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Strategic Placement of Low Voltage Connected Voltage Regulation Devices

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SUMMARY

A methodology for locating low-voltage connected voltage regulation technologies to mitigate undervoltage conditions throughout a given distribution circuit is proposed in this paper. In particular, the placement of a unified power flow control (UPFC) and multiple static voltage compensators (SVC) is assessed. Siting is driven by the magnitude and duration of the undervoltage conditions estimated for each low voltage service using a quasi-static time-series (QSTS) model of the distribution feeder. An iterative evaluation process, siting each device one at a time, is employed to effectively capture the influence on neighboring services as well as to enforce additional siting constraints. The placement methodology is applied to a representative 12.47-kV distribution feeder where one UPFC and 15 SVC devices are available for deployment. Prior to deployment, QSTS simulation of the circuit estimated that during the highest summer peak load day, as many as 12.2% of service points experienced undervoltage violation of below 0.95 pu between 1 and 8 pm for a total of 377 minutes. These undervoltage conditions are clustered in three relatively enclosed neighborhood. Using a limited number of strategically located edge-connected voltage regulation devices, QSTS simulation shows that the placement approach was able to completely eliminate undervoltage conditions. Furthermore, it is interesting to point out that about 9.5% of the service points experience voltages between 0.95 and 0.96 pu while the remaining points (90.5%) have voltages of higher than 0.96 pu.

KEYWORDS

Distribution circuit, in-line power regulator, static voltage compensator, voltage regulation, undervoltage area

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INTRODUCTION

Coordination of real and reactive power in distribution systems is becoming increasingly important and more complicated. Traditional distribution circuits have employed load tap changer (LTC) transformers, line voltage regulators, and fixed or switched capacitor banks for managing voltage and reactive power. These devices are installed on the primary feeder and are electromechanically controlled to perform voltage regulation. These approaches accomplish the traditional goals of minimizing overall reactive power flows on the distribution system and managing the voltages within the required limits. However, in the competitive market environment existing today, distribution utilities are focused on improving their operational efficiencies, minimizing losses, and improving service quality. New operation requirements like conservation voltage reduction (CVR), secondary-side voltage reduction for load management, and loss minimization cannot be achieved by using traditional voltage regulation methods. Another issue associated with traditional voltage regulating devices is their inherent mechanical nature. Capacitor switching and voltage regulator tap changing are typically limited to three or four times per day which is not sufficient to handle all of the dynamics that may be associated with new loads, like fast charging for electric vehicles (EV), or distributed energy resources (DER) such as photovoltaic (PV) generation and energy storage systems (ESS). These reasons emphasize the need for electronically controlled devices that are able to provide fine control for effective voltage regulation [1].

Modeling, simulation, and advanced analytics are key components to better understanding the performance and application of these emerging technologies as well as their seamless integration into system operations and design. An approach for placing new voltage control technologies, connected at the low-voltage services or "edge" of the distribution system, in order to eliminate undervoltages throughout a given distribution circuit are presented in this paper. In particular, the placement of a unified power flow controller (UPFC) and multiple static var compensators (SVC) is evaluated for an example circuit.

VOLTAGE REGULATING DEVICES

The UPFC is based on a commercially available single-phase, 50-kvar device that can provide voltage regulation as well as reactive power compensation, see [2] and [3]. The series connected device is located between the distribution transformer and end-use customer (at 240V) and can be configured to operate in voltage regulation, power factor correction, or both voltage regulation and power factor correction modes. Additional details on the Quasi-static time-series (QSTS) model used in the analysis can be found in [4]. In this paper, the device is used to regulate the voltage to 1.0 pu.

The SVC units are also low voltage (240V) connected devices. Each unit consists of four 4.375-kvar stages that are shunt connected. They are switched in and out of service to provide voltage regulation or reactive power compensation. In this paper, SVCs are set to provide voltage regulation to the circuit. Required number SVC stages are switched on when the voltage at the SVC location is below 1.0 pu to boost up the voltage to above 1.0 pu. Similarly, the SVC stages are switched off sequentially when the voltage at the SVC location is above 1.0125 pu.

PLACEMENT CIRCUIT

The one-line diagram of the test system is shown in Figure 1. Note that the colors of the distribution lines are in accordance with their distances from the substation, with red indicating distribution lines farthest from the substation and blue indicating those closest to the substation. This circuit has a 69/12.47-kV 10.5-MVA substation transformer with a load tap changer (LTC) control and three single-phase mid-line voltage regulators installed in each phase. Seven switched capacitors (five three-phase capacitors and two single-phase capacitors) are installed along the feeder to provide voltage regulation and power factor correction. Additionally, each distribution transformer is explicitly modeled and an equivalent secondary service is assumed connecting the equivalent lumped load.

QSTS simulation of the test circuit – before including the additional voltage regulation devices – is performed for a 24-hour peak day at a 1-minute resolution. The detailed simulation results are illustrated

in Figure 2. The statistical summary of the load voltages is contained in Figure 2(a) with the contour of the probability density function is plotted along with the lines corresponding to the minimum, mean, and maximum voltages. The contour's color signifies the count (in percent) of customer voltages at a particular magnitude for each time step. The total reactive power output of the capacitors over the course of the peak day is presented in Figure 2(b). Although all capacitors are switched capacitors, only 900-kvar and 600-kvar capacitors switch on and off regularly. All 1200-kvar capacitors are always offline, but both 50-kvar capacitors are always online.

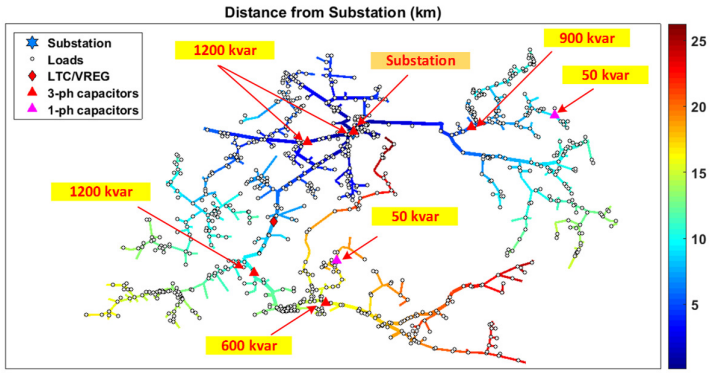
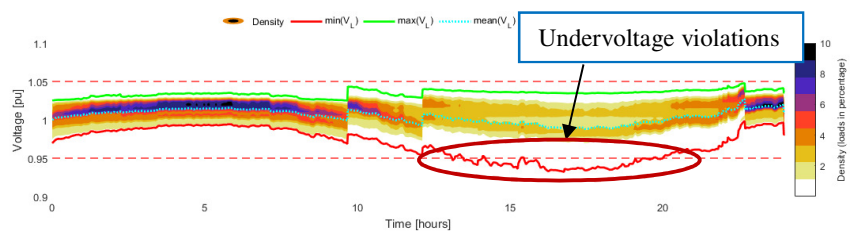
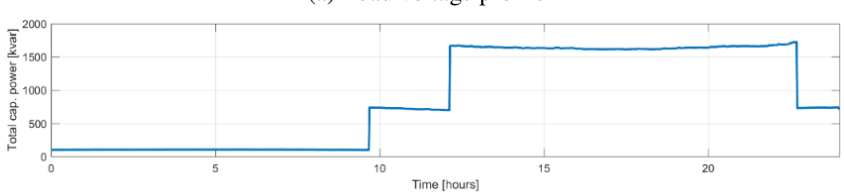


Figure 1. One-line diagram of the test circuit

As shown in Figure 2, the undervoltage violations (voltage less than 0.95 pu) occur during a 377-minute period between 1 and 8 pm. However, given the regulator operation, the lowest voltage and the maximum number of service points experiencing undervoltage conditions is not coincident. While not performed in this study, the incorporation of AMI data could potential be used to better model the load diversity and corresponding temporal variations in the expected service voltages. Nonetheless, approximately 12.2% of the service points are indicated to experience undervoltage conditions during the course of the simulated peak day.



(a) Load voltage profile



(b) Reactive power produced by the capacitors

Figure 2. Base case QSTS simulation results

PLACEMENT CRITERIA

Three potential criteria, as illustrated in Figure 3, could be considered for the device placement in response to undervoltages: lowest minimum voltage magnitude, longest undervoltage duration, and largest undervoltage area. As shown, the undervoltage area is simply the area bounded by the voltage profile curve and the voltage threshold line. For this study, a 0.95 pu voltage threshold was initially assumed and the voltage curves are obtained for each load through the QSTS simulation.

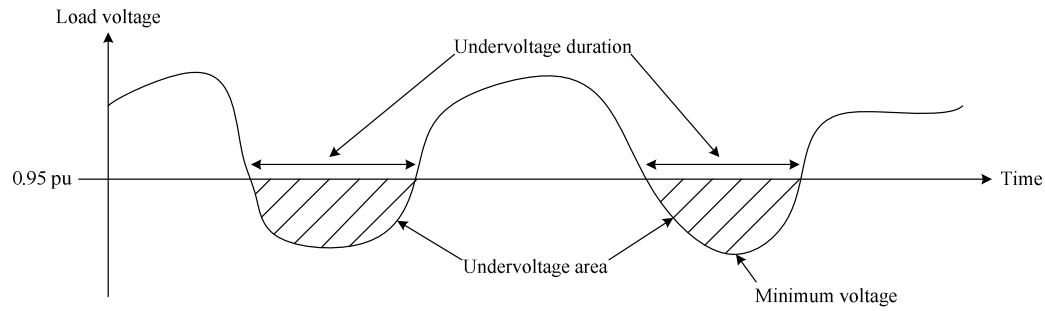


Figure 3. Voltage profile with minimum voltage magnitude, undervoltage duration, and undervoltage area

To best utilize the UPFCs and SVCs, the devices need to be placed at locations with the most severe undervoltage conditions. Characterization of the undervoltage conditions, however, needs to consider both magnitude and duration of the undervoltage condition [5]. While these metrics can be calculated individually, the undervoltage area provides a more robust indicator of how to strategically site a limited amount of dynamic reactive compensation to mitigate long duration voltage deviations. Specifically, it reduces the likelihood of bias in the criterion introduced by extreme but relatively temporary deviations.

Heat maps showing each service point's minimum voltage, undervoltage duration, and undervoltage area are presented in Figures 4 through 6, respectively. In these maps, each service point is represented by a single dot whose color represents the specific value of the respective metric computed based on the 24-hour simulation results. The maps show that the locations of undervoltages are clustered in three areas. The two areas on the left and in the middle of the figures (marked with red circles) are on one phase, while the area on the bottom right of the figures (marked with a blue circle) is on a different phase.

Finally, only a single device is permitted to be located at any given service point location – given physical installation constraints. Furthermore, as it is a series device and rated for 50 kVA, the location choice for the UPFC is limited to distribution transformers that are 50 kVA or less to avoid overloading of the UPFC.

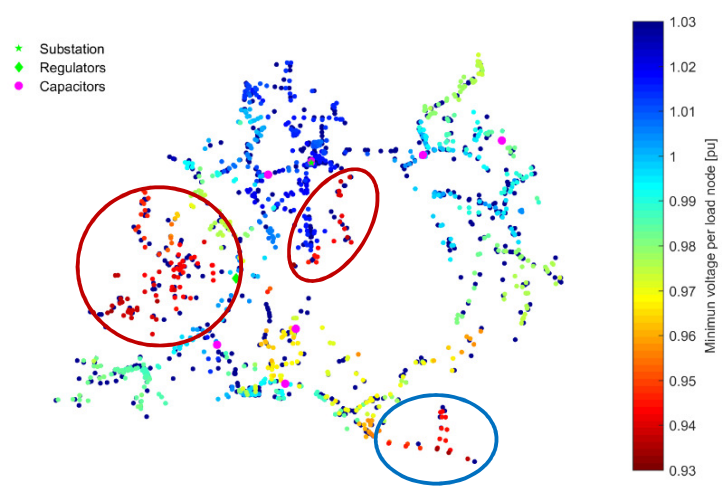


Figure 4. Base case map of minimum service voltages per location and clusters with voltages below 0.95 pu.

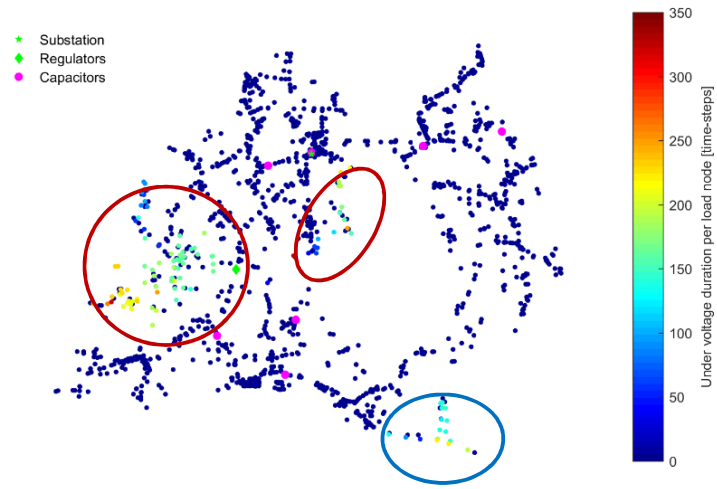


Figure 5. Base case map of undervoltage duration per location and potential groupings.

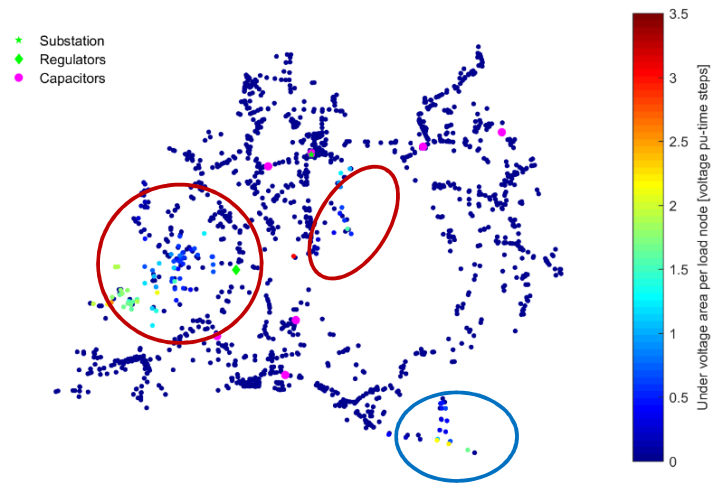


Figure 6. Base case map of computed undervoltage area per service point and potential groupings.

PLACEMENT METHOD

Potential locations for UPFC and SVC are selected to maximize the performance of the devices in eliminating the undervoltage violations. The placement procedure involves the following steps:

1. Perform the peak day QSTS simulation without any devices installed in the circuit. Then, determine the load with the largest area of undervoltage violation.
2. Check whether a device is already installed at that candidate location. If so, select the next immediate service transformer that is electrically closest but does not already have a device installed.
3. Check the rating of the corresponding transformer. If the transformer rating is equal to the size of a UPFC, install a UPFC at the transformer secondary. Otherwise, consider the location as a candidate location for installing an SVC.
4. Add the device to the feeder model at the selected location and rerun the peak load day QSTS simulation. Determine the service point with the largest area of undervoltage violation.
5. Repeat steps 2 through 4 until all the undervoltage violations are eliminated or the planned number of UPFCs and SVCs are deployed.

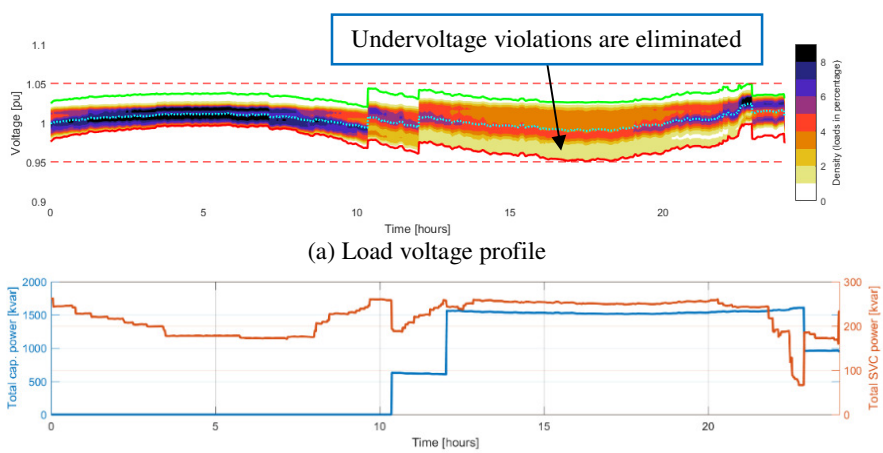
If the number of devices required to eliminate undervoltage violations is less than the planned number of devices, the threshold used to determine the undervoltage violation area can be raised to provide an increased level of conservatism to the estimates.

PLACEMENT SCENARIO

In this example scenario, one UPFC and 15 SVCs are available for deployment on the test circuit. However, neither of the 50-kvar single-phase capacitors are assumed to be in service. The voltage threshold, used to calculate the undervoltage area, is set to 0.96 pu. This is done to identify potential locations for all the available UPFC and SVC devices. Examination of the 0.95 pu voltage criteria, however, indicated only 13 of the 15 SVCs available would be needed to mitigate the undervoltage conditions.

QSTS simulation results and the locations of UPFCs and SVCs are shown in Figures 7 and 8, respectively. As shown, after the devices are added to the system model, the undervoltage conditions are completely eliminated. It is interesting to note that only about 9.5% of the service points experience voltages between 0.95 and 0.96 pu during the peak period while the remaining points (90.5%) have voltages of higher than 0.96 pu. The 900-kvar and 600-kvar capacitors are switched on during the afternoon. However, all 1200-kvar capacitors are always offline. The devices were generally located at the three areas identified in Figure 6, with one SVC being placed at a location where one of the 50-kvar capacitors was removed from service. Note that the number of SVCs located in each of the three defined regions does not directly correlate with the number of load points determined to fall with the undervoltage criteria, see Figures 4 through 6. This highlights the importance of capturing network connectivity and load flow information as well as an iterative placement algorithm.

In the above scenario, both 50-kvar single-phase capacitors are out of service. When both are in service, load voltage throughout the feeder becomes more robust than that with both 50-kvar capacitors out of service. As expected, no load nodes experience any under voltage condition. On the other hand, 1.2% of load nodes have voltages between 0.95 and 0.96 pu, while the remaining load nodes (98.8%) have voltages higher than 0.96 pu.



(a) Load voltage profile

(b) Reactive power produced by the capacitors and SVCs

Figure 7. QSTS simulation results for a placement scenario

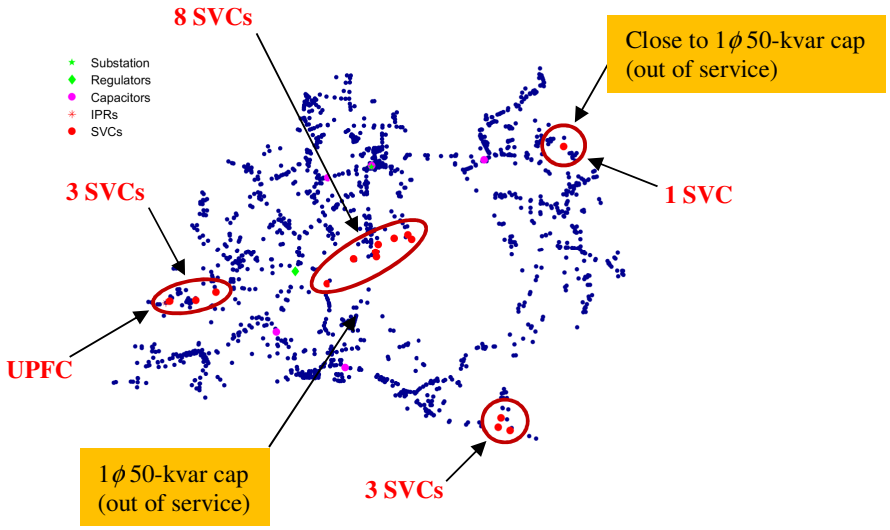


Figure 8. UPFC and SVC locations for eliminating undervoltage violations

CONCLUSION

This paper develops an approach for placing UPFCs and SVCs to mitigate undervoltage violations. The proposed method places the devices at the locations with the largest undervoltage area. One device is placed at a time, and the placement process is repeated until all available devices, i.e., one UPFC and 15 SVCs, are installed. Analysis of simulation results of the test circuit has shown that the method is effective in eliminating undervoltage violations.

BIBLIOGRAPHY

[1] H. V. Padullaparti, Q. Nguyen, and S. Santoso, "Advances in Volt-var Control Approaches in Utility Distribution Systems," in *Proc. 2016 IEEE Power & Energy Society General Meeting*, Boston, pp. 1-5.

[2] B. McMillan, P. Guido, O. Leitermann, V. Martinelli, A. Gonzaga, and R. McFetridge, "Application of Power Electronics LV Power Regulators in a Utility Distribution System," in *Proc. 2015 IEEE Rural Electric Power Conference*, Asheville, pp. 43-47.

[3] M. A. Tabrizi, M. Sahni, N. Prakash, V. Martinelli, and J. Simonelli, "Utilization of Low Voltage In-Line Power Regulator for reliable integration & performance of DER technologies," in *Proc. 2015 IEEE Power & Energy Society General Meeting*, Denver, pp. 1-5.

[4] D. Montenegro and J. A. Taylor, "Open Source Unified Power Flow Controller Model for Quasi-Static Time Series Simulation," CIGRE Grid of the Future, Philadelphia, 2016.

[5] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd ed. New York: McGraw-Hill, 2012.