21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

The use of innovative tools in the medium voltage grid development, a case study of series voltage regulator

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Abstract: The rapid technological improvements concerning the renewable energy sources and the energy policy of the European Union, and the National Energy Strategy are leading to a rapid increase in the number of intermittent renewable power plants. Thus, new challenges emerge in the operation of the distribution system. To operate the system efficiently, the use of innovative technologies must be considered, because conventional network development strategies cannot always provide an optimal solution for the problem. This paper analyses the effects of large-scale wind power generation on a medium voltage system and a solution of the problems faced through a case study of a serial voltage regulator. The difference between the profiles of generation and loads causes the residential transformers at the end of the line to encounter large, more than 8% voltage fluctuation. To assess the site's voltage profile, time series symmetrical load flow calculations were performed. After the thorough analysis of the circumstances a serial voltage regulator device was implemented at 3 different nodes of the system and a placement analysis was carried out with statistical tools. The results showed a 3% decrease in the voltage fluctuation at the end of the line even when the device was far from these nodes; and with an optimal placement, the device could halve the largest voltage fluctuation on the line.

Key words

Voltage fluctuation, Renewable energy integration, Voltage control, Time series Simulation, Serial voltage regulator

1. Introduction

The rapid technological development of renewable generators and the energy politics of the European Union (RepowerEU, FF55, Net-zero) leads to the large-scale integration of intermittent renewable power plants into the distribution system. Until 2030, the European Union plans to reach the integrated photovoltaic capacity of 600 GW [1][2][3]. This number also affects the Hungarian Transmission System Operator and Distribution System Operators (DSOs) on the national level. The National Energy Strategy of Hungary is planning the integration of over 6300 MW power of photovoltaic generation by 2030 and 10000 MW by 2040, which is quite large compared to the highest system load of around 7200 MW [4]. The Hungarian medium and low voltage (MV and LV respectively) distribution system mostly consists of overhead lines [5]. With the high penetration of the intermittent generators and the typical characteristics of the Hungarian distribution system (long overhead lines with high resistance to reactance ratio), these renewable generators create high voltage fluctuation at the end of the feeders [6][7]. This problem can be solved with conventional grid development solutions (increase in line cross section, establishment of new substations etc.), but with the DSOs lack of time and human resources, these development methodologies are not necessarily efficient. To be able to integrate the previously stated numbers of generators, DSOs need innovative solutions that can be deployed quickly and may act flexibly.

This paper focuses on innovative tools of the grid development strategies to solve problems arising from relatively large-scale voltage fluctuation on an MV distribution line with large amount of wind generation. Section 2 discusses the used methodologies and the technological attributes of the series voltage regulator (SVR). The case study parameters, such as load, and generator measurements are presented in Section 3. This section also discusses the placement concept and the statistical analysis of the results. At the end of Section 3, a proposal for the optimal placement of the SVR is made. Section 4 summarizes the results and the proposed methodologies of the paper, and a conclusion is made. The method outlined here provides a general approach for DSOs to the assessment of SVR investments, which seems a more promising technology due to the proliferation of renewables. This technology is relatively new for the Hungarian DSOs, previously there had not been such a device integrated into the Hungarian grid.

2. Methodologies

A. Country-level regulations and standards on voltage quality

The MSZ EN 50160 regulation (which applies to all Hungarian DSOs) states about the effective value of line voltage (MV and LV) that 95% out of the average value of the 10 minutes measurements in a week range, must be in the range of ±10%, while for the LV network must always be in the range of +10% -15% range [8]. DSOs define guaranteed voltage quality services that contain an even smaller range for voltage magnitude, which must not be higher than ±7.5% [9]. Unlike most European distribution systems, the grid in Hungary mostly consists of long overhead lines and often with small cross sections. This results in great voltage drops and in large voltage rises due to the application of intermittent generators. The difference in time of the generation and load causes high voltage fluctuation at the end of the line, which usually results in the contravention of the rules stated by the regulations. The MV wide range of voltage fluctuation which occurs at the MV line without breaching the regulations does not mean that the LV lines operate also in the stated range. Due to the decrease of voltage fluctuation on the MV line, thus the decrease of LV bus voltage fluctuation makes it possible to connect more generators or loads to the distribution grid.

B. Solutions for the voltage fluctuation problem

Distribution system voltage regulation is not a novelty, many options are available depending on the source and the location of the problem. For example, a MV/LV on-load tap changing transformer (OLTC) can regulate the voltage fluctuation coming from the MV side and provides a much smoother range of voltage for the customers at the LV side. This paper analyses a MV line with large penetration of wind turbines, and to solve this problem the application of a Series Voltage Regulator (SVR) device was chosen.

The SVR device is practically a series OLTC transformer. It shares the same logic as a regular OLTC transformer, but the technological representation is different.

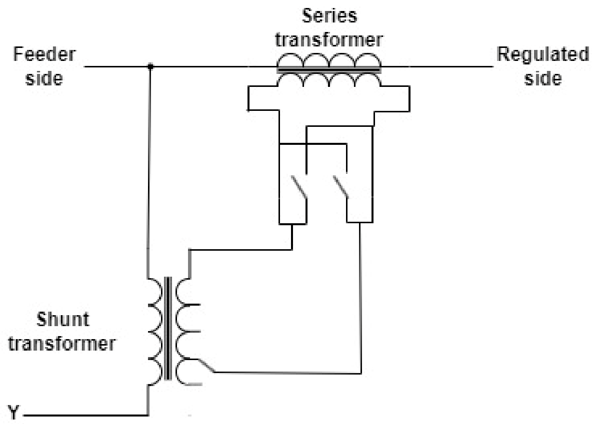

Fig. 1. 1-phase figure of an SVR

In Fig. 1, a 1-phase diagram of an SVR device is presented. This concept has 2 main components, 1 shunt transformer (feeder transformer) and 1 series transformer (booster transformer). The feeder transformer's primer side is in star connection with the other phases to supply the line voltage value for the secondary side. The tap switching module is located on the secondary side of this transformer. The regulation shorts a defined number of windings on the secondary side, which means that the voltage value that supplies the feeding of the booster transformer is regulated. The switches before the booster transformer are the polarity switches. These switches may switch the polarity of the primer side of the booster transformer, and with that, can increase or decrease the voltage on the line [10].

C. State of the art in series voltage regulation

DSOs in other countries have already integrated SVR devices into their grid. For example, the German DSO Westnetz integrated an 8 MVA device into one of their 20 kV MV grids. A grid study was performed which concluded that other grid development methods are not economical for their use-case. Consequently, an SVR device was implemented. Their chosen grid is a long (25 km) MV line with high renewable penetration. These aspects result in high voltage fluctuation along the line. The pilot concluded that the SVR can effectively manage the voltage fluctuation caused by these generators [10].

Reference [11] showcases how more than 1 SVR can manage the voltage of extremely long MV lines. Integrated into the around 200 km long grid in Thailand was a mini hydro generator. The paper also concluded that there is a direct connection between the output power of the generator and the placement of the SVRs [11]. Another study presents the negative effects of the 1-phase generators on the grid and provides a compensation solution with SVR devices [12].

A solution for the power quality unbalances caused by mechanical switches of the SVR is proposed in [13]. It compares and analyzes the use of their novel solution with a normal mechanical stepped SVR regarding power quality [13]. With the ever-growing generator capacity integrated into the grid, Hungary needs fast and effective reaction; therefore, these innovative devices like SVR are important to be piloted to gather information for future implementations.

D. Network model and input data

The simulation study was done in Pandapower, which is a Python-based programming environment [14]. The goal was to simulate an MV line with high renewable penetration, and to analyze the voltage magnitudes along the line in the presence of the SVR with time series load flow calculations. For this, a real MV line from Northwestern Hungary was chosen. The network data was provided by the local DSO. The chosen network is a good representation of typical MV networks in the country. For the load and generation profiles, measurements, and Synthetic Load Profiles (SLPs) were used. SLPs are synthetically generated data, which represent different customer profiles [15][16]. With SLPs and the yearly consumption curve of electrical energy, the DSO can forecast relatively realistically the consumption of different load groups, such as industrial, residential, commercial and municipality groups. Time series measurements were available for all the generators and for all MV customers on the line. The LV customer effects were simulated with concentrated loads at the MV/LV secondary substations. This customer data was available in different SLPs for each group, and these were aggregated onto the MV feeder. The accuracy of the load profiles was later validated with real measurements from the regional grid operators' Supervisory Control and Data Acquisition system (see Section 3). The used data made the time series load flow and loading analysis possible, which were used to determine the voltage magnitudes at every 15-minute step.

3. Simulation study

This section covers simulation studies performed in the chosen programing environment. The case study covers an example from a real-life area, and the characteristics are quite usual in rural MV power grids in Hungary.

Table 1. Conductor parameters in the network model

std_type	length_km	r_ohm	x_ohm
_3×50_AASC_22_kV	3.571	2.399712	1.3801915
_3×95_AASC_22_kV	17.11275	6.17770275	6.213639525

Table 1 contains some of the used conductors of the network. As the data shows, the resistance to reactance ratio of most lines is around 1. This proves that this network is an accurate representation of a typical Hungarian MV network. The network contains over 31 km line, out of which the feeder length is 12.54 km.

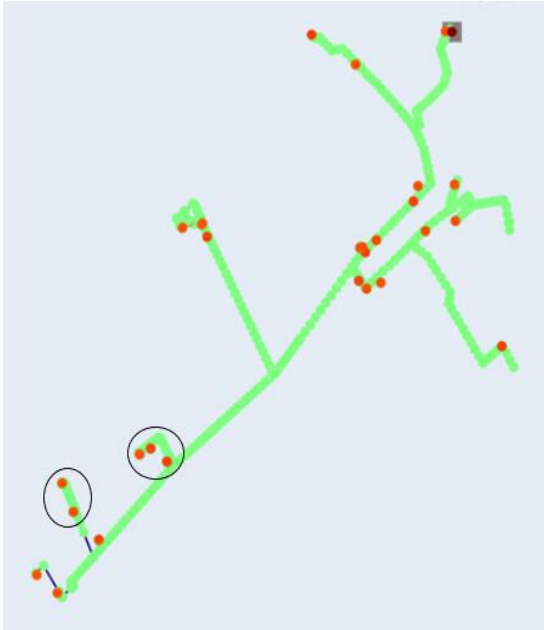

Fig. 2. The examined network

Fig. 2 shows the considered network topology. The red dots are the locations of the MV/LV transformers connected to the 22 kV MV distribution grid. These were the transformers where the concentrated loads were applied. Besides the concentrated loads, time series measurements of active and reactive power values were available from the MV customers and from the wind turbine MV/LV transformer. The substation (external grid in the simulations) is in the right top corner, marked with a gray square. The lack of voltage measurements of the external grid forced to set the voltage magnitude to a constant value: 1. This simplification is acceptable with the HV/MV transformer OLTC module and the usage of 15 min measurements. At the end of the line, there are 6 MW of wind turbines the transformers of which are marked with black circles. Current measurements from the high-voltage transformers MV side were available, from those the apparent power values were calculated.

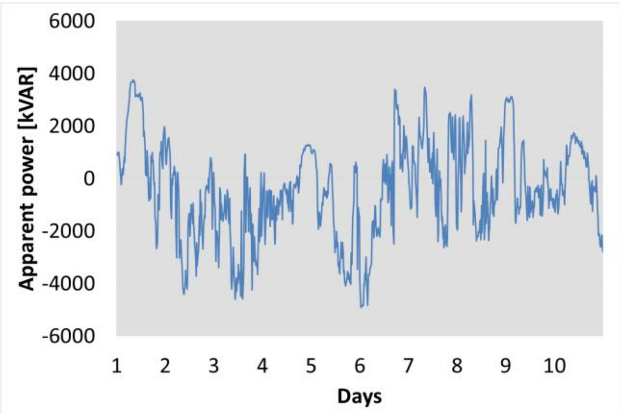

Fig. 3. Calculated Power values at the HV/MV transformer

Figure 3 represents the power values flowing through the HV/MV transformer in a year range. The size of the data being handled forced the limitation of the simulation time.

With this in mind, a time range of 30 days was chosen. It is noticeable that the highest power value flowing back to the HV grid was around -5MW, and in April a wide range of flowing power was witnessed. This high value of power flow indicates to a high range of voltage fluctuation on the line, that is why the month of April was chosen for the simulation.

A. Baseline case

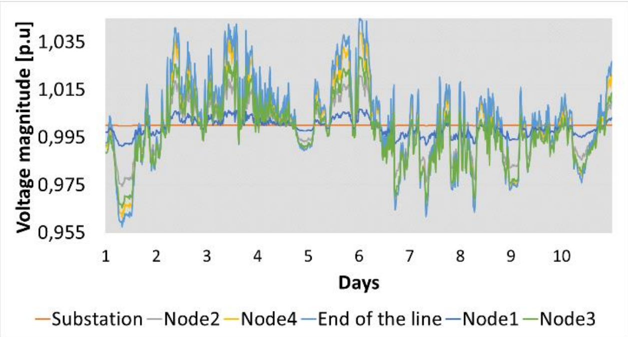

Fig. 4. Voltage magnitude on given nodes of the network

Figure 4 depicts the baseline case (without SVR). To present the problems caused by the intermittent generation of wind turbines, the voltage-time diagram is presented. To present the voltage magnitude curve, 6 nodes were chosen: the substation, nodes 1–4 downs the MW feeder line, and the end of the feeding line. Even in the middle of the line (node 3) a fluctuation range of over 6% is present. At the end of the MV line, a magnitude of 8% voltage volatility can be seen, which results in the breaching of values engaged in the regulation, because the high value of voltage volatility at the beginning of the LV grid increases along the line.

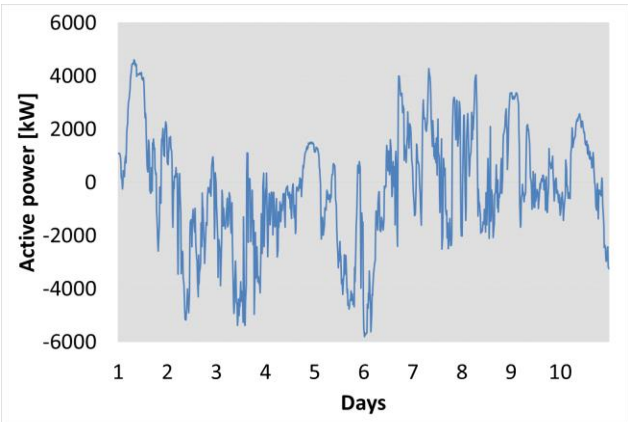

Fig. 5. Summarized transformer (MV/LV) power kW in a range of 10 days simulation

Figure 5 depicts the summarized active power of all transformers in the grid. A comparison of Figures 5 and 3 reveal that the extreme values of the curves are similar.In Figure 5 only the active power values are presented, Figure 3 presents the apparent power values. The imprecision of Figure 5 comes from the neglection of reactive power and the loses on the lines.

This figure represents that the use of SLPs and time series measurements were accurate compared to the measurements from the substation, and the simulation model is a good representation of the real operating state of the system.

B. SVR placement analysis

The chosen simulation environment does not contain an SVR, but with the right parameters, an OTLC transformer can mimic the characteristic of an SVR. Different manufacturers have different technological representation for this device. In this paper, a 10 MW SVR was chosen with a total number of 33 taps (+/-16) and a tap step percent of 0.625%, which results in a voltage regulation range of ±10%. For transformer losses, the values of a real SVR were taken, around 0.73%.

The placement analysis discusses the optimal location of the device. 3 different placements were simulated, each considering a different aspect, and a tradeoff between satisfying all (MV and LV) or just certain customers. The different placements are presented in a certain order. The first 2 (number 2 and number 3) represent the two extreme options: number 2 being upstream, close to the residential customers at the beginning of the line, while number 3 is downstream, regulating the connection points of the wind turbines. After the conclusions of these 2, placement number 1 is presented, which results the lowest fluctuation range at all nodes on the line.

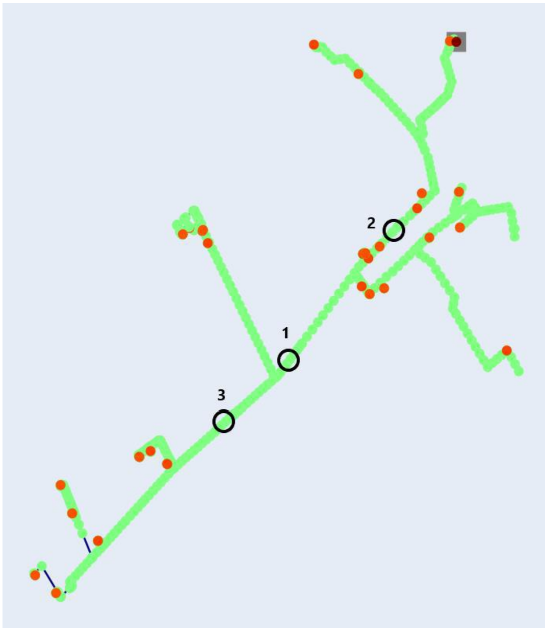

Fig. 6. Placements of the device

Figure 6 shows the different placements for the effect analysis.

Placement number 2 takes into consideration the communal LV transformers near the substation. With this option, the negative effect of the high wind generation at the end of the line cannot be fully eliminated, thus there is still a high level of fluctuation.

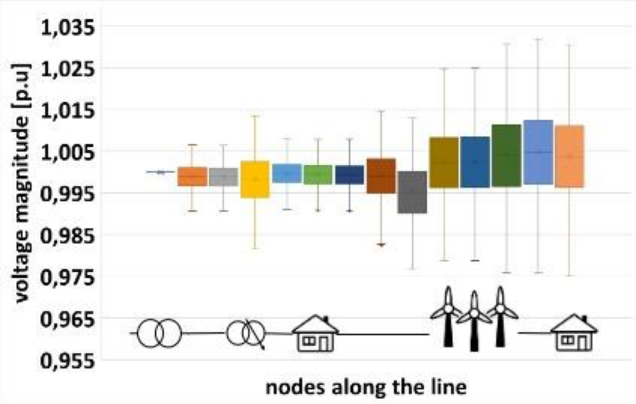

Fig. 7. Voltage magnitudes along the line (placement number 2)

Figure above is a box-plot diagram for selected nodes of the feeder. The different colors represent different variations of voltage magnitude at nodes of the line. The selected nodes are critical in the measurement of the voltage magnitude. These are for example the end of the lines connected to the main feeder MV line. the connection points of MV loads and the wind generators. The upper and lower part of the box itself signals the upper and lower quartile of the variation, which means the area of the box corresponds to 50% of the results. Outside the boxes the other 2 quartiles are marked by the whiskers. Thus, the figure presents the full range of voltages, the boxes are arranged in the order which they are present in the network model.

Figure 7 shows the effects of the control: from left to right, the boxes show the variation of the voltage magnitude values in 30 days along the line (from the high-voltage transformer). As one would expect, the voltage fluctuation effect widens downstream, at the end of the line a range of 6% is present. The decrease of voltage fluctuation after the yellow box signals the presence of the SVR.

Placement number 3 focuses on a different aspect of the network, where the boundaries of using the SVR device can be represented. This placement focuses on the nodes downstream, more precisely the nodes of the generators.

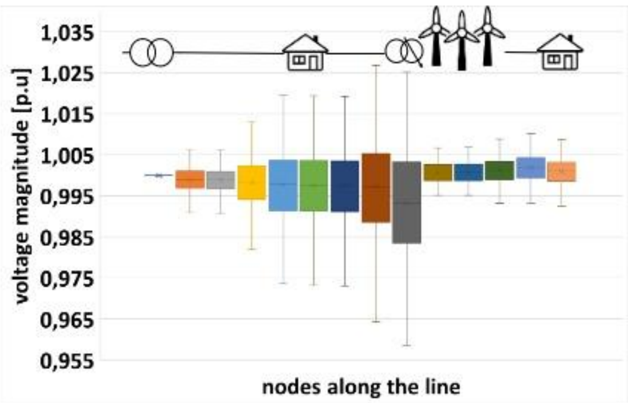

Fig. 8. Voltage magnitude along the line (placement number 3)

The effects of the control can be recognized with the reduced volatility after the grey box downstream.

In this case, the MV/LV transformers at the beginning of the line, whose bus voltages were secured with the previous placement, face a great magnitude of fluctuation. The device does not affect the voltage magnitude of the nodes further up the line, because power still flows freely back to the HV/MV substation, and this affects the nodes further upstream.

Placement number 1 is a tradeoff between the previous two options. This combines the previously mentioned use-cases.

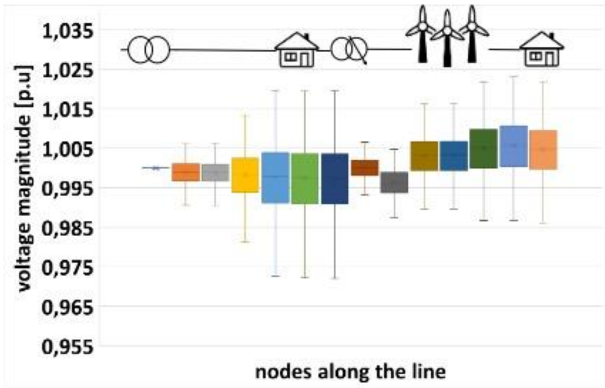

Fig. 9. Voltage magnitudes along the line (placement number 1)

Figure 9 shows that this placement is optimal for the network, the highest value of fluctuation is around 4.7% and at the end of the line it is only 3.4%. If this placement is applied, customers suffer from a lower range of fluctuation near the substation and at the end of the line as well.

C. Optimal placement of the device

The previous sections provided information and results about the time series simulation that was carried out with the chosen network. 3 different options were presented to decide the location of the SVR. To make such decision, other factors must be taken into account as well. The high voltage fluctuation does not call for this kind of voltage regulation directly, MV industrial customers should endure such ranges of fluctuation. The problem of the network stated in this paper could be solved with the switching of regular MV/LV transformers to OLTC transformers, but this comes with a different range of expenses, much higher than the device suggested here. On the one hand there is a small town connected to the line upstream from the generators. On the other hand, there are also residential customers at the end of the line. For these reasons, the voltage magnitude needs to be regulated on the whole network. Therefore, the optimal location for this device is placement number 1, but the type of the customers should be always considered by the integration of such device.

4. Conclusion

The rapid increase in the number of intermittent generators in the distribution system calls for new, fast and value efficient innovative solutions for grid development. This paper discusses the problem integrating a high value renewable power plants into the grid and provides solution for voltage fluctuation caused by these generators. SVR can effectively solve the voltage fluctuation problems caused by the high penetration of wind turbines at the end of the MV distribution line. The effect analysis study offers a look into the challenges of deciding the placement of the device. The simulation results are examined with statistical tools and the optimal placement for this network is concluded. The type, amount and placement of the loads and generators all need to be considered in the placement of an SVR device. For the MV customers 8% voltage fluctuation is not critical because their connection is short in length to the grid, or they have their own voltage regulation methods. On the other hand, for LV customers this range on the MV line summarized with the fluctuation of the LV grid results in a much wider range. Therefore, they are more sensitive for this problem, and it is the DSOs task to provide a decrease in fluctuation for the customers. Based on the results, DSOs can understand the value of an SVR device from a realistic case study. The time series-based load flow analysis presented in this paper proves that it can be an accurate methodology to find the optimal placement for such a device. Section 3 presented a real-life example of the challenges in finding the optimal placement for an SVR. This paper also shows the limitations of the device, which is the inability to solve the voltage rising effect of the reverse power flow, upstream from the device.

Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation Programme through the Project OneNet under Grant 957739.

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