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Benefits of Single-Phase Capacitor Switching in Conservation Voltage Reduction

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SUMMARY

Distribution system operations have changed significantly over the last few decades due to the rapid proliferation of distributed energy resources. Single-phase rooftop PVs as well as electric vehicles can significantly impact the level of voltage imbalance in the system. Voltage balance is particularly critical to three-phase motor loads, which can experience significant derating in the presence of voltage imbalances. Conventional capacitor switching algorithms, that are based on three-phase switching, employed for conservation voltage reduction (CVR) purposes cannot address this voltage imbalance issue. In order to correct these emergent issues, there is a need to move to single-phase capacitor switching. This paper presents one such single-phase capacitor switching algorithm that improves upon existing CVR techniques. A case study is included with a modified IEEE 34 node feeder to illustrate the new proposed methodology. To aid in comparison, a base case using default (automatic) settings on the load tap changer and capacitor banks, as well as a three-phase capacitor switching case is presented. The results are in line with expectations that single-phase capacitor switching will be a necessary transition in distribution systems especially those with large, unbalanced loads or DERs.

KEYWORDS

Volt/VAR control, Voltage Optimization, Conservation Voltage Reduction, Distribution System Optimization.

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1. INTRODUCTION

The electrical distribution system has undergone dramatic changes in a way it has operated over the last few decades, especially with the integration of various types of distributed energy resources (DERs) [1]. DERs like Solar PV, battery energy storage systems (BESS), generators, etc. have been added to the distribution system either for reducing energy costs, or carbon credits or as a backup source of power [1,2]. However, there have not been any significant changes in a way that capacitor banks have been controlled and operated.

Capacitor banks are used to help offset the VAR requirements of various loads locally as most of these loads are inductive in nature (motors, fans, HVAC, refrigeration) [3]. They have proven to be beneficial in reducing the reactive power drawn from the substation (reducing transformer loading), as well as reducing the losses on the distribution system [4]. However, capacitors banks are generally operated as three-phase banks (gang-operated) and are located across the distribution system. They are switched in and out of circuit using a controller that operates based on user-defined settings (voltage, time, temperature, etc.), which sends a single TRIP/CLOSE command to three individual single-phase switches.

One application for which capacitor banks are especially well suited is conservation voltage reduction (CVR), which, due to the relation between voltage and load, reduces both distribution system's peak demand and energy and reduce system losses [5]. Capacitor banks are used to flatten the voltage profile across the feeder, following which the load-tap-changer (LTC) (or voltage regulators) at the substation is adjusted to lower the feeder voltage to a lower but acceptable value [5].

However, in the ever-changing landscape of electrical distribution systems, this mode of operation is no longer suitable; three-phase switching tends to overcompensate lightly loaded phases or undercompensate heavily loaded phases in unbalanced systems. With the rapid proliferation of single-phase rooftop solar and increased levels of electric vehicles as loads, there can be a significant voltage imbalance between phases. Voltage imbalance is particularly harmful to industrial customers where relays are set to trip if the voltage imbalance exceeds 1.5-2% (to protect motors); thus, causing process disruptions. According to NEMA MG1 standard, 5% voltage imbalance can reduce a motors output by 25%, which could result in overheating/motor damage, as well as process disruptions if unprotected [6,7]. While it is possible to correct voltage imbalance by means of single-phase line voltage regulators, there are couple of drawbacks to this approach. First, voltage regulators compared to the capacitor banks, have higher operating and maintenance costs due to the larger number of moving mechanical parts. Second reason, which is more important, voltage regulators can balance line-to-ground voltages (in terms of magnitude, but not in terms of voltage angle). However, balancing line-to-ground voltages does not result in balance line-to-line voltages (as motors are sensitive to line-to-line voltage imbalances, rather than line-to-ground voltage imbalances).

In order to address the shortcoming of three-phase capacitor bank switching, new methodology for the implementation of CVR on a feeder has been developed that utilizes single-phase capacitor switching algorithm with the target of reducing system peak demand and losses while improving the voltage balancing index on a feeder. The new approach highlights its advantages over traditional three-phase capacitor bank switching while also exploring upon some additional operational feeder constraints. In addition, this work also builds up upon the work in [8] and [9]. This algorithm is illustrated by simulating a case study with a publicly available feeder with some modifications. The remainder of this paper is presented as follows: Section 2 describes the proposed methodology, along with other considerations and assumptions, Section 3 describes the case study used to illustrate the benefits of the methodology proposed, Section 4 discusses the results obtained from this study. Finally, Section 5, presents the conclusions of this paper and the way forward.

2. SINGLE-PHASE CAPACITOR SWITCHING METHODOLOGY FOR CVR

The first step of the new CVR method based on single-phase capacitor bank switching is to calculate the voltage drop or "*Vdrop*" table. This table represents the impact of switching of each capacitor bank on the voltage at every point that has measurements on the feeder (which most of the time are capacitor banks, voltage regulators and substation). Once the switching impact of all the capacitors on the feeder is captured, the "*Vdrop"* table obtained will help ascertain the correct capacitor switching combination that will help in minimizing the target objective function. Note that the "*Vdrop*" table can be created for several load levels (peak, shoulder, etc.), but the switching sequence for individual capacitors does not change regardless of which one of these tables is used.

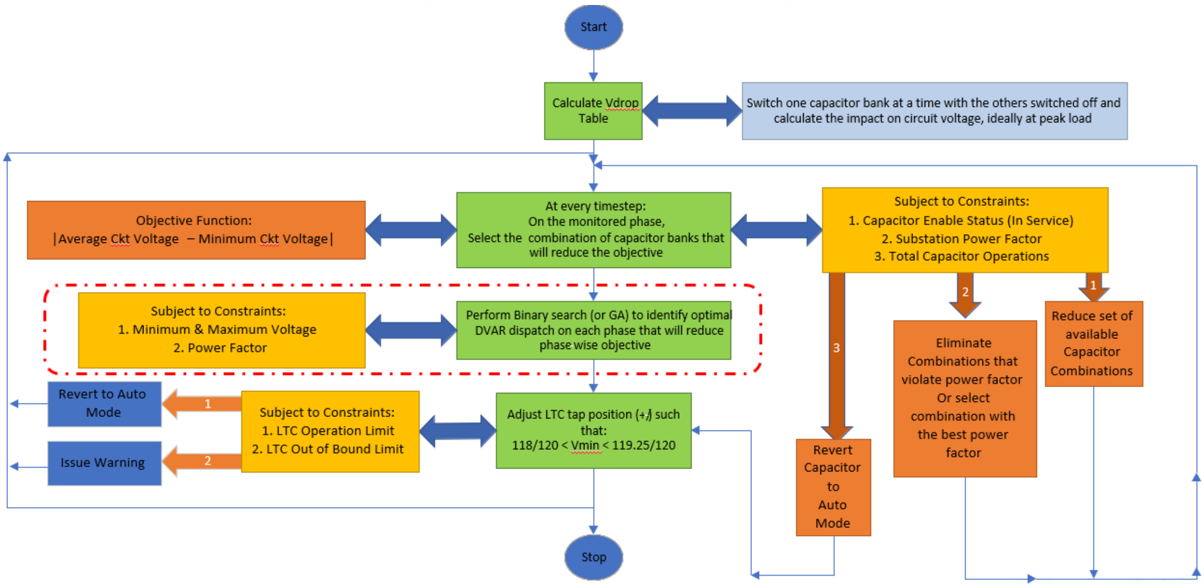

Figure 1. Proposed methodology

OBJECTIVE FUNCTION

The objective function for the new CVR algorithm is now defined as:

$$F_i(t) = avg\left(V_{i,j}(t)\right) - \min\left(V_{i,j}(t)\right) \; \forall \; i \in [1, 2, 3], j \in N \qquad (1)$$

Where $V_{i,j}(t)$ is the voltage (in per unit - p.u.) on phase *i*, at node *j*, at time *t*. *N* is the set of all nodes whose voltages are monitored, and $F_i(t)$ is the objective function calculated for phase *i*.

It must be noted that the impact of cross-coupling, i.e., the impact of switching one capacitor on a particular phase, on the voltage of the other two phases have been ignored for simplicity. Theoretically, there will be some impact but practically, this can be ignored for small feeders and/or capacitor banks of moderate size. Ignoring cross-coupling makes it possible to use this rules-based approach, one phase at a time, to optimize the above-stated objective. This also has the effect of limiting the number of combinations to choose from, i.e., in a system with three

three-phase capacitor banks the number of combinations would be: $\sum_{m=1}^{3\times3} {}^{3\times3}_{m}C$, which is 115, while the number of combinations for a feeder with five three-phase capacitor banks is 32,767, which is many combinations to assess, especially for a real-time rules-based approach.

CONSTRAINTS

The following constraints are incorporated into this algorithm:

1. **Capacitor Status**: In case any phase of any capacitor (bank) is taken out of service or has failed to operate and cannot be included in the algorithm, it will be excluded from the combinations available to reduce the objective. In a practical implementation, this status would be passed on from SCADA. Mathematically this constraint is described by equation 2.

$$Cs_{i,j}(t) \leq Cstat_{i,j}(t) \quad \forall\, i \in [1,2,3], j \in K \tag{2}$$

   Where, $Cs_{i,j}(t)$ is the dispatch command for the capacitor on phase *i*, in bank *j*, at time *t*. $Cstat_{i,j}(t)$ is the availability status (healthy status) of the capacitor on phase *i*, in bank *j*, at time *t*. *K* is the set of all capacitor banks that will be controlled. Both, $Cs_{i,j}(t)$ and $Cstat_{i,j}(t)$ are binary variables.

2. **Substation Power-factor**: This constraint is enforced on a per-phase basis. Thus, if any combination results in a substation power-factor beyond 0.95 leading or lagging, then that combination would be excluded from the list of available combinations. A case may arise where none of the combinations can keep the substation power-factor (on any phase) within the prescribed limits, in that case, the combination which yields the highest power factor, i.e., nearest to the prescribed limits is chosen for that phase. These conditions are described by equations 3 to 5.

$$-0.95 \leq \psi_i(t) \leq 0.95 \quad \forall\, i \in [1,2,3] \tag{3}$$

   Where, $\psi_i(t)$ is the power-factor, measured at the substation on phase *i*, and is given by:

$$\psi_i(t) = \frac{kW_i(t)}{kVA_i(t)} \times sig(kVAR_i(t)) \tag{4}$$

   Where, $kW_i(t)$ is the real power on phase *i*, at time *t*. $kVA_i(t)$ is the apparent power on phase *i*, at time *t*, and $kVAR_i(t)$ is the reactive power on phase *i*, at time *t*. sig is the signum function.

   If equation 3 cannot be enforced, then:

$$\psi_i(t) = max\left(\frac{kW_i(t)}{\sqrt{(kVAR_i(t) - CapkVAR_i(t))^2 + kW_i^2(t)}}\right) \tag{5}$$

   Where, $CapkVAR_i(t)$ is the total capacitive reactive power due to all the capacitors dispatched on phase *i*, at time *t*.

3. **Capacitor Operations**: To prevent excessive operations (wear and tear) of capacitors, a predefined limit – of total operations per day – is set. If the total number of operations

of any capacitor exceeds this limit, then it is operated in an *"auto"* mode and excluded from the algorithm. Equation 6 describes this constraint.

$$\sum_{t=2}^{T} |Cs_{i,j}(t) - Cs_{i,j}(t-1)| \leq Cmax_j \; \forall \; i \in [1,2,3], j \in K \tag{6}$$

Where, T is the total simulation time, $Cmax_j$ is the maximum allowable capacitor operations for a capacitor in bank j for time-period *T*.

4. **LTC Operations**: Similar to the limit on capacitor bank operations, the number of operations of LTC is also limited to prevent excessive operations. In case the limit is reached then the LTC will operate in "*auto*" mode. This constraint may be mathematically understood as:

$$\sum_{t=2}^{T} |LTCp(t) - LTCp(t-1)| \leq LTCmax \tag{7}$$

Where, $LTCp(t)$ is the LTC's tap position at time *t*, and $LTCmax$ is the maximum allowable LTC operations in time-period *T*.

5. **Voltage limits**: Feeder voltage limits are defined as 120V±5% or 114V – 126V. During the feeder voltage flattening portion of the algorithm, that involves the capacitor bank switching, the algorithm ensures that the voltage on any point on the feeder does not exceed the high voltage of 126V. During the voltage reduction portion of the algorithm, in order to ensure that all the measured voltages are within the acceptable range at the substation, two constraints are enforced, one on the minimum voltage and one on the maximum voltage:

$$\frac{118}{120} \leq \min\left(V_{i,j}(t)\right) \leq \frac{119.25}{120} \qquad \forall \; i \in [1,2,3], j \in K \tag{8}$$

As stated in figures 1 and 2, the LTC taps are adjusted so that the minimum circuit voltage is between the limits shown in equation 8. The reason for having 1.25V bandwidth is to ensure that the LTC does not operate excessively, as each tap operation changes the voltage by 0.25V. If the field data shows that the LTC has excessive number of daily operations, this bandwidth can be increased to 1.5 or 2.0V.

However, the taps are not increased (boosting the voltage) if the maximum voltage is above 1.05pu, given by the following equation:

$$\max\left(V_{i,j}(t)\right) \leq \frac{126}{120} \quad \forall \; i \in [1,2,3], j \in K \tag{9}$$

Apart from these constraints, in case the LTC is out of bounds, i.e., the algorithm requires switching taps beyond its limit, then a warning is issued via SCADA.

3. CASE STUDY DETAILS

For the case study, a modified IEEE 34 node feeder [10] is used. Five capacitor banks are placed along the backbone of the feeder (see Figure 2). The original two capacitors and line voltage regulators have been disabled/bypassed. In addition, system peak load has been scaled down to 6.7MW.

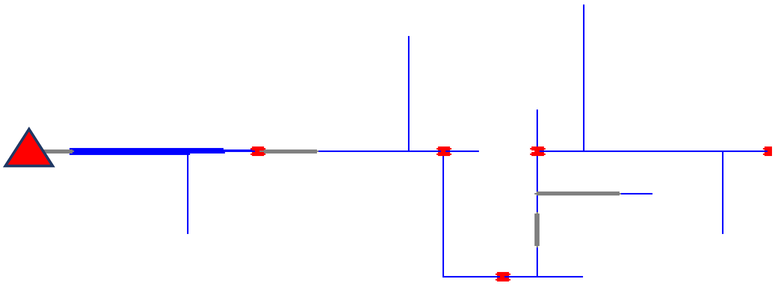

Figure 2. Modified IEEE 34 node feeder - red dots highlight the locations of capacitor banks, from left to right: 900kVAR, 600kVAR, 300kVAR, 300kVAR, and 300kVAR, red triangle – substation

Figure 3 shows the load profile used for the purpose of this study, it includes the peak day of each season in the order: winter, fall, summer, and fall, with the circuit peaking in summer (6.6MW load peak). The time resolution of the load profile data is 5-mins.

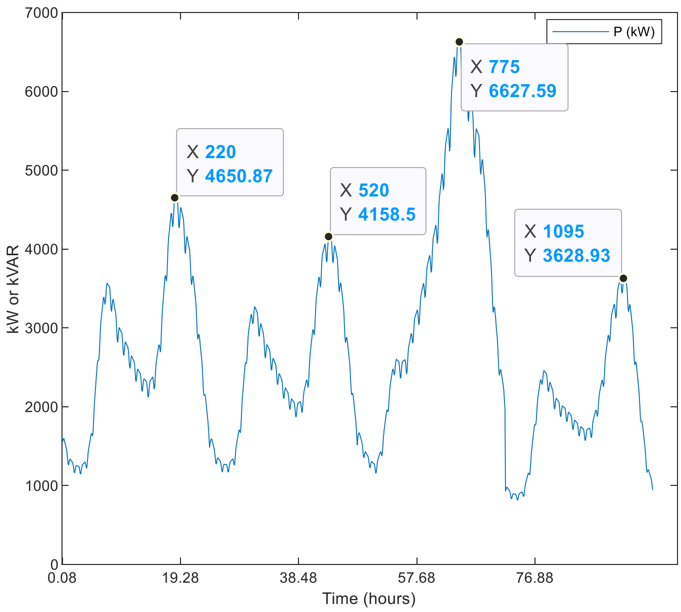

Figure 3. Load profile used for the case study

The *auto* settings used in this study for the LTC are Band Center=124V and Bandwidth=2V, and for the capacitor are: On < 118V, Off > 124V. The delays are not considered since the time-step considered is more than the typical delays considered in practice.

Using the above data and feeder information, the following cases are simulated with OpenDSS software in order to compare the efficacy of the single-phase capacitor bank switching algorithm:

1. Base case (auto settings)
2. Three-phase capacitor switching – phase A monitored
3. Single-phase capacitor switching – all phases monitored

4. CASE STUDY RESULTS

Figure 4 below shows the overall voltage statistics, at each node, for each phase using the load profiles in Figure 3. For the three-phase capacitor banks switching case, phases B and C are overcompensated being lightly loaded. Results for single-phase capacitor switching show that the maximum voltage has reduced by a considerable amount, especially in phases B and C.

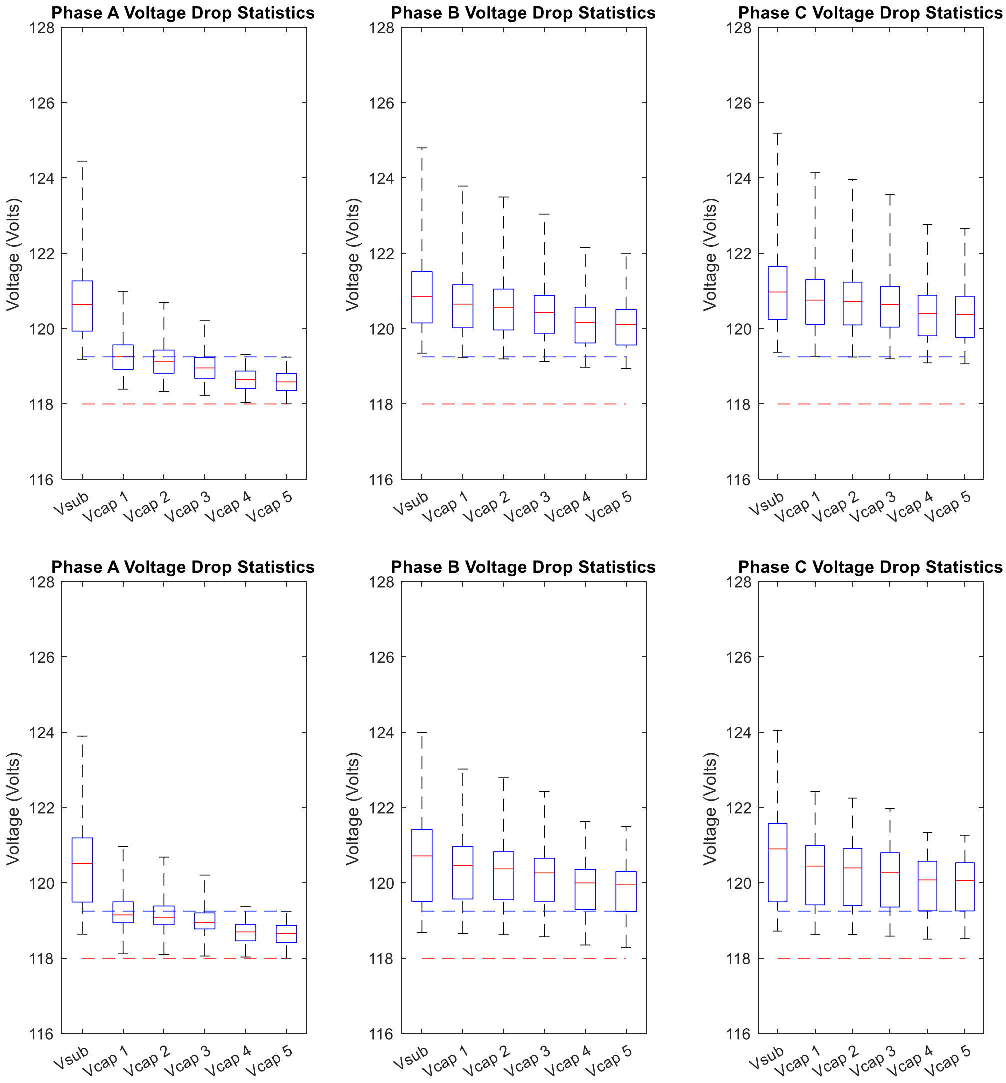

Figure 4. Top: phase-wise voltage drop statistics on each monitored node with three-phase capacitor switching, Bottom: phase-wise voltage drop statistics with single-phase capacitor switching

While the improvement in using single-phase capacitor switching is considerable compared to the three-phase capacitor bank switching, the results are always limited by the capacitor bank rating. In order to further improve the voltage balancing on the feeder e new type of devices called distribution VAR compensator may yield substantial benefits in such scenarios.

Figure 5 below shows the voltage imbalance statistics for both single-phase and three-phase capacitor bank switching scenarios as part of the CVR algorithm. As seen from the figure, single-phase capacitor switching can reduce the voltage imbalance compared to the traditional three-phase capacitor bank switching.

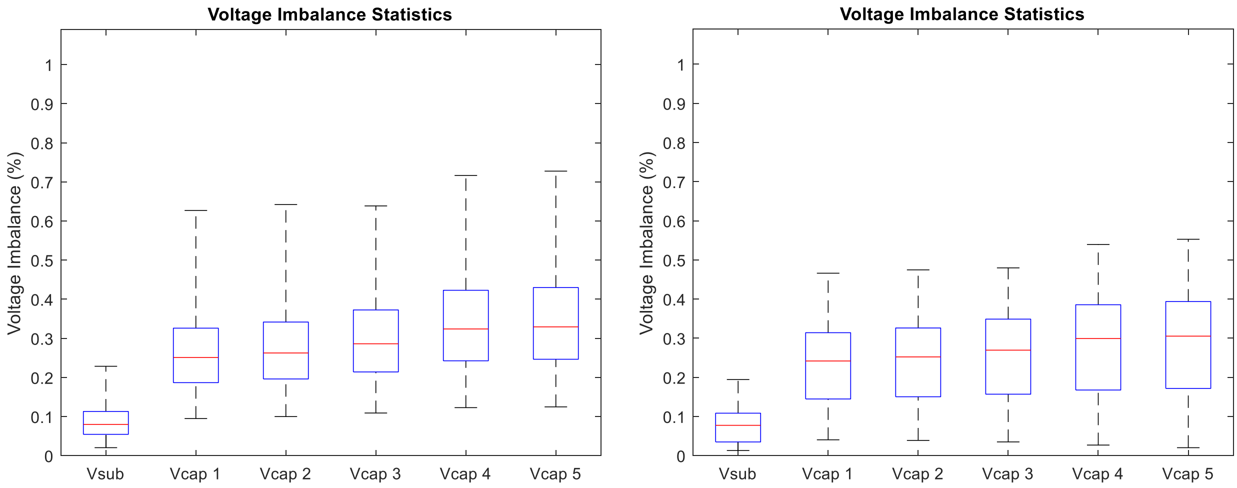

Figure 5. Top: Voltage imbalance statistics on each monitored node with three-phase capacitor switching, Bottom: voltage imbalance statistics with single-phase capacitor switching

Table 1 shows how the new proposed CVR algorithm that includes the single-phase capacitor bank switching algorithm improves upon the performance of the traditional CVR algorithm with three-phase capacitor bank switching, especially in terms of overall peak demand (MVA), real and reactive power loss, maximum circuit voltage, and maximum voltage imbalance. It must be noted that the single-phase capacitor bank operations are approximately three times that of the three-phase case since each capacitor operation within the bank is counted individually.

Table 1. Summary of Results

Sr. No.	**Metric**	**Units**	**Base Case**	**3 Phase (A)**		**Single Phase**	
				Value	% Change wrt BC	Value	% Change wrt BC
1	Peak Demand	MVA	7.34	7.13	-2.9%	7.06	-3.8%
2	Peak Demand	MW	6.72	6.73	0.1%	6.71	-0.1%
3	Peak Demand	MVAR	3.02	2.37	-21.5%	2.24	-25.8%
4	Total Real Losses	MWh	3.07	2.55	-16.9%	2.52	-17.9%
5	Total Reactive Losses	MVARh	137.67	39.8	-71.1%	34.2	-75.2%
6	Total LTC Operations	Nos	6	54	800.0%	51	750.0%
7	Total Capacitor Operations	Nos	4	28	600.0%	67	1575.0%
8	Min Ckt Voltage	pu	117.37	118	0.5%	11	0.5%
9	Max Ckt Voltage	pu	125.54	125.19	-0.3%	124.05	-1.2%
10	Max Voltage Imbalance	%	0.73%	0.73%	0.0%	0.55%	-24.7%

While the move to individual/single-phase capacitor switching does appear to have merit, certain modifications to the capacitor health monitoring software may needed in order to be able to seamlessly integrate this device into electric utility SCADA systems. Generally, the neutral current (magnitude) of three-phase capacitor bank is monitored to detect when either the can or the disconnect switch on the capacitor bank are either failing or have already failed.

. Under the normal operating conditions, neutral current (60Hz) is usually less than 5A. Upon the failure of the capacitor bank, this current can exceed 15A. However, using single-phase capacitor switching will render this methodology unusable, because switching individual phase of any capacitor bank will result in neutral current exceeding 15 A (assuming the minimum capacitor bank size of 600 kVAR on 12.47kV system). For that reason, if capacitor banks disconnect switches do not have the status ‘a’ switch wired into junction box and connected to the digital inputs on the capacitor bank controller, new method is needed in order to properly detect the state of each phase of the capacitor bank. This can be done by measuring the magnitude and angle of neutral current, where the angle of the neutral current provides the information regarding the switch status and the magnitude of the neutral current provides the information about the health of each of the phases of capacitor bank (can or disconnect switch failure).

5. CONCLUSION

This work proposes a rules-based single-phase capacitor switching algorithm for distribution systems. A case study was simulated to emulate the functioning of this algorithm in comparison to a base case and a case with three-phase capacitor switching. The results point to the benefit of this approach as a significant reduction in many key parameters like system peak demand (MVA), maximum circuit voltage, real and reactive power loss, and voltage imbalance was observed. Future work involves rigorous testing on multi-feeder distribution systems and rolling out the algorithm onto actual distribution systems.

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