Impact of On-Load Tap Changers and Smart Controllers on the Distributed Renewable Energy Hosting Capacity

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Abstract- In the course of the global energy transition, the power infrastructure is subject to fundamental change taking place at unprecedented speed. Existing electrical networks are increasingly exposed to operation near their technical and thermal limits due to the impact of grid-integrated renewable energy sources as well as by variable loads such as electric vehicles. Most current networks were not designed to operate under today's conditions. Distribution network operators are taking measures to keep their networks complaint to grid codes while considering the pressure to integrate variable distribution generation and consumption units to meet the climate goals. It is a challenging task to operate distribution networks with high volatility in the generation and consumption. New technologies, such as smart transformers, battery storage systems, and advanced load and generation controllers, have emerged to help mitigate the effects of distributed renewables and variable loads, but established technologies, such as on-load tap changers, can also provide very effective solutions for increasing the hosting capacity of variable renewable energy resources, as demonstrated in this paper. Simulation results show that on-load switches combined with smart controllers can improve the hosting capacity by a factor of 1.92 in distribution feeders where overvoltage is the main constraint to the integration of distributed renewable energy sources.

Keywords On-load tap changers, smart grid technology, hosting capacity, integration of renewable energy resources, power quality, voltage regulation, distribution network operator.

1. Introduction

In regard to the commitment to increase the shares of renewable energies to meet the global 1.5 °C climate target and decarbonize the electrical power system, distribution network operators face significant challenges to maintain voltage stability, low power losses as well as secure and stable system. However, many governments worldwide are adopting policies to integrate distributed renewable energy sources (DRES) in Low Voltage (LV) networks [1], such as rooftop photovoltaic (PV) systems and small-scale wind and biomass plants. DRES are weather-dependent and any change in the weather impacts the generation and hence the power quality.

Voltage levels rise when the infeed power by solar PV increases, and energy consumption is low. Abnormal voltage stress can cause damage to the insulations of power equipment as well as of household devices. Other problems such as increasing short circuit current and power quality issues can also limit the Hosting Capacity (HC) of the RES in distribution networks [2].

1.1. Improving the Hosting Capacity Methods

HC in distribution networks can be limited by voltage violations, overload of lines and transformers, increasing of short circuit power and power quality issues (i.e. harmonic distortions, and flickers). Different methods and technologies were developed to improve and increase the HC in distribution networks. The following sub-sections provide an overview of some of these methods.

1.1.1. *Reactive Power Control*

Reactive power control provided by the DRES power inverters can support the regulation of the voltage at the connection point. In distribution grids, reactive power control can be used to limit the voltage rise caused by DRES. A study in [3] shows that the hosting capacity can be improved by approximately 20% using power inverters with reactive power control functionalities.

1.1.2. *Network Reconfiguration*

Network reconfiguration is a less common method to increase the HC. It requires a complicated yet flexible infrastructure to ideally change the topology of the network. Two methods have been identified [4]: static and dynamic network reconfiguration. In case of static reconfiguration, the topology is planned and executed without the possibility to change it again. On the other hand, dynamic reconfiguration involves switches, information and communication technology and different protection devices to actively adjust the topology according to the actual network conditions. By changing the topology, the power flow can be redirected from the loaded feeders to less loaded ones and hence, balancing the power flow in the system.

1.1.3. *Energy Storage Systems*

The most common form of energy storage systems in Low Voltage (LV) networks is Battery Energy Storage Systems (BESS) and they are used mainly to manage the demand of electricity in peak hours. The BESS can reduce the loading of the equipment, by smoothing the peak demand, and provide a support to the voltage, by regulating the reactive power at the connection point.

1.1.4. *On-Load Tap Changer (OLTC)*

OLTC transformers are normally used in high voltage substations for nearly 90 years [5]. Their applications in distribution networks are recently gaining attention due to their ability to dynamically control the voltage. Transformers with OLTC can adjust the voltage on the secondary side while connected to the load.

This paper analyses the use of OLTC in combination with Phasor Measurement Units (PMU) and smart controllers, to achieve an optimal regulation of the voltage which maximize the hosting capacity of the grid.

PMUs are measurement devices which provide high-resolution, time-stamped, spatial, and temporal measurements of the state of the power systems [6]. Voltage is measured at the LV nodes of the distribution feeders and elaborated by the smart controller to dynamically calculate the optimal set point of the transformer tap changer. The set point of the tap changer will depend on the minimum and maximum voltage measured in the feeder, which varies in function of the RES generation and network loading conditions.

In this research, OLTC power transformers, PMUs and smart control algorithm are used to study their effect on the HC.

1.2. *Methodology*

Two LV feeders, named Village 1 and Village 2 are analysed, both supplied by MV/LV transformers with a rated power of 100 kVA. Each feeder has two main branches, with 5 to 6 nodes each. Each node provides power to a variable number of households, see Fig. 1.

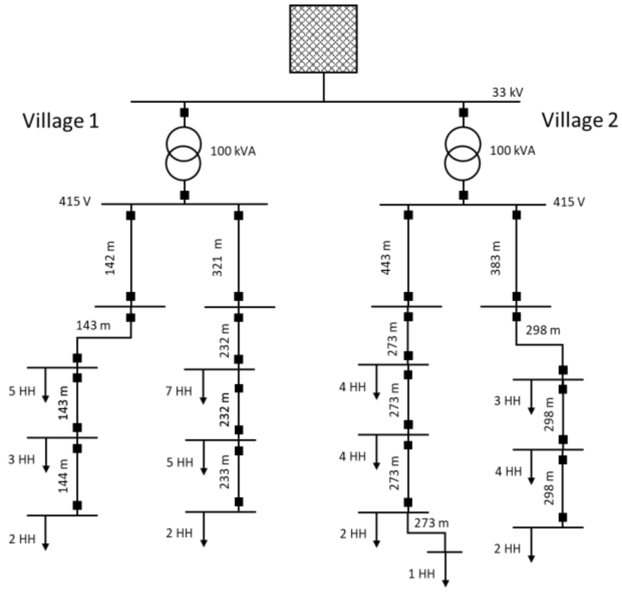

Fig. 1: A typical distribution network with two distribution feeders

The analysis evaluates the potential deployment of PV generation systems in the above LV feeders. A Monte Carlo (MC) method is used to consider the randomness of the number of PV installations and relevant location of the connection points. At each iteration of the MC analysis, a random number of PVs are selected for each feeder, and these PVs are randomly assigned to different connection nodes of the LV grid, with uniform probability.

After the selection of the number of PVs and connection nodes, the rated power of the PVs is gradually increased and a time series load flow is conducted for a typical day of operation, with time steps of 15 minutes. When voltage or loading constraints are reached, the simulation stops and passes to the next MC iteration, until all the iterations are consumed.

Two case studies have been analysed, with MV/LV transformer equipped with no-load tap changer (NLTC), a standard solution for LV systems and OLTC, controlled by a smart algorithm balancing the maximum and minimum voltage on the feeder, to allow maximum DRES penetration. The algorithm is continuously equalizing the module of the difference between the maximum voltage U_{max} and 1.0 p.u. and the minimum voltage U_{min} and 1.0 p.u., as per following equation:

$$|U_{max} - 1.0| = |U_{min} - 1.0|$$

2. Simulation

Fig. 2 shows a comparison of the simulation results between the two case studies, for the two feeders, named Village 1 and Village 2.

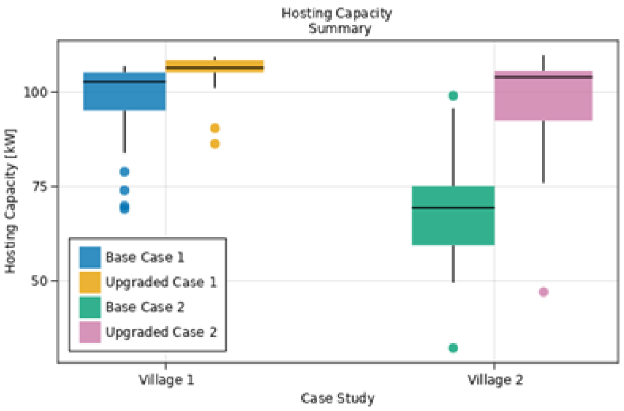

Fig. 2: HC using no-load and on-load tap changers

Here the Base Case refers to the case study with transformers equipped with NLTC, while the upgraded case refers to the simulations with OLTC and smart controllers.

The improvement of the HC of the feeder Village 2 is very significant, the mean values of hosting capacity rise from 68 kW to 97 kW (a ratio of 1.42), while in Village 1, the improvement is much limited by the MV/LV transformer loading.

As expected, the use of OLTC and smart controllers would have most benefits in feeders where voltage constraints represent a major limiting factor for the HC (i.e., Village 2). The calculated ratio of improvement of 1.42 could be even higher if a larger transformer size were adopted.

In Village 1, on the contrary, the HC limits for voltage and loading constraints are comparable, and therefore the increasing of DRES is soon limited by the loading of the transformer. In this case, the adoption of OLTC shall be combined with an increase in the size of the MV/LV transformer.

The results of Fig. 3 show the hosting capacity calculated in each iteration of the MC analysis (first 40 iterations), with NLTC (Base Case) and OLTC (Upgraded Case). Each iteration is the results of a time series analysis, where the PV injected power is increased till the voltage or loading constraints are reached. Values of hosting capacity around 100 kW are mostly limited by the transformer loading, while lower values are limited by voltage violations.

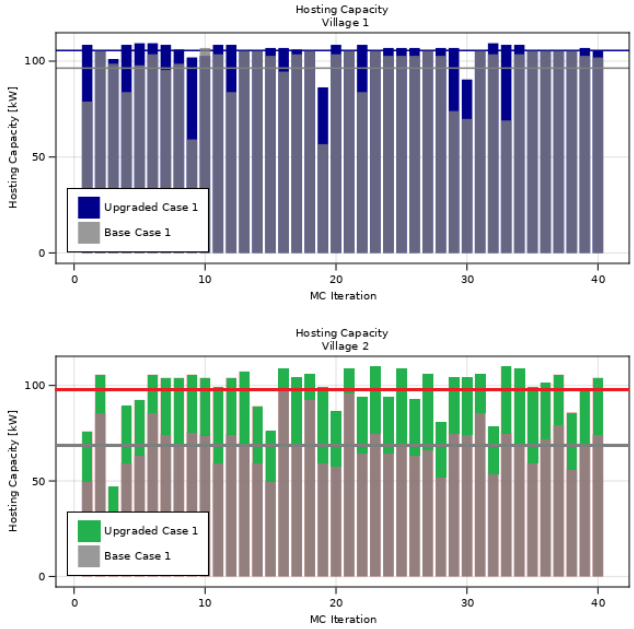

Fig. 3: HC for each iteration in Village 1 and Village 2

The two horizontal lines in the diagrams of Fig. 3 represent the expected value (mean) of hosting capacity with and without the adoption of OLTC and smart controllers. The results confirm major improvements for Village 2, where voltage constraints represent the major limiting factor of the HC.

Note: The HC calculation algorithm allows small overloads in the equipment to simply accommodate the progressive increasing of PVs during the calculation. Otherwise, we could stop the simulations to loading values strictly below 100%. Both approximations would lead to comparable results.

3. Optimization of the Voltage Control

The mechanism for which the hosting capacity increased with the use of transformers equipped with OLTC can be understood by analysing one of the MC iterations in more detail, as in the Fig. 4, which refers to the results of Village 2.

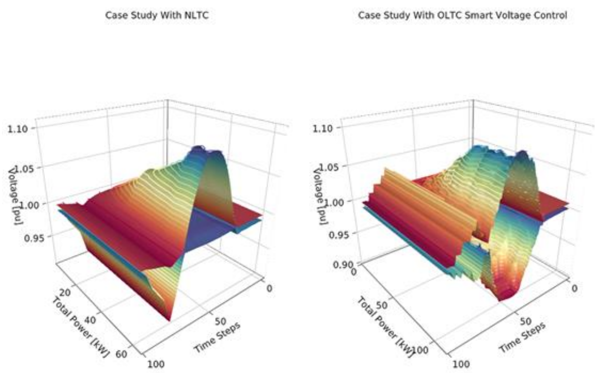

Fig. 4: Voltage profile and total power vs. time steps

Fig. 4 shows the voltage profile (z-axis) in function of the total power injected by the PVs (y-axis) and the hour of the day (x-axis), indicated in the form of time steps (96 quarterly hours of a day).

The left subplot in Fig. 4 shows that the voltage is reaching the maximum allowed threshold of 1.10 p.u. at a maximum power of about 54 kW of PV power. As there is no voltage control at the transformer terminals, the shape of the surface diagram is the results of the PV contribution and load profile only, and it is not symmetrical. On the contrary, the subplot on the right of Fig. 4 shows a symmetrical profile of the maximum and minimum voltage in the feeder, exploiting the maximum range of permissible voltage, and maximizing the hosting capacity.

For the case study with OLTC, a maximum PV power of about 103.2 kW is calculated, touching the loading limits of the MV/LV transformers.

The same results are presented in the Fig. 5. Here the plots show different curves for different levels of PV injected power.

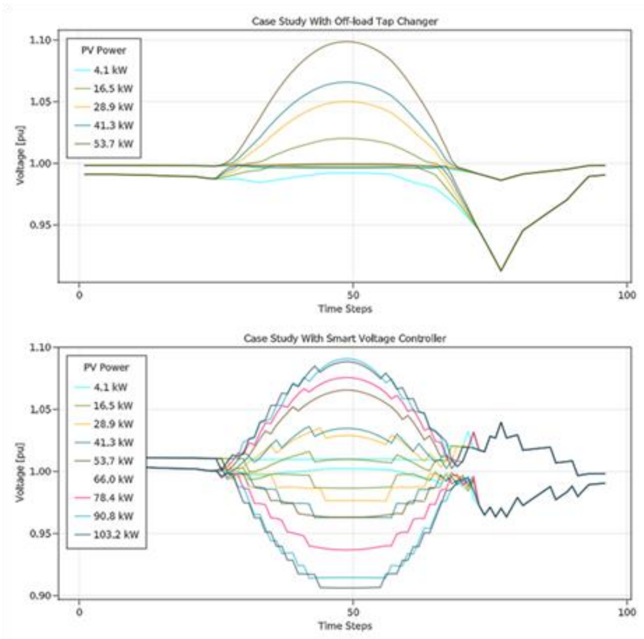

Fig. 5: Voltage profiles using NLTC and OLTC

According to Fig. 5, for this specific MC iteration, the hosting capacity is improved by the use of OLTC and smart controllers by a factor of 1.92 (from 53.7 kW to 103.2 kW). In this specific iteration, with the OLTC and smart controller, voltage is no longer a constraint, and the limiting factor for hosting capacity become the transformer loading. As a confirmation of this fact, the relevant diagram in Fig. 5 (subplot in the bottom) is not reaching the 1.10 p.u. or 0.90 p.u. boundaries

4. Conclusion

The simulation results show that OLTC, PMUs and smart controllers can contribute to significantly increase the HC in networks, where voltage violations represent the major impeding factor. A factor of 1.42 improvement of the HC is reached in average for the simulated cases of Village 2, where voltage violations represented a major constraint.

In networks where overloading of equipment represents the major obstacle, traditional network expansion measures should be investigated first.

In all cases, replacing transformers with units of higher rated power equipped of OLTC and smart controllers provide a promising solution to increase the HC of DRES.

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