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Impact of New Voltage Optimization Strategies on Power Distribution System

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SUMMARY

Due to increasing penetration levels of distributed energy resources (DERs), there is a requirement for a change in the voltage control in a power distribution system. Conventional voltage control devices are slow operating devices, but DER can create adverse conditions in sub-cycle time, hence we require faster voltage control devices. In this regard, AMSC has developed a STATCOM called "DVAR-VVO" for voltage control in the distribution system. In this paper, we have analysed the performance of the distribution system with the inclusion of DVAR-VVO in collaboration with legacy devices. Traditionally, capacitor banks are gang-operated, which leads to the suboptimal operation of a distribution system. Here, we have analysed the performance of the system with single-phase switching of capacitor banks. The combined control of DVAR-VVO with three-phase and single-phase switching with voltage control are performed for energy efficiency, peak demand reduction and management of the voltage balance index. The different control strategies were evaluated for three representative distribution feeders.

KEYWORDS

DVAR-VVO, energy efficiency, voltage balance index, voltage control, volt-var optimization.

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I. INTRODUCTION

Due to green energy initiatives, a growing number of distributed energy resources (DERs) comprised of solar photovoltaic (PV), wind turbines, and battery energy storage systems (BESS), etc. are being installed in the distribution system [1]. The inclusion of DERs in the power distribution system is changing what was traditionally a passive network into an active network. As most DERs are an intermittent source of energy, there are several power quality problems such as overvoltage, undervoltage, voltage flicker, voltage imbalance, harmonics etc. associated with them. To reduce the power quality issues presented by these conditions and to improve the operation of a distribution system with a growing volume of DERs, several vendors are developing and manufacturing new power equipment. Companion measures in the distribution system operations space are also being deployed to control both conventional and the aforementioned new power equipment to reduce energy consumption and improve overall system efficiency. Several techniques have been developed for the optimal operation of distribution line equipment; One such technique is volt-var optimization (VVO) which controls the nodal voltage along the feeder to achieve the desired objective. VVO objectives are loss minimization, conservation voltage reduction (CVR), and voltage imbalance reduction. For the CVR objective, VVO controls the voltage controllable devices such as voltage regulators, capacitor banks and load tap-changers (LTCs), to reduce the voltage along the feeders while maintaining operation within permissible limits. The voltage reduction leads to a reduction in power flow from the substation due to a reduction in power consumption by the voltage dependent loads. By coordinating capacitor banks, voltage regulators and LTCs, CVR tries to flatten the voltage towards the lower voltage limit within an acceptable range [2].

Conventionally, legacy devices (voltage regulators and capacitor banks) were controlled based on a set of rules applied *locally* at each device separately. With the advancement in the communication infrastructure and the inclusion of several smart sensors in the distribution system, there is a paradigm shift from local control to centralized control. The centralized control requires information like the total number of voltage controllable devices, their current statuses, statuses of the switches as well as the topological configuration of the feeder. Depending on the objectives, centralized control provides the desired control statuses. Currently, three-phase capacitor banks are gang-operated meaning they are switched ON/OFF using a three-phase switch, typically based on measurement from only one of the phases [3,4]. It has been observed that in an unbalanced distribution system due to gang-operated capacitor switching, there is overcompensation for lightly loaded phases and under-compensation for heavily loaded phases. This leads to voltage imbalance among the phases. Voltage imbalance is harmful to industrial customers and associated motor loads. The industrial practice is if the voltage imbalance exceeds 1.5- 2%, the relays are required to trip. Further, at least one study has shown that if the voltage imbalance is 5% at the three-phase motor terminal, the output of the motor will reduce by 25%, which will cause overheating, ultimately resulting in motor damage or process disruption if the process is unprotected [5,6]. Thus, there is a requirement for maintaining voltage imbalance within an acceptable range. Single-phase voltage regulators can alleviate this power quality issue to some extent, however, due to higher operation counts and maintenance costs, these devices may not present an optimal solution. Also, these are series devices which can be difficult to integrate and operate effectively in a distribution system. The single-phase capacitor bank switching is another viable option for reducing the voltage imbalance as these are shunt connected devices [7]. *In this paper, we are investigating the effect of single-phase capacitor banks over three-phase switching for the conservation voltage reduction.*

Due to the inclusion of DERs, voltage control via legacy devices can be difficult due to the slow operation of these devices. Hence, there is a requirement to install a fast-operating device which can synchronize with the fast voltage change caused due to DERs. To achieve this, the American Superconductor Corporation (AMSC) is developing one such device named "DVAR-VVO". This is a Static Compensator (STATCOM), which has the ability to provide dynamics VARs for a wide range of operational requirements. In the transmission network, it has the capability to correct voltage instability problems, and provide dynamic steady-state voltage and power factor control and regulation in both the transmission and distribution systems. It helps in power qualities issues that arise at the interconnection of DERs. Typically, the device can be connected to a 15 kV voltage level and can inject/absorb 1 MVAR of reactive power continuously. The device can be operated in multiple control modes viz. VOLT-VAR curve mode, voltage control mode, pf control mode, and reactive power mode. *In this paper, we are investing only the VOLT-VAR curve mode and analyzing the effect of DVAR with single-phase capacitor banks over three-phase switching for the conservation voltage reduction.*
The remainder of this paper is as follows: Section II discusses the coordination of VVO and DVAR-VVO devices; Section III describes the circuit model and its characteristics; and Section IV discusses the results and observations. Finally, Section V presents the conclusion of the findings and recommended future work.

II. DIFFERENT VO TECHNIQUE WITH DVAR-VVO

In this section, we will discuss different approaches which are used to control the voltage-controllable devices in the distribution system for the conservation voltage reduction. The voltage controllable devices used in this paper are LTC, line regulators and capacitor banks. Further, we have included a DVAR-VVO device which will maintain the voltage at the connected node.

II-A. Voltage Optimization (VO) with Three-Phase Capacitor Banks Switching

The proprietary Cyme Volt-VAR Optimization (VVO) module is utilized for the purpose of evaluating the system under this category. In the module, we selected conservation voltage reduction (CVR) as our objective for controlling the voltage regulators and three-phase capacitor banks. CVR function optimizes the position of the taps and the VARs required to reduce the voltage along the feeder to reduce the energy consumption for the voltage dependent loads. Further, we provide an additional objective to remove the abnormal conditions in the distribution system. Next, we put constraints on the substation reactive power supply to lie between 0 kVAR to a maximum of 600 kVAR. The output of the algorithm will be the tap position for the LTC and voltage regulators and the switching status of the capacitor banks. In this case, all the capacitors are gang operated.

II-B. VO with Single-Phase Capacitor Banks Switching

In this case, also we used the Cyme Volt-VAR Optimization (VVO) module. The objective and constraints described in the previous case will remain the same. However, in this case, we modelled all the three-phase capacitor banks in the system as three single-phase capacitor banks connected to each phase separately. The VVO module will determine the control status for each of the capacitor banks separately for each phase connected to a bus.

II-C. VO with Three -Phase Capacitor Banks Switching and DVAR-VVO

In addition to the Cyme VVO module for obtaining the optimal status of the LTC, VR and three-phase capacitor banks, here DVAR-VVO is utilized to control the feeder voltage. The

DVAR-VVO will control locally by sensing the voltage at the connected node to determine the required reactive power support to maintain the voltage. The device features multiple control modes, but for this analysis, we have considered the volt/var curve based control.

II-D. VO with Single -Phase Capacitor Banks Switching and DVAR-VVO

In this case, the DVAR-VVO will coordinate with the single-phase capacitor bank switching to reduce the power consumption for a feeder. Similar to the previous case, the device is operating locally in the volt/var curve based control.

III. CIRCUIT MODEL and CHARACTERISTICS

In this section, we discuss the circuit models for the three distribution feeders which are selected for analyzing the performance of the previously mentioned VO techniques. These three feeders are from ComEd territory in Illinois. We have selected these feeders based on the recommendations from capacity planning perspective, where voltage optimization was required. Figure 1 shows the single line diagram for all three analyzed distribution feeders. The feeder X consist of a total of 1853 nodes with 314 spot loads. The feeder has a LTC installed at the substation and a voltage regulator along the feeder. There are two three-phase capacitor banks of 1200 kVAr installed along the feeder. Next for feeder Y, total number of nodes are 1150 with 256 spot loads. In this feeder, we have a LTC installed at the substation and a three-phase voltage regulator along the feeder. Here, two two-phase voltage regulators are also connected to support the voltage along the feeder. Next, we have two three-phase capacitor banks of 1200 and 600 kVAr ratings connected in the feeder. Finally, feeder Z which is comparatively a smaller circuit has a total of 442 nodes with 136 spot loads. Here we don't have any line voltage regulator, but a LTC is connected at the substation. There are a total of six capacitor banks in the feeder with 600 and 450 kVAr ratings.
Please note that for the single-phase switching operation, we have replaced the three-phase capacitor banks as single-phase capacitors connected to each phase separately. Next, a location of DVAR-VVO is based both on placing it in the reactive load center while also optimizing the fault power to X/R ratio.

Figure 1. Single line diagram for Feeder X, Y and Z.

IV. RESULTS and DISCUSSION

In this section, we will discuss the effect of the different control techniques on each of the three feeders discussed earlier. Each feeder is compared on parameters such as total peak demand reduction, peak loss reduction, voltage balance index etc. It is worth noting that the voltage balance index (VBI) is calculated for the line-line voltage. For the calculation of the total number of regulator operations, we count for LTC all three phases simultaneous movement as one movement and for line regulator, each phase movement is counted independently. Please note that the comparison of each technique will be based on the baseline model. For the baseline, there is no DVAR-VVO installed in the system and all the voltage controllable devices in the system are operating in the local control mode. Please note that for comparison, we have referred basecase as case 1 and the other four voltage control algorithms are named case 2 to case 5, in the increased order as described in section II.

IV-A. Feeder X

The circuit is analysed for all the four seasons for a day which includes summer peak, winter peak and a normal spring and fall day. During the analysis, the power flow is monitored at the feeder breaker and the voltages are monitored at the capacitor bank buses. In this circuit, the location for the worst voltage balance index (VBI) is reported at one of the capacitor banks. The table I, shows the comparison of the parameters after implementing different control techniques in the circuit for all the seasons. The table shows that the peak load demand increases for all seasons for case 4 and 5 (shown in Red). However, the performance of case 5 is better than case 4. It can be observed from the table that there is a reduction in the peak loss from basecase for all the cases. The maximum loss reduction occurred for case 5 for all seasons except for winter where the maximum reduction is observed for case 4. It is observed that with the introduction of voltage optimization in the test system there is an increase in the number of operations of regulators during the summer peak day. However, for all other seasons, there is no impact on the regulator operations. Further, it was observed that for the case 3, there is an increase in the number of operations of capacitor switching during a day for the fall and spring season. Unfortunate, we are unable to determine the rationale for this abnormal behaviour in the system. Form the table, it can be observed that there is increment in the VBI value with the inclusion of DVAR-VVO in the system. Please note that, if the objective is to minimize the VBI indices the DVAR-VVO will provide the required reactive power support to achieve the desired objective.

Table I. Comparison of different control technique for Feeder X

Season	Peak active demand (pu)	Peak active loss (pu)	VBI (%)	# Regulator Switching	# Capacitor Switching
Basecase					
Summer	6.153	0.103	0.47	7	-
Winter	2.395	0.102	0.18	2	-
Fall	2.539	0.102	0.24	4	-
Spring	2.187	0.102	0.20	1	-
VO with Three-Phase Capacitor Switching					
Summer	6.149	0.098	0.47	55	1
Winter	2.394	0.099	0.18	3	4
Fall	2.537	0.099	0.26	4	4
Spring	2.187	0.099	0.22	2	1
VO with Single-Phase Capacitor Switching					
Summer	6.149	0.098	0.48	57	2
Winter	2.396	0.098	0.21	2	0
Fall	2.539	0.100	0.41	8	24
Spring	2.188	0.099	0.42	2	24
DVAR VVO and VO with Three-Phase Capacitor Switching					
Summer	6.16266	0.098	0.49	50	4

Winter	2.39732	0.099	0.21	1	0
Fall	2.541	0.099	0.25	4	0
Spring	2.189	0.098	0.21	2	0
DVAR VVO and VO with Single-Phase Capacitor Switching					
Summer	6.154	0.098	0.66	58	11
Winter	2.396	0.098	0.39	2	2
Fall	2.539	0.098	0.32	2	1
Spring	2.188	0.098	0.29	2	1

It was observed that at the capacitor location, the voltage profile is flattened with the introduction of DVAR-VVO in the system for all seasons. The most effective case is case 5, where the difference in voltages among each phase is reduced due to reactive power support from DVAR-VVO. It was observed that the reactive power support from DVAR-VVO occurs mostly at the peak load of each season. Further, it was observed that there is no significant involvement by the DVAR-VVO for the voltage control at the connected node for other seasons except summer. Also, it was observed that with the introduction of DVAR there is no significant impact on the change in the number of operations of capacitor banks and regulators.

Table II. Annual metrices comparison for Feeder X

Annualized Metrices	Case 1	Case 2	Case 3	Case 4	Case 5
Peak kW(pu)	6.407	6.405	6.405	6.417	6.408
Peak kVAR (pu)	1.503	0.198	0.198	1.703	1.105
Energy (unit)	6,857,077	6,853,796	6,853,742	6,863,059	6,860,304

The seasonal analysis was applied to the annual, by phase SCADA data to extrapolate the metrices for all the test cases as shown in Table II. It can be observed from the table that the peak demand reduces for case 2 and 3 in comparison to basecase, however, with the introduction of DVAR VVO, there is a slight increment in the peak demand. A similar trend is observed for the energy unit consumed in a year. It is worth mentioning that case 5 is more effective as compared to case 4.

IV-B. Feeder Y

The comparison of the circuit for different control techniques is shown in Table III. Please note that the capacitor bus is the location for the maximum VBI. In this circuit, it was observed that there is a reduction in the power consumption from the substation at peak load condition for all the seasons except summer (shown in Red). The maximum power reduction is with the introduction of DVAR-VVO and single-phase capacitor bank switching. However, for the peak real loss, it is observed that each of the control techniques is able to reduce it to basecase. Again, the maximum reduction in the peak real loss is observed for case 5. The reduction in peak demand and loss is higher for case 5 compared to case 4. However, there is an increment in the number of capacitors switching from case 4 to case 5. Next, it was observed that there is a large voltage deviation at the capacitor location for summer, spring and fall, however, the deviation is reduced for winter for case 5. The VBI for this feeder is deteriorating with the introduction of DVAR-VVO.

The reactive power support from DVAR-VVO is higher for the summer season with the increment in the load demand for both the cases. But much reactive power support is observed during a day for other seasons.

Table III. Comparison of different control technique for Feeder Y

Season	Peak active demand (pu)	Peak active loss (pu)	VBI (%)	# Regulator Switching	# Capacitor Switching
Basecase					
Summer	5.421	0.164	0.22	12	0
Winter	2.037	0.024	0.11	4	0
Fall	4.325	0.102	0.31	15	0
Spring	3.068	0.051	0.20	1	0
VO with Three-Phase Capacitor Switching					
Summer	5.591	0.149	0.23	45	0
Winter	1.968	0.023	0.11	47	1
Fall	4.335	0.094	0.29	35	1
Spring	3.008	0.047	0.19	12	1
VO with Single-Phase Capacitor Switching					
Summer	5.591	0.149	0.20	45	0
Winter	1.991	0.024	0.35	39	4
Fall	4.321	0.094	0.31	32	1
Spring	3.022	0.048	0.21	23	1
DVAR VVO and VO with Three-Phase Capacitor Switching					
Summer	5.616	0.154	0.27	44	2
Winter	1.957	0.024	0.12	25	0
Fall	4.300	0.094	0.27	33	4
Spring	2.981	0.049	0.19	10	6
DVAR VVO and VO with Single-Phase Capacitor Switching					
Summer	5.550	0.152	0.53	44	0
Winter	1.957	0.024	0.12	25	0
Fall	4.290	0.094	0.37	37	12
Spring	2.977	0.049	0.24	56	21

The annualized metrices for all the test cases are shown in table IV. There is a reduction in the peak demand for all the cases in comparison to basecase. Also, the energy consumption is reduced for case 4 and 5 with respect to the base case. It is worth noting that the reduction in peak demand and energy consumption is higher for case 5 compared to case 4.

Table IV. Annual metrices comparison for Feeder Y

Annualized Metrices	Case 1	Case 2	Case 3	Case 4	Case 5
Peak kW(pu)	6.312	6.290	6.290	6.291	6.258
Peak kVAR (pu)	6.708	1.837	1.837	3.743	3.018
Energy (unit)	6,086,937	6,060,485	6,087,972	6,052,727	6,028,904

IV-C. Feeder Z

The comparison of the circuit for different control techniques is shown in Table V. Please note a recloser in the system is the bus for the maximum VBI. In this circuit, it was observed that there is a reduction in the power consumption from the substation at peak load condition for all seasons. The maximum power reduction is with the introduction of DVAR-VVO and single-phase capacitor bank switching. Unlike other feeders, here there is an increase in the number of capacitor operations for case 4 and 5. Next, it was observed that there is a reduction in voltage deviation at the capacitor location for summer and winter whereas a slight increase for fall and spring for case 5. Further, the reactive power support from DVAR-VVO is higher for the summer season with the increment in the load demand for both cases. But for other seasons the reactive power support is observed during a day when the load demand is lesser.

Table V. Comparison of different control technique for Feeder Z

Season	Peak active demand (pu)	Peak active loss (pu)	VBI (%)	# Regulator Switching	# Capacitor Switching
Basecase					
Summer	5.492	0.076	0.24	0	0
Winter	2.387	0.014	0.17	0	0
Fall	1.552	0.006	0.13	0	0
Spring	1.571	0.006	0.12	0	0
VO with Three-Phase Capacitor Switching					
Summer	5.400	0.069	0.28	30	7
Winter	2.287	0.014	0.18	24	36
Fall	1.476	0.00622	0.14	6	0
Spring	1.493	0.00632	0.13	6	0
VO with Single-Phase Capacitor Switching					
Summer	5.400	0.069.03	0.61	10	7
Winter	2.245	0.01323	0.17	2	22
Fall	1.448	0.00602	0.51	0	3
Spring	1.464	0.00910	0.49	0	3
DVAR VVO and VO with Three-Phase Capacitor Switching					
Summer	5.310	0.068.36	0.25	8	12
Winter	2.223	0.01277	0.17	0	4
Fall	1.459	0.00625	0.13	0	0
Spring	1.461	0.00583	0.13	0	0
DVAR VVO and VO with Single-Phase Capacitor Switching					
Summer	5.307	0.06912	0.60	11	27
Winter	2.250	0.01357	0.18	4	0
Fall	1.460	0.00608	0.13	3	5
Spring	1.462	0.00577	0.51	3	5

The annualized metrices for all the test cases are shown in table VI. There is a reduction in the peak demand for all the cases in comparison to basecase. However, the energy consumption is increased for the case 4 and 5 with respect to the basecase.

Table VI. Annual metrices comparison for Feeder Z

Annualized Metrices	Case 1	Case 2	Case 3	Case 4	Case 5
Peak kW(pu)	4.489	4.368	3.478	3.420	3.422
Peak kVAR (pu)	2.010	0.337	0.270	0.383	0.363
Energy (unit)	4,797,331	3,697,911	3,007,848	2,960,790	2,990,568

V. CONCLUSION

In this paper, we analyse the performance of the four types of a voltage control algorithms for energy efficiency in three different distribution systems. It was observed that for most of the cases the single-phase capacitor banks switching with DVAR-VVO is able to reduce the voltage unbalance among the phase at a node. This helps in reducing the VBI index but is not universally true. Further, it was observed that for most cases there is a reduction in the active power consumption from the substation when DVAR-VVO is used in tandem with single-phase capacitor banks switching. However, there is no concrete conclusion that this algorithm is the best algorithm as other parameters may deteriorate.

Future work in this direction will be to evaluate the performance of the DVAR-VVO by including it in the optimal power flow problem. Also, the work involves a rigorous testing on multiple feeders with different load mixes, DERs locations and multiple DVAR-VVO installed.

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