum generation-maximum loading) conditions.

Most of the precautions taken according to the worst-case scenarios are hard to implement and costly. Reduction of line impedance by reinforcing the distribution feeder or moving connection point closer to the substation may not be applicable due to physical and economic conditions in small scale systems [8]. Power factor control (PFC) may not be very effective as well, particularly in networks with low X/R ratio (compared to active power control) [22]. Advanced control of tap changer at SDN substation is another prospective solution, since it is an existing control option in many places [24]. However, it may not be effective for local under/over voltage issues at feeders with multiple DGs [25]. Therefore, more proactive and effective solutions are required. Additionally, microgrids including renewable based DGs and improved measurement and control capabilities can be benefited in proactive studies. According to a comprehensive survey study on DG and microgrids, the primary areas that the microgrids will be deployed in the following years are public buildings, hospitals, military facilities and rural areas with LV and MV distribution networks [26]. According to the results of the same study, the key enablers of microgrids are distribution management and energy management systems which can play significant role in mitigation of negative impacts of DG penetration. Thus, there is an increasing need for detailed analysis in which daily supply/demand profiles are considered [27]. Advanced analysis of LV networks with variable daily generation and load profiles can provide valuable insight into long term operation of the system and enable development of active mitigation methods. In addition, stochastic and quasi-steady state simulations can reveal magnitudes of critical events in daily operation, contributing to studies on evaluation and sizing of solution options. The works proposed in [28–30] include consideration of daily PV and load profiles in LV distribution network operation. However, interruptions in PV panel output due to cloudiness are not reflected to the PV models. Cloudiness is taken into account in some studies as in [31], without covering daily profiles. Furthermore, studies with daily profiles mostly use hourly data, neglecting the minutely changes in PV supply and residential consumption, which are of importance for the development of corrective power management methods [32–34]. Moreover, most of the studies use aggregated load profiles, while individual consumption behavior of each consumer can be used to simulate more realistic cases [35–36]. A study of the International Energy Agency (IEA) states that, the level of PV penetration on a specific feeder depends on the minimum load on that feeder [37]. Relevant literature lacks of the studies that compare the worst case analysis with high resolution and stochastic daily profile analysis in LV networks. Investigation of the occurrence rates and magnitudes of extreme conditions in daily operation can foster the development and evaluation of active mitigation methods and sizing of solutions. What is more, seasonal differences in PV profiles are rarely included in the related studies, restricting possible variabilities of analysis results. Additionally, microgrids require particular attention since local generation and consumption are at the same point of connection to distribution feeder, with more possibility of hosting higher penetration of renewables.

This paper is therefore devoted to detailed daily operation analysis of SDNs including renewable-based microgrids. Note that the analysis is also valid for a SDN where renewable DG and loads are located at the same feeder with short distances. Profiles of PV panels in the microgrid and typical residential loads in a SDN were simulated using a virtual test bed to monitor the changes in bus voltage magnitudes and network losses. Steady-state voltage variation in radial SDN including microgrids or DG penetration is explained in section 2. Section 3 describes the virtual test bed used in the study and section 4 includes the detailed daily analysis of a sample system. The last section is devoted to the discussion of the results and real applications.

2. Steady-state voltage variation and line losses in distribution networks with renewable-based microgrids

Conventionally, secondary distribution networks have been designed for one-way power flow from substation to consumers using a radial topology (Fig. 1).

The cross-sectional areas of the LV distribution lines are smaller and their R/X ratios are higher when compared with MV and HV lines [8]. Therefore, the relative voltage drops are high in these systems. The substation voltage phasor of a distribution network, $\dot{V}_s$, can be expressed as in Eq. (1).

$$\dot{V}_s = \dot{V}_R + \frac{P - jQ}{\dot{V}_S^*}(R + jX) \quad (1)$$

Here, P and Q denote the active and the reactive powers supplied by the utility, respectively. $\dot{V}_R$ represents the voltage phasor at the receiving end. R and X are the line parameters and the superscript $*$ denotes the conjugate of a complex quantity. Due to the fact that the angle difference between the substation and consumer voltage phasors is very small, the real part of the voltage drop dominates the expression (2).

$$\Delta V = \dot{V}_s - \dot{V}_R \cong \frac{RP + XQ}{V_S} \quad (2)$$

The expression can be adopted to represent the voltage relation between each consecutive bus pair of an N bus system (Fig. 2).

Active line losses for this operational condition can be calculated using Eq. (3).

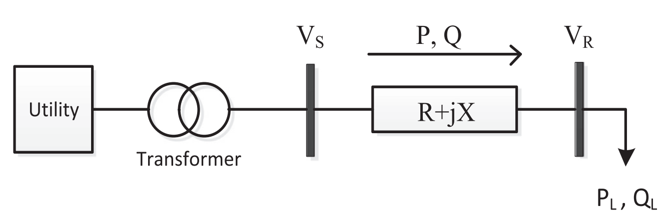

Fig. 1. Unidirectional power flow in a traditional radial distribution system with two busses.