Performance comparison between single-phase and IEEE-1547 three-phase voltage-reactive power controls for three-phase photovoltaic systems

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***Abstract*—This work focuses on a comparison between the effects, on an electrical power system, of adopting, for three-phase inverters, a three-phase averaged Volt/Var algorithm, as proposed by IEEE 1547 standard, and employing three, separate, control references for each phase. In order to carry out its proposal, two daily simulations were performed on the IEEE 34-Bus test case feeder. Three-phase phovoltaic systems were placed across the feeder, and, for each batch of power flows, they were configured to apply each one of the evaluated control algorithms. The single-phase Volt/Var performed significantly better, while not producing higher losses. Depending on the conditions of the circuit, it could also be observed that there may be a higher or lower effort from the inverters in order to satisfy the requested reactive power output demanded by the algorithm.**

***Index Terms*—volt/var, voltage-reactive power control, three-phase inverters, single-phase control**

I. Introduction

Distributed energy resources (DERs) assets have been increasing their influence in electrical power systems (EPS) over the world. This can be explained because of their environmental friendly nature, as well as the incentives provided for acquisition of them. DERs are capable of providing several benefits for an EPS; however, high levels of penetration also impose challenges for the grid in both time and frequency domains. In particular, the most evident of them belonging to the former class is the overvoltage issue, attributed to the occurence of reverse power flow caused by the mismatch, locally, between a lower consumption and a higher generation [1].

Even though overvoltage issues are caused by DERs, they can also be mitigated by the units themselves. In the case of grid-connected photovoltaic systems (PVs), since an inverter is required in order to allow interaction with the EPS, it is possible to take advantage of them to provide support to the system. The advantages of this strategy justify the requirement, in several national grid codes, of voltage regulation support from inverter-based units applied to DERs connection.

One of the most well-known standards regarding this subject is the IEEE 1547, which provides a guideline for the capabilites these inverters should have. In particular, for steady-state operation, several different voltage-support algorithms are required [2].

The most influential of these modes in medium-voltage may be Volt/Var. The Volt/Var algorithm specifies a reactive power reference to be injected or absorbed by an inverter based on the voltages at its point of common connection (PCC). The reactive power output is calculated according to a piece-wise linear proportional control law:

$$Q(\bar{V}) = \begin{cases} \alpha \cdot (V_l - \bar{V}) & V_{min} < \bar{V} < V_l \\ 0 & V_l < \bar{V} < V_u \\ \beta \cdot (V_u - \bar{V}) & V_u < \bar{V} < V_{max} \end{cases} \quad (1)$$

where $\bar{V}$ is the measured value of the applicable voltage, α, β, V_l and V_u are parameters that define a desired curve in specific. Figure 1 depicts a generic Volt/Var curve, based on equation 1.

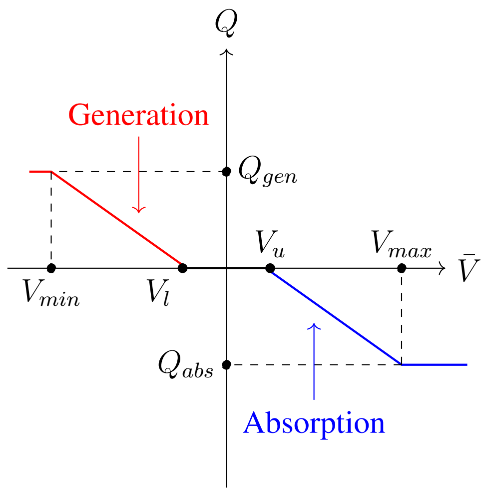

Fig. 1: Generic Volt/Var characteristic curve.

The quantity $\bar{V}$, for a single-phase inverter, is defined as the measured phase-to-neutral, phase-to-phase, or phase-to-ground voltage according to the connection level (medium or low-voltage side of the EPS), as well as the system configuration itself. For two-phase or three-phase units, $\bar{V}$ is defined as the average value of its phases applicable voltages.

Although this criteria for definition of applicable voltage is simple, it may degrade the performance of steady-state grid-regulation algorithms. There is a significant coupling effect between different phases of a multiphase system [3], which can reduce the effectiveness of voltage regulation algorithms if their control laws are uniformly exerted on all phases. Most works (which usually consider single-phase inverters because they are more common) propose solutions [3]–[9] that, although show significant improvement, rely on a possibly not available communication infrastructure.

However, the related assumption that the Volt/Var performed by three-phase inverters may be improved by simply considering each phase separately should also be considered, since it is an alternative which still requires only local measurements for its execution, one of the strongest points of the algorithm.

A similar question was raised in the literature for the case of on-load tap changers (OLTCs) [10]. The proposed answer was that employment of single-phase-controlled OLTCs, in comparison with three-phase counterparts resulted in significant regulation improvement.

Hence, the objective of this work is to compare the performance of imposing a single-phase Volt/Var regulation algorithm for three-phase inverters with the traditional three-phase average strategy, as imposed by IEEE 1547 standard. One of its main contributions is to demonstrate how much improvement can be obtained, in unbalanced systems, by providing independent voltage support for each phase, if compared with the traditional strategy.

II. Methodology

In order to evaluate the impacts of three, individuals, Volt/Var references calculations against an unique, three-phase, average-value-based method, a simulation scenario is proposed with the IEEE 34-Bus test case. This feeder, which was developed based on an actual EPS located in Arizona [11], United States, is characterized by its moderate degree of unbalance, low X/R ratio and weak voltage regulation. Those characteristics compose the set of reasons that motivated its choice, since the first may be useful to evaluate how well the two control approaches contribute to reducing voltage unbalance between nodes located at a single bus, while the others allow the analysis of differences in effort requirement from units and overall regulation performance, respectively.

IEEE 34-Bus, as originally specified, does not contain any distributed energy resource. Hence, it is necessary to populate the feeder with units to execute this work. All of them were considered as PV systems. Figure 2 shows a map of their positions and installed capacities along the feeder. It is important to note that all placed units are three-phase.

The open-source software OpenDSS was used to execute two sequences of power flows. First, before executing them, the tap changers of the feeder were deactivated in order to avoid the effects of coordination issues between them and the DERs inverters. Then, during the first sequence, all of the PV systems were configured to execute a three-phase Volt/Var regulation through a daily

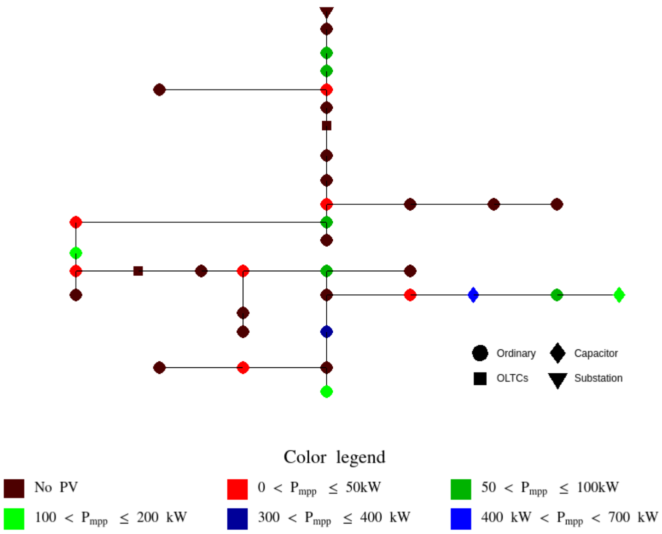

Fig. 2: Map of photovoltaic systems placement and sizing on IEEE 34-Bus test case.

simulation, comprising of 24 timesteps of one hour each. The control law for each phase reactive power output is given by equation (2):

$$Q_i^k = Q_\alpha(\bar{V}^k) \tag{2}$$

where $\bar{V}^k$ is the average value between bus k RMS phase-neutral node voltages, Q_i^k corresponds to the reactive power output for the i-th phase of the same bus, and Q_α is a fixed Volt/Var parametrization, exhibited in Fig. 3.

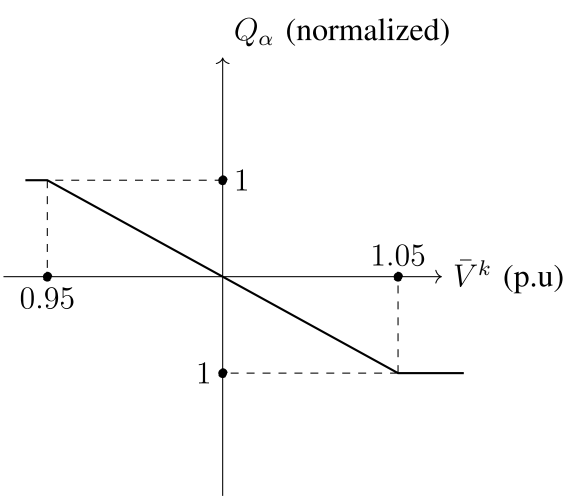

Fig. 3: Configured Volt/Var characteristic curve for inverters in executed simulations.

After finishing the first sequence of simulations, the inverters were reconfigured to allow independent control of reactive power output for each phase, as specified by (3):

$$Q_i^k = \frac{1}{3}Q_\alpha(V_i^k) \tag{3}$$

It is expected from the controlled units that they should be able to process, in each phase, a maximum of one third of its respectives nominal ratings. The factor $\frac{1}{3}$ is inserted in (3) in order to make them comply with this constraint. Finally, the same daily simulation, i.e, with the same load and solar irradiation conditions, was repeated, allowing to compare the performance under each configuration. The normalized load and solar irradiation curves can be seen in Fig. 4.

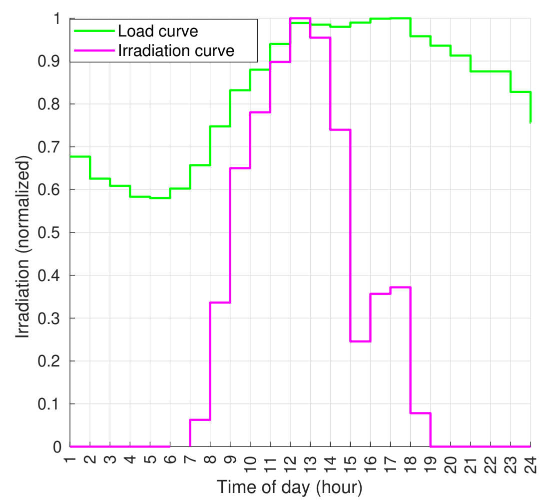

Fig. 4: Load and solar irradiation curves considered in the two executed daily simulations.

III. Results

It is intended to compare, according to different criterias, Volt/Var effectiveness if performed by three-phase inverters, under two different cases, as specified previously. First, the phase-neutral node voltages for each batch of power flows on the feeder were compared. Figures 5 and 6 show a series of boxplots for, respectively, the voltages in the three-phase and single-phase regulation scenarios. Although it is physically possible, the inverters were configured to not operate during periods without solar irradiation. Therefore, in order to simplify visualization of the graphics, since the voltages on those intervals (before 7:00 and after 19:00) should be same, they were excluded from the figures, as well as from all the subsequents results.

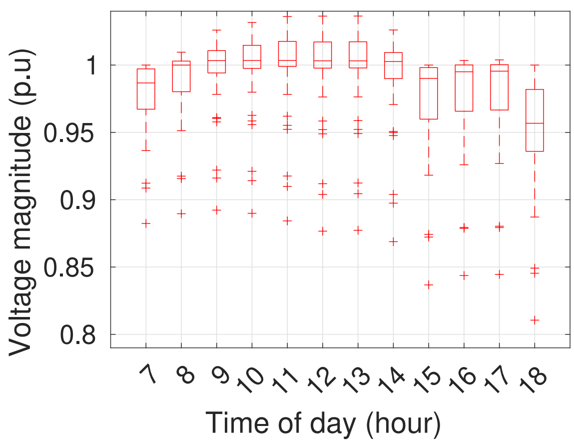

Fig. 5: Voltages boxplots for three-phase regulation case.

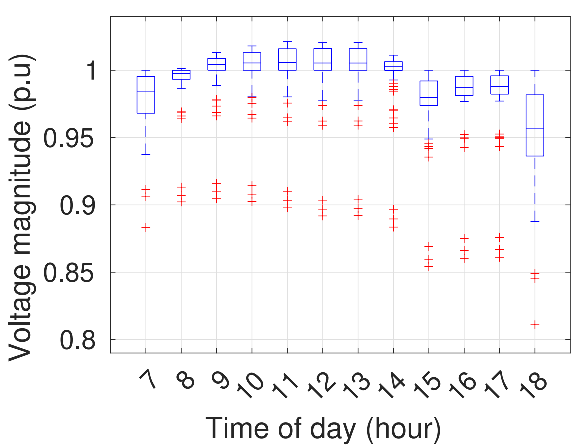

Fig. 6: Voltages boxplots for single-phase regulation case.

It can be observed, by comparing Figs. 5 and 6, that during peak irradiation hours (between 10:00 and 14:00) there is a tendency, when using three-phase Volt/Var, of higher voltages on the feeder. This is not desired because, close to noon, reverse power flow is impacting most the system with overvoltages.

Figure 7 exhibits an histogram of the feeder voltages during the interval in which the inverters operated.

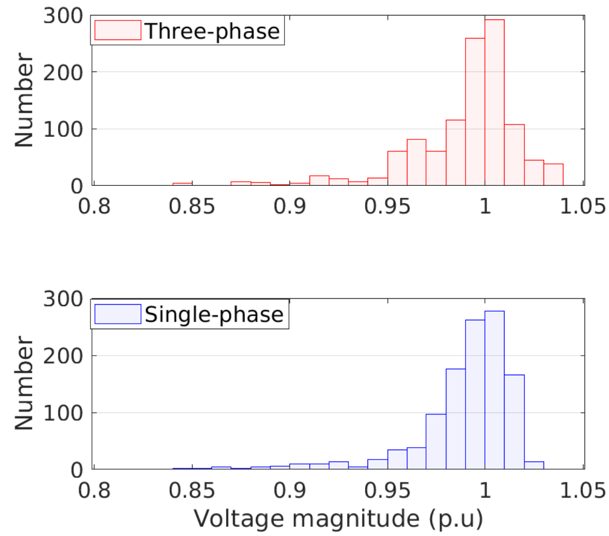

Fig. 7: Histogram of phase-neutral node voltages between 7:00 and 19:00.

Figure 7 shows, again, that overvoltage mitigation can be improved by operating with the single-phase Volt/Var, since the last bin on the red histogram (three-phase Volt/Var) disappeared on the blue one (single-phase Volt/Var). Not necessarily the same could be said to undervoltages, but it is still unclear what caused the behavior observed in this figure.

Not only improved overvoltage mitigation can be atributed as a benefit of the single-phase Volt/Var, but it can also contribute to reduce the unbalance between the phase-neutral voltages of each bus. In order to account for this statement, the IEEE phase voltage unbalance rate (PVUR) was used to measure the intensity of unbalances of the three-phase buses of the feeder during the two sequences of simulations. Figure 8 depicts two histograms pertaining to the three-phase (blue) and single-phase (red) cases, while figure 9 represents hourly histograms of the differences between the three-phase and single-phase results that composed the same histograms mentioned. The two figures, together, clearly demonstrate the statement proposed initially, since the blue histogram, pertaining to the single-phase case, represents an overall weaker unbalance (because most of the bins closer to zero have a higher height), while the boxes and whiskers in fig. 9 are entirely contained above the horizontal axis.

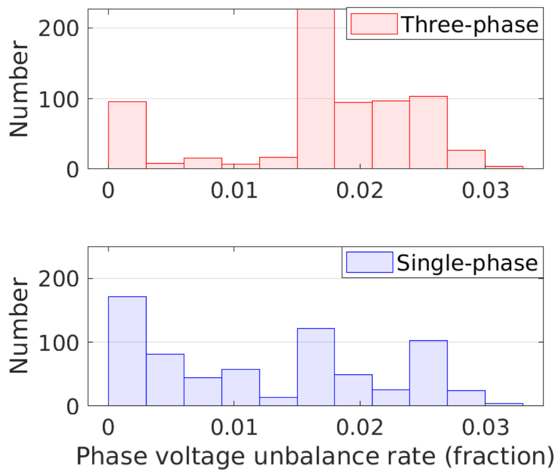

Fig. 8: Histogram of maximum voltage unbalances for the feeder.

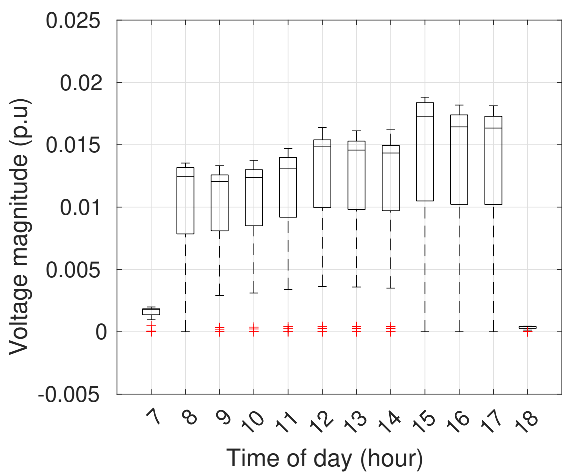

Fig. 9: Boxplots of the differences between the buses phase voltage unbalance rates of the three-phase and single-phase cases.

Until now, it seems that the single-phase Volt/Var is capable to provide a better contribution to voltage support. It is important to investigate whether this difference was caused due to a higher demand from the PV systems inverters. For each hour, the apparent powers processed by each inverter were compared between the two scenarios. Figure 10 depicts those differences.

Three different behaviors can be observed by visualizing Fig. 10. During the first hour, there is a large difference in demand between the three-phase and single-phase Volt/Var scenarios, favoring

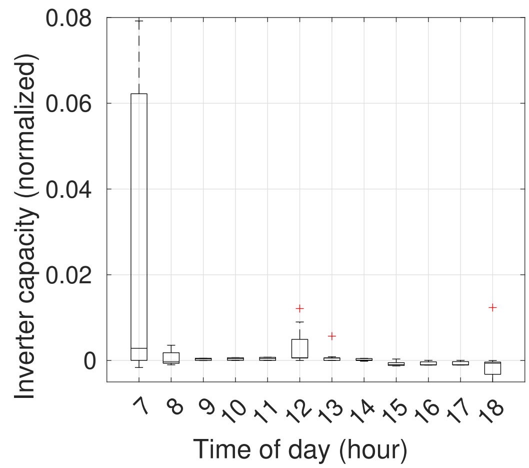

Fig. 10: Boxplots of capability usage differences between three-phase Volt/Var and single-phase Volt/Var scenarios.

the single-phase case. After that hour, and before the boxplot on hour 15:00, there is a slight advantage again from single-phase Volt/Var. However, during the final hours of solar irradiation in the day, three-phase Volt/Var resulted in a lower overall usage of inverters.

The first behavior occurred in a moment of the day where solar irradiation was low, and the load curve was not close to its peak. Thereafter, the generation from the distributed resources exceeded the loads consumption. From 15:00 onwards, loads are drawing the highest amount of power from the EPS, while the generation from the PV systems, due to the shading in the irradiation curve (as can be observed in Fig. 4) was low.

These observations suggest that single-phase Volt/Var requires more from inverters depending on the condition of the grid. When there is a low demand, single-phase Volt/Var can improve inverter usage efficiency due to a higher effectiveness, compared to the three-phase counterpart. This difference should not be significant when generation is high. Finally, in situations where the difference between consumption and generation is at its highest, a higher sensitivity of single-phase Volt/Var would justify the negative conclusion observed in the final hours of Fig. 10. However, further investigation of these affirmations should be considered.

Asserting whether if changing three-phase

Volt/Var to single-phase impacts the feeder losses is also important. Figure 11 show the accumulated energy dissipated in cables, for the two cases. As can be seen, there is not a significant difference between the two cases, from a global point of view, albeit single-phase Volt/Var performed better.

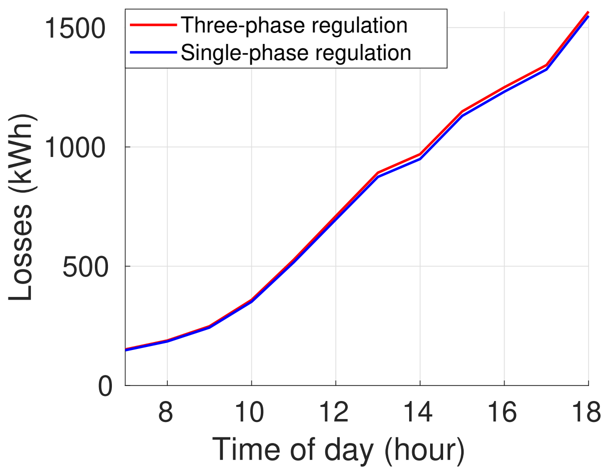

Fig. 11: Integrated losses on the feeder cables, for each batch of simulations.

IV. Conclusions

This work compares the performance of switching the traditional three-phase Volt/Var algorithm, as specified by IEEE 1547 standard, to independently control each phase's reactive power output under different criterias through two sequences of simulations of a feeder with the same conditions.

The single-phase Volt/Var contributed better to voltage support, because it was more effective in mitigating overvoltages and voltage unbalances between the feeder phases. It was also identified that there is no significant difference in terms of loss increase in the system. Mixed results were obtained in the analysis of its impact in the contribution demand from inverters, requiring further investigation, which can be considered as a future work, as well as an analysis of the variance, across the feeder, of the observed variables.

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