Analysis of critical operating conditions for LV distribution networks with microgrids

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Abstract. Increase in the penetration of Distributed Generation (DG) in distribution networks, raises the risk of voltage limit violations while contributing to line losses. Especially in low voltage (LV) distribution networks (secondary distribution networks), impacts of active power flows on the bus voltages and on the network losses are more dominant. As network operators must meet regulatory limitations, they have to take into account the most critical operating conditions in their systems. In this study, it is aimed to present the impact of the worst operation cases of LV distribution networks comprising microgrids. Simulation studies are performed on a field data-based virtual test-bed. The simulations are repeated for several cases consisting different microgrid points of connection with different network loading and microgrid supply/demand conditions.
Keywords. microgrids, smart grids, co-simulation, distributed generation, distribution networks.

1. Introduction

Penetration of renewable energy resources into the power system has a rising trend in many countries. DG from renewables provides technical, environmental and economic benefits both for the utility and for the customers [1]. In spite of its numerous advantages, it may have some negative impacts on the system. DG facilities are mostly connected to the grid through current source inverters, which follow network voltage and supply current in relation with the generated power. The prospective impacts of an inverter-based generation facility on a network are voltage limit violations and increase in line losses. The problems may be more significant in LV distribution networks, due to bidirectional power flow both in a radial topology and over the lines with high R/X ratios.

In order to supply power from a local generation unit to the utility in a radial network, the voltage of its connection node should be higher than the substation. The amount of voltage difference between the utility grid and the microgrid depends on the supplied power, substation voltage and line parameters.

There are several studies in the literature focused on analysing DG impact on LV networks. The dependency of voltage levels to active power flow in LV networks is stated with the related equations in [2]. Scenarios to investigate the local generation impact are proposed in [3]. Voltage variation and its mitigation by generation reduction are studied in [4]. In addition to solely DG centred analysis, there is a need to investigate the renewable-based microgrid impacts over LV networks.

Microgrids are one of the leading areas of Smart Grid technologies. Comprising storage and manageable load units close to distributed generators and advanced local control infrastructures, they may enable penetration of more renewable generations into the power systems. According to a comprehensive survey study done with 460 smart grid experts from different countries, microgrids will primarily be deployed in rural areas, military facilities, hospitals and public buildings that have mostly MV and LV distribution networks [5].

This study focuses on the critical operating conditions for LV networks with microgrids. A virtual test bed that represents the steady state operational behaviour of a small scale microgrid and a rural LV network model is used in the analysis. Both the bus voltages and the line losses are investigated for different points of connection, local generation output and network loading cases.

2. The Virtual Test Bed

The virtual test bed used in the analysis is previously developed as a part of a bilateral research project (Smart Electric Energy Management and Buildings Energy Efficiency Technologies-SEEMBEET) led by authors [6]. It represents the steady state operational behaviour of a small scale microgrid laboratory. The real system has two groups of PV panels with 2.2 kW power output in total, one 1 kWp wind turbine, a lead-acid battery group with 600 Ah storage capacity and 5 groups of loads with approximately 2.3 kW total demand.

The reason for developing a virtual test bed is to conduct research beyond the pilot applications. A laboratory has some operational constraints, such as single point of connection to the distribution grid, limited number and capacity of devices in the system and dependency on local conditions (like solar irradiation, wind speed, temperature and etc.). On the other hand, a virtual test system that has identical behaviour with the real microgrid can allow analysis with different points of connection to a larger system, including different scenarios with several operating conditions. Moreover, long term operation can easily be investigated. With combined simulation solutions, it is possible to implement energy management actions and a virtual test bed can provide in depth analysis of different algorithms.

The virtual test bed used in this study is developed using PSCAD software [7]. At the first stage, individual models of local generations (PV panel groups and wind turbine), storage (lead-acid batteries) and manageable loads are developed. Steady state power output of PV panel groups, P_{pv}, for their whole operational range is modeled by (1). In (1), I_r denotes the solar irradiation in W/m^2 and T is the temperature in °C. During modeling, a data set that is generated with the existing PV block in the software library together with the developed MPPT and inverter models, is used and a first order equation is derived (1).

$$P_{pv} = 8.542173377 - 0.1719887T + 0.170425778I_r \qquad (1)$$

A similar approach is preferred for wind turbine model. The test data including all power outputs at all operational wind speeds (taking into account tip speed ratio), is used to derive a fourth order equation (2) [8].

$$P_w = 0.0768v_w^4 - 3.7371v_w^3 + 55.024v_w^2 + 189.02v_w + 186.76 \qquad (2)$$

R-squared fitting performance for PV and wind turbine models are found to be 0.9968 and 0.9969, respectively. Comparison of real data with the model output for the whole operational range can be found in Figure 1 and Figure 2.

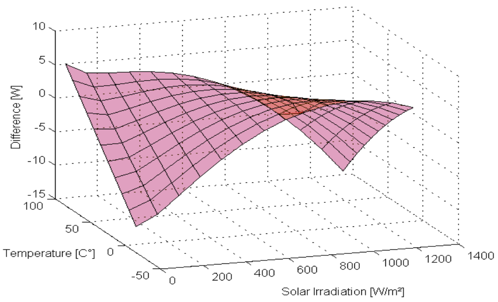

Figure 1. The difference between the real data and the fitted curve for PV model

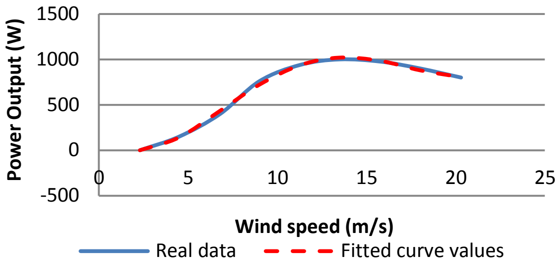

Figure 2. The difference between the real data and fitted curve for the wind turbine model

The authors have another publication regarding the development of the virtual test bed. Interested audiences can find the details of the modelling process in [7].

3. Case Study

In this study the test bed is connected to a LV distribution network to analyse the critical operating conditions. The chosen network is a 50 kVA, 400/230 V, 50 Hz system previously proposed in [2] (Figure 3). It is a small scale distribution network with long lines and high R/X ratios (Table 1). Its two feeders with 10 consumer nodes are modelled in PSCAD.

Table 1. LV distribution network line types with R/X ratios

Line Types	R/X Ratio (per km)
AMKA 3x35+50	8.35
AMKA 3x25+30	11.32
AMKA 3x16+25	17.69
AMKA 4x50S	7.28
AMKA 3x10+10	20.8
AMKA 3x6+6	34.22

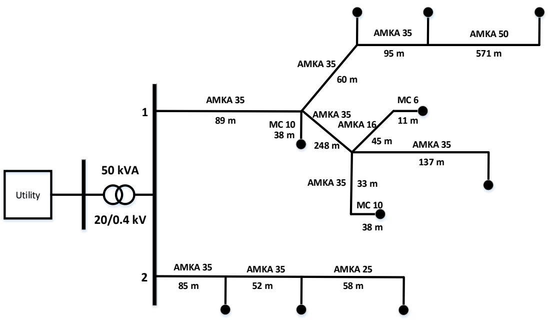

Figure 3. Sample LV distribution network with two feeders and 10 consumer nodes [2]

3.1. Scenarios

In order to investigate the impact of a microgrid on a distribution network, the test bed is connected to the three different nodes; namely, close point of connection, medium point of connection and far point of connection. Four different microgrid supply/demand cases are simulated for each connection point. The first case refers to maximum microgrid local generation and minimum microgrid demand profile. The second case is just the complement of the first one, where the local generation is minimum and microgrid demand is maximum. The last two cases are maximum local generation with maximum demand and minimum local generation with minimum demand. Note that the first two cases and the last two cases correspond to high and low power exchanges between the microgrid and the network, respectively. All those four cases, are simulated together with maximum and minimum total demand in the LV network. Table 2 illustrates the simulation cases for each point of connection to the grid. Combining with three different points of connection, 24 different scenarios are investigated. Moreover, each scenario includes switching from grid-connected mode operation to islanded mode operation to compare the bus voltage magnitudes and the line losses.

Table 2. Scenarios for each microgrid point of connection

Scenario No	Network Load	Microgrid Load	Microgrid Supply
1 (max. demand)	High	High	Low
2	High	High	High
3	High	Low	High
4	High	Low	Low
5	Low	Low	Low
6 (max. supply)	Low	Low	High
7	Low	High	High
8	Low	High	Low

3.2. Simulation Results

The most critical cases for each point of connection are illustrated in Figure 4, Figure 5 and Figure 6. In each figure, the bus with the worst voltage level is shown in a red circle, while the most loaded line is shown in a blue circle. Bus voltages, line loadings and total % line losses are given for the critical scenarios. The network loading during scenario 1 is 2.7 kW per connection point, the average of daily peaks faced with in the field. For scenario 6, the amount of loading per consumer is 0.5 kW, which represents continuously working loads like refrigerators and air conditioners, together with stand-by consumption of electronic devices.

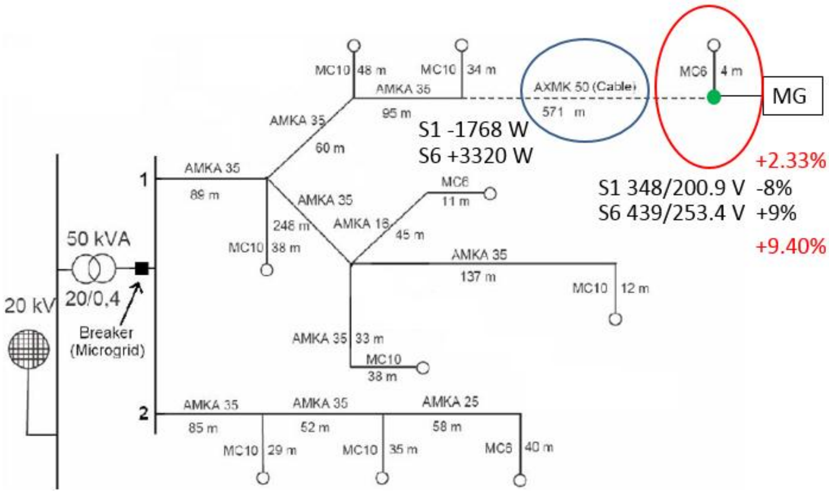

Figure 4. The most critical impacts for far point of connection

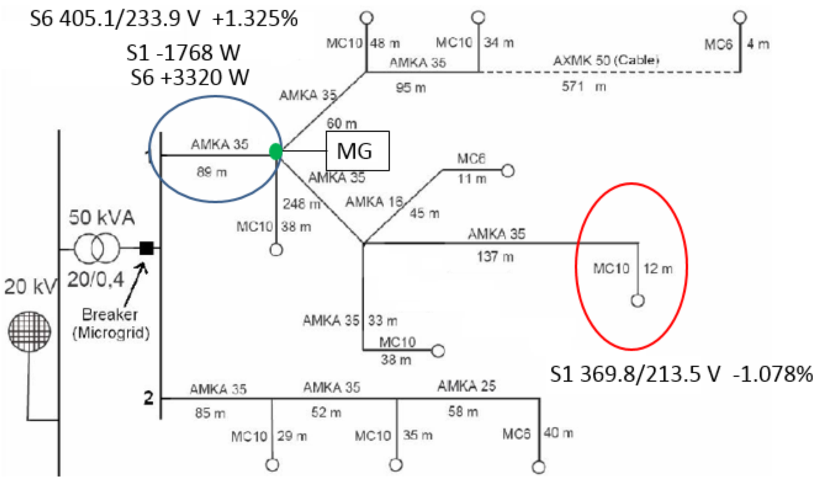

Figure 5. The most critical impacts for near point of connection

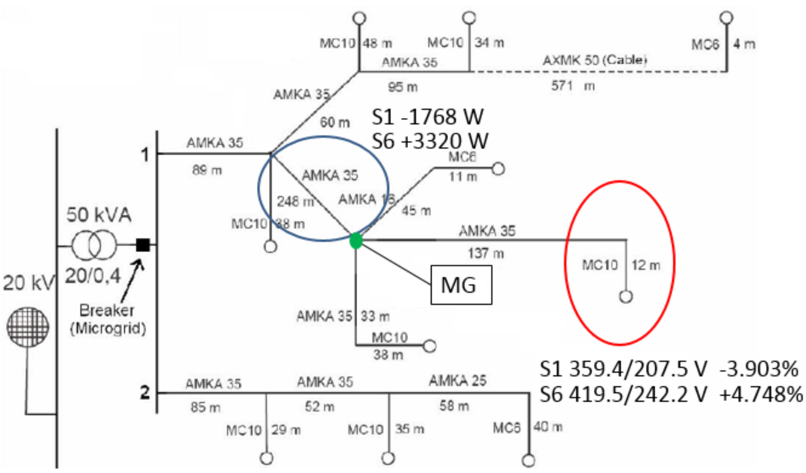

Figure 6. The most critical impact for middle point of connection

Among 24 representative scenarios for three point of connections, the most critical voltage magnitude and line loadings are faced for the maximum demand (scenario 1) and for the maximum supply (scenario 6) cases. According to the numerical results, far point of connection caused highest negative impacts, while near point of connection resulted in the lowest impacts. One of the main reasons of this result is the value of the impedance between the microgrid and the distribution substation. Higher impedance increases the voltage drop over that path and consequently, the microgrid needs to increase its connection point voltage to higher levels to supply the utility grid. Another reason is the availability of a single line between the microgrid and the neighboring busses. However, there are several other alternative lines to other costumers which reduce the line loadings for near point of connections. In other scenarios, power exchanges between the microgrid and the network are not too high and therefore, the impact of the microgrid is low.

4. Discussions and Conclusion

In this study, the most critical operating conditions for LV distribution networks with microgrids are investigated. Using previously developed virtual test bed and a small scale LV network model, several scenarios are simulated for different points of connection.

The study provides several valuable outcomes that can be used both for network planning and for network operation. During the planning stage, the main aim should be the minimization of the impedance between the microgrid and the network. In order to achieve that, it is more preferable to connect the microgrid closer to the substation. In addition, the number of connections between the microgrid and the neighbouring consumers can be increased.

After deciding the location of connection, the microgrid equipment capacities can be scaled considering the two most extreme cases, which are maximum supply/minimum demand and maximum demand/minimum supply in both the microgrid and the network.

It should be noted that the microgrid used in this study is a three phase balanced system. Additional analysis is required for unbalanced loadings and for single phase microgrid connection cases. Transient analysis can also provide more valuable insight about new advanced operational approaches. Further studies are planned for long-term operation of the microgrid with the network by integrating daily supply/demand profiles. It can be done to see the occurrence rates of critical cases in daily operation.

Acknowledgments

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