Improve Distribution System Energy Efficiency With Coordinated Reactive Power Control
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Abstract—In the distribution management system (DMS), an essential application for the energy efficiency improvement is loss reduction. Loss reduction often involves the control of reactive power (var) resources to optimize the var flow in the network. Traditionally, most available var resources in the distribution network have been switchable shunt capacitor banks. Today distributed energy resources (DER) are becoming another significant var resource due to their increasing penetration, which brings new opportunities as well as challenges for loss reduction. This paper proposes an advanced loss reduction approach to achieve the optimal control coordination among multiple capacitors and DERs. The proposed approach and solution are developed on the basis of the detailed multi-phase distribution network modeling and the state-of-the-art optimization technology. This work also investigates the impact of the DER var control on the loss reduction improvement and voltage violation correction. The effectiveness of the proposed approach is demonstrated on practical utility distribution circuits with varying degree of unbalance and model complexity. The performance of the solution method proves the capability of online solution speed for large and complex distribution systems.

Index Terms—Distributed energy resources, distribution management system, energy efficiency, loss reduction, reactive power (var) flow optimization, shunt capacitor banks, voltage violation correction.

I. INTRODUCTION

In nowadays power systems, about 10% of electric energy generated by power plants is lost in the power delivery system, and around 40% of this loss occurs in the distribution network. Therefore, loss reduction is a critical function in the distribution management system (DMS) to improve energy efficiency. The system loss in distribution networks mainly comes from the power dissipation on current-carrying conductors, such as feeders, laterals, and transformer windings. Given the conductor resistance, the amount of power dissipation is proportional to the square root of the current magnitude, which is determined by its active and reactive components. Decreasing the current reactive component while maintaining the required real power supply (active component) has been an effective means to reduce the loss.

In order to decrease the reactive component in the current flow, distribution utilities traditionally often place switchable capacitor banks at strategic locations to supply reactive power (var) locally. As a result, the control of capacitor banks has been the focus of most existing loss reduction approaches [1]–[7]. In recent years, various factors including environmental concerns, system expansion constraints, and technology advances in distributed energy resources (DERs) have led to the proactive penetration of DERs in distribution systems. Many DERs allow the control of their var output within a certain range and thus become another important var resource in the distribution network.

Comparing to the on/off capacitor switching, the control of DER var output has two major advantages: (1) the capacitor switching is usually limited to 4–6 times per day in the operating practice, while the DER var control has no such restriction and can be conducted more often; (2) the DER var output can be adjusted in a continuous/small-amount manner that prevents/corrects the over-/under-var compensation resulting from the discrete capacitor switching. These advantages make the DER var control a promising means for loss reduction in addition to the capacitor switching.

The availability of DER var control presents both new opportunities and extra challenges. Some research efforts have been devoted to integrating DERs in the loss reduction: Reference [8] decouples the capacitor and DER var control into two sub-problems that are solved in separate steps. The decision of capacitor switching is made first, based on which the DER var output is determined. References [9] and [10] integrate the impact of DER power injection on the system loss into the optimal power flow (OPF) model. The solution of the OPF provides the DER var settings. References [11]–[15] adopt meta-heuristic techniques such as the genetic algorithm, ant colony algorithm, particle swarm optimization, and tabu search to solve volt/var optimization problems for loss reduction purpose. References [16] and [17] propose a three-level hierarchical volt/var control structure, in which DERs are used in both the primary voltage control and the tertiary control aiming for day-ahead planning.

Most of these loss reduction approaches attempt to avoid the complex mathematic modeling and solution either by decoupling the control of capacitors and DERs into different stages or adopting meta-heuristic solutions. The decoupling method does not achieve optimally coordinated control between capacitor banks and DERs; while the meta-heuristic solution in general has performance issues when dealing with practical large scale systems. Moreover, most of these approaches ignore the unbalanced nature of the distribution network and develop solutions using the oversimplified single-phase balanced network model. Furthermore, the developed approaches and solution methods are only demonstrated on small test systems, their effectiveness
and performance on practical large-scale utility circuits are unclear.

This work aims to develop a distribution system loss reduction approach that can overcome above drawbacks. Based on authors’ experience in applying multi-phase model in the traditional loss reduction approach using capacitors only [1], this work attempts to achieve more advanced optimally coordinated control among multiple capacitors and DERs and take into account the impact of control actions on the voltage profile. In particular, comparing to the existing approaches, the contributions of this work are illustrated as follows:

1) Few research work in the literature has addressed the inherent unbalanced nature of the distribution network due to the model complexity and the resulting large-scale optimization problem. This work integrates the practical multi-phase model in the loss reduction application to reflect the unbalanced nature of the practical distribution network, which enables more accurate loss reduction application and provides valuable experience for other DMS applications.

2) This work presents a quantitative insight on the impact of the oversimplified balanced distribution network model to the accuracy of power flow analysis. The power flow analysis is the fundamental function for loss reduction and many other DMS applications. The errors caused by the balanced single phase network model will inevitably propagate to the loss reduction and other applications, which shows the rationale behind choosing the multi-phase network model.

3) The proposed approach achieves optimal coordinated control among multiple capacitors and DERs that can take fully advantage of the continuous DER var control capability to compensate the over-/under-var compensation caused by the discrete nature of capacitor switching. In addition, this approach can also determine the control actions according to the priorities of voltage correction and loss reduction in the operating practice.

4) This work adopts real-world distribution circuits to demonstrate the effectiveness and performance of the proposed approach and solution method on the common personal computer platform. The test results on practical distribution circuits with varying level of unbalance and model complexity ascertain that the proposed approach and solution is suitable for online applications for large-scale systems.

Overall, this paper presents a successful attempt in adopting the multi-phase model for loss reduction application, investigates the impact of balanced model on power flow accuracy, and achieves optimal coordinated control of various var resources with online performance for practical problems.

This paper is organized as follows: Section II analyzes the technical challenges faced by the advanced loss reduction technology. Section III describes the proposed approach in detail, including multi-phase distribution network modeling, loss reduction approach formulation, and solution method. Section IV provides case study results as well as the impact analysis of the DER var control on loss reduction and voltage correction. Section V states the conclusion and future work.

II. Technical Challenges

The objective of the loss reduction application is to minimize the distribution system loss while taking into account the system voltage correction. The available controls include both the capacitor switching and DER var output adjustment. Distribution systems in reality have unbalanced circuit construction and loading levels on three phases. The unbalanced characteristics and various configurations of the distribution circuits exhibit in the following aspects:

- unbalanced device constructions, such as single-, two-, or three-phase lines, loads, transformers, capacitor banks, and DERs;
- radial or meshed circuit configuration with single or multiple sources;
- various transformer connections (e.g., Y/Y, Y/Δ, Δ/Y, Δ/Δ, open Δ); grounded/ungrounded, leading/lagging;
- Y or Δ load and capacitor bank connections;
- various voltage dependent load characteristics such as constant impedance load and constant power load;
- ganged or unganged control devices including capacitors and DERs.

The loss reduction problem in essence is a nonlinear combinatorial optimization problem with the following features:

- mixed continuous (DER var output) and integer (on/off capacitor switching) control variables;
- nonlinear objective (system loss) function and operating constraints in terms of implicit or explicit control variables;
- non-convex objective function and solution set;
- high dimension optimization problem resulting from the large-scale distribution circuits with thousands of distribution lines nodes, and other components.

As a result, major challenges in achieving an advanced loss reduction function include: 1) realistic representation of the unbalanced distribution system characteristics and various circuit configurations, 2) efficient and robust optimization algorithm to achieve coordinated control between the continuous and discrete controls, and 3) online solution performance to achieve real time loss reduction for practical large-scale distribution systems.

III. Advanced Loss Reduction Approach and Solution

This work proposes an advanced loss reduction approach and solution method developed on the basis of the multi-phase distribution network modeling and advanced optimization technology. The multi-phase model is able to reflect the unbalanced distribution system nature and various circuit configurations. The proposed optimization technology can optimally coordinate the control among multiple capacitors and DERs and provide online solution speed. This section describes the multi-phase distribution system modeling, optimization algorithm, and the solution method.

A. Multi-Phase Distribution System Modeling

The multi-phase distribution system modeling technique explicitly models every existing phase, the multi-phase configuration for each device, and the connection among different devices. The detailed distribution system modeling enables the accurate calculation of system loss and the evaluation of
control actions on loss reduction as well as voltage correction. This section illustrates representative distribution network device models (e.g., the distribution line, transformers with various configurations, load/capacitor bank connections, and the DERs), the unbalanced load flow formulation, and the comparison between power flow results based on single phase and multi-phase models.

1) Multi-Phase Distribution Line: The distribution line (such as feeders, cables, and laterals) is the backbone for a distribution system. Not all the line sections are built with balanced three phases, some laterals may include only single or two phases. The pi-equivalent model is used for both balanced and unbalanced line sections in this work. Fig. 1 shows a pi-equivalent model for a three-phase line section, in which each phase is modeled explicitly with self-impedance, shunt susceptance, and the mutual coupling with other phases. The detailed mathematical equations of the line model can be found in [18]. Similar model is developed for unbalanced line sections with only single or two phases.

2) Transformer Configuration: Transformers in the distribution system include substation transformers such as on-load tap changers (OLTC), transformers along the line section such as voltage regulators, and service transformers that directly connect to customers. These transformers may be balanced or unbalanced and present various configurations in practical distribution circuits. The main configuration types include the following: Wye/Wye, Wye/Delta, Delta/Wye, and Delta/Delta. Additional variations also derive from these types, such as grounded/ungrounded connection based on the grounding scheme of the wye connected side, leading/lagging Wye/Delta or Delta/Wye connection based on if the primary voltage is leading or lagging the secondary voltage, and open delta connection which provides three-phase voltages from two single-phase banks. All these transformer configurations are supported in this work. Fig. 2 shows a Wye/Wye grounded transformer example.

3) Load/Capacitor Connection and Modeling: Loads and capacitors are important components in the distribution network. They can be single-/two-/three-phase devices and in delta or wye connection. In this work, two types of load models, constant impedance and constant power loads [18], are adopted to represent different load voltage dependent characteristics. Capacitors may have either ganged or unganged control. For a capacitor with unganged control, each phase is modeled with an individual control variable to represent the unganged control capability. Fig. 3 shows a three-phase delta-connected load example and a three-phase wye-connected capacitor with three unganged control variables \(u_a\), \(u_b\), and \(u_c\) that are integrated with each phase impedance. These variables can take values of 0 or 1, corresponding to the open or close switching of each phase.

4) Distributed Energy Resource: Distribution systems have increasing power supply from various types of DERs such as wind turbines, photovoltaic arrays, fuel cells, micro-turbines, diesel generators, and energy storage devices. The capabilities of these DERs in controlling their var output are different, and some of these DERs have their var output controllable, they can operate at different given power factors. Considering that loss reduction is a steady state application in DMS, only the steady state characteristics of DERs are of interest. A DER with var controllability is represented with the PQ model that allows its var output vary within a certain range. The var output of the DER \(Q_{\text{der}}\) at a given time interval is limited by the DER's capacity \(S_{\text{der}}\), active power output \(P_{\text{der}}\), and the power factor lagging or leading limits \(\text{PF}_{\text{lim}}^{\text{lag}}\) or \(\text{PF}_{\text{lim}}^{\text{lag}}\), as expressed in (1) and (2). Many DERs are renewable resources such as wind or solar, their active power output may fluctuate within the given time interval. The estimated maximum active power output is used in determining the var output range. Based on (1) and (2), and (3) and (4) are derived to calculate the maximum/minimum DER var outputs \(Q_{\text{der}}\), i.e., \(Q_{\text{der}}\) is the minimum value of the two values determined by the lagging power factor limit \((-P_{\text{der}})/(\text{PF}_{\text{lim}}^{\text{lag}})\sqrt{1-(\text{PF}_{\text{lim}}^{\text{lag}})^2})\) and the DER maximum var injecting capacity \((\sqrt{S_{\text{der}}^2-P_{\text{der}}^2})\), \(Q_{\text{der}}\) is the maximum value of the two values determined by the leading power factor limit \((-P_{\text{der}})/(\text{PF}_{\text{lim}}^{\text{lag}})\sqrt{1-(\text{PF}_{\text{lim}}^{\text{lag}})^2})\) and the DER maximum var absorbing capacity \((-\sqrt{S_{\text{der}}^2-P_{\text{der}}^2})\). Note that the positive value means that the DER injects reactive power, and the negative value means that the DER absorbs reactive power:

\[
\begin{align*}
Q_{\text{der}} & \leq \sqrt{S_{\text{der}}^2-P_{\text{der}}^2} \\
\frac{P_{\text{der}}}{S_{\text{der}}} & \geq \left(\text{PF}_{\text{lim}}^{\text{lag}}\right) \text{or} \left(\text{PF}_{\text{lim}}^{\text{lag}}\right) 
\end{align*}
\]
Q_{\text{der MAX}} = \min \left\{ \frac{P_{\text{der}}}{PF_{\text{lim}}^{\text{ag}}} \sqrt{1 - (PF_{\text{lag}}^{\text{ag}})^2} \sqrt{S_{\text{der}}^2 - P_{\text{der}}^2} \right\}

Q_{\text{der MIN}} = \max \left\{ \frac{P_{\text{der}}}{PF_{\text{lim}}^{\text{ag}}} \sqrt{1 - (PF_{\text{lead}}^{\text{ag}})^2} \right\} - \sqrt{S_{\text{der}}^2 - P_{\text{der}}^2} \right\}

where

\begin{align*}
S_{\text{der}} & \quad \text{DER power capacity;} \\
P_{\text{der}} & \quad \text{(estimated) active power output for the specified time interval;} \\
Q_{\text{der}} & \quad \text{DER reactive power output;} \\
PF_{\text{lim}} & \quad \text{DER lagging/leading power factor limits;} \\
PF_{\text{lag}} & \quad \text{DER reactive power output limit} \\
PF_{\text{lead}} & \quad \text{DER lagging power factor limit} \\
Q_{\text{der MAX}}, Q_{\text{der MIN}} & \quad \text{maximum/minimum DER var output.}
\end{align*}

5) Unbalanced Load Flow: Based on each multi-phase device model, the unbalanced load flow (UBLF) model is further built by forming power balance equations at each node in the system. The UBLF formulation provides a realistic representation of the practical distribution network nature including unbalanced circuit construction and loading level, various device connections and configurations, ganged/unganged control characteristics, and so on. The realistic system representation enables more accurate power flow analysis and results in more optimal and granular control decisions to improve loss reduction and voltage correction comparing to other methods, in which the control decisions are usually made based on the oversimplified balanced network model.

6) Impact of Network Models on Load Flow Analysis: Although the multi-phase model can better represent the unbalanced nature of the real-world distribution network, the balanced single-phase model has traditionally been widely applied in the DMS applications due to its simplicity. Few research efforts have addressed the error brought by the single-phase model to DMS applications in a quantitative way.

This section compares the load flow results obtained from single- and multi-phase models respectively to examine the impact of different network models on the accuracy of load flow analysis. This comparison is conducted on two representative practical distribution networks. In particular, the multi-phase model based load flow result is used as the benchmark, the differences in the node voltage magnitude are obtained using (5), which shows error percentages of the single phase model-based load flow result:

\[ V_e = \frac{V_n - |V|_e}{V_n} \times 100\% \]

where

\begin{align*}
|V|_e & \quad \text{voltage magnitude obtained from single-phase model;} \\
|V|_m & \quad \text{voltage magnitude obtained from multi-phase model;} \\
|V|_e & \quad \text{voltage error (from single-phase model) in percentage.}
\end{align*}

TABLE I

| No. | Maximum $|V|_e$ | Percentage of node w/$|V|_e > 5\%$ |
|-----|---------------|-----------------------------------|
| 1   | 8.82%         | 12.42%                            |
| 2   | 6.32%         | 27.64%                            |

For each distribution circuit, the maximum error percentage in the voltage magnitude as well as the number percentage of nodes with the voltage magnitude error greater than 5% are summarized in Table I. Such information provides a quantitative indication of the impact on the load flow analysis accuracy by adopting the oversimplified single-phase model.

Considering this work is developed on the basis of the load flow, the load flow error caused by the single phase model will inevitably propagate to the proposed loss reduction approach. The error information obtained in this section shows the rationale behind choosing the multi-phase model for the proposed approach and can also be used as a proxy to reflect the approximate error level of the proposed approach if the single phase network model is adopted.

B. Advanced Loss Reduction Approach

Facilitated by the detailed multi-phase network model, an advanced loss reduction optimization approach is developed to achieve optimally coordinated control among multiple capacitors and DERs. The formulated optimization problem is shown in (6)–(13).

1) Controllable Devices: In this optimization problem, controllable devices include DERs besides switchable capacitor banks. Control variables are the continuous DER var output ($u_d$) and the discrete capacitor switching ($u_c$). Both ganged and unganged control of these controllable devices are included in this work.

2) Objective Function: In the objective function of the formulated optimization problem, the first term is to calculate total power loss using real and reactive current components and the branch resistance. While controlling capacitors and DERs to reduce loss, their impact on the voltage profile cannot be ignored. Distribution utilities often set higher priority for the voltage correction over loss reduction in the operating practice. That is, when the voltage violation exists, utilities desire to correct the voltage violations while reducing loss or even sacrificing the loss reduction for voltage correction; when no voltage violation exists, the loss reduction should not lead to any voltage violations. To address this practice, the objective function also includes a penalty function for each line-to-neutral/line-to-line voltage violation. By appropriately selecting the weight factor ($w_k$), the capacitor and DER var control targets to improve voltage violations while achieving the loss reduction.

3) Constraints: The constraints in the formulated optimization problem include both current and voltage operating limits. The calculation of these parameters is based on their base values plus the estimated changes caused by the control actions. Equations (7)–(9) enforce the current magnitude. Equation (10) enforces the maximum and minimum DER var output limits. Equations (11)–(13) are the constraints for each line-to-neutral/line-to-line voltage magnitudes:

\[ \text{Min } f = \sum_{i=1}^{N_k} \left\{ \left( I_{i}^r \right)^2 + \left( I_{i}^l \right)^2 \right\} \times R_i \]
\[ I_d = I_d(0) + \sum_{c=1}^{n_c} S_{i_{ac}} I_{i_{ac}} + \sum_{i=1}^{n_b} u_d \]

\[ I_q = I_q(0) + \sum_{c=1}^{n_c} S_{i_{alc}} I_{i_{alc}} + \sum_{i=1}^{n_b} u_d \]

\[ \sum_{k=1}^{n_b} \{ V_k^+ + V_k^- \} \cdot w_k \]

subject to

\[ (I_d^2 + I_q^2) \leq (I_{\text{max}}^2) \]

\[ Q_d^\text{MIN} \leq Q_d(0) + u_d \leq Q_d^\text{MAX} \]

\[ V_k = V_k(0) - V_k^+ + V_k^- + \sum_{c=1}^{n_c} S_{V_k} V_k \cdot u_c \]

\[ \sum_{k=1}^{n_b} \{ V_k^+ + V_k^- \} \cdot w_k \]

C. Reflection of the Multi-Phase Network Model in the Formulated Optimization Problem

All parameters in the objective function and constraints shown in (6)–(13), such as voltages, currents, resistances, are the parameters used in the multi-phase network model. Two examples are provided below to illustrate how the multi-phase distribution network model is adopted in the optimization problem formulation.

In the objective function, based on the detailed multi-phase network model, the power loss on each existing phase of the distribution line and transformer winding is explicitly taken into account. For instance, given a lateral section (l) that only consists of two phases (e.g., phases a and b), which is very common in many distribution networks, the two phase resistances \( r_{la} \) and \( r_{lb} \), as well as the real and reactive current components on the two phases (\( I_{\text{la}}^2 \) and \( I_{\text{lb}}^2 \) for phase a, \( I_{\text{la}}^2 \) and \( I_{\text{lb}}^2 \) for phase b) are used to calculate the loss for the lateral section as shown in (14).

No unrealistic three-phase balance assumption is made for this two-phase lateral.

In a nutshell, both objective function, constraints for currents and voltages are also derived based on the detailed multi-phase network model, i.e., each constraint reflects the limit for each phase or line variable. For example, if a single-phase load is connected between the two phases of the lateral (l), the constraint for the line-to-line voltage of the load connecting between the two phases is expressed in (15). Again, the impractical assumption for a three-phase balanced load is not necessary, and the constraint set only includes one line-to-line voltage for this load:

\[ V_{\text{MIN}}^\text{MIN} \leq V_{ab} \leq V_{\text{MAX}}^\text{MAX} \]

IV. CASE STUDIES

The advanced loss reduction approach and solution are tested with nine practical distribution utility circuits. This section illustrates these circuits and test results based on the proposed coordinated control technology. Besides, this section also presents the test results from a benchmark approach that only includes capacitor control. The detailed benchmark formulation is provided in the Appendix, which is derived by removing DER var

\[ P_i = \{ (I_d^2)^2 + (I_q^2)^2 \} \cdot r_{la} + \{ (I_{\text{la}}^2)^2 + (I_{\text{lb}}^2)^2 \} \cdot r_{lb} \]
control related parts from the advanced approach formulation in (6)–(13). The benchmark approach is implemented and solved in the same environment and tested with the same nine distribution circuits as that of the advanced approach. Test results from the two approaches are compared for the purpose of investigating the impact of DER var output control on the loss reduction and voltage correction.

A. Test Circuits

Table II lists the information of nine distribution circuits (C1-C9) used to test both advanced and benchmark approaches. Each circuit has multiple feeders, and the average number of feeders is 10. Regarding distribution lines including both feeders and laterals, about 60% are three-phase and 40% are single-/two-phase. Voltage levels vary between 4.16 kV to 23.9 kV. In these circuits, the number of switchable capacitors (#Cap) varies between zero to four, which are either ganged or unganged controllable. As these distribution circuits originally do not include controllable DERs, a number of PQ mode DERs are added to the circuits at randomly selected locations. The number of added controllable DERs (#DER) varies between two to ten. Load models include two types: constant power and constant impedance model.

The numbers of circuit nodes (#Node), loads(#Load), and lines(#Line) shown in Table II are the numbers without counting the actual phases. In other words, each node, load, or line may have single, two, or three phases. Each load and capacitor may connect in delta or wye connection. Besides the components listed in the table, each circuit also includes multiple transformers (on-load tap changer, voltage regulators, etc.) in various configurations as discussed in Section II.

All these test systems are typical practical distribution circuits with representative features in terms of distribution network dimension and complexity. The test results based on these circuits provide meaningful information in the effectiveness and performance of the proposed loss reduction approach and solution for practical distribution systems.

B. Test Results

The test results of advanced and benchmark loss reduction approaches on the nine circuits are classified into three categories. The circuits in each category exhibit certain common features in the loss reduction and voltage correction. Tables III–V present test results for circuits in each category, respectively. Each table includes the following information:

- Base Case: no loss reduction function is applied
- Cap Only: Apply the benchmark loss reduction approach based on capacitor control only
- Cap+DER: Apply the advanced loss reduction approach based on the coordinated control among capacitors and DERs
- Loss: the circuit power loss in kW
- Reduction %: the power loss reduction in percentage with respect to the base case power loss
- #VV: the number of voltage violations
- Max[VV]: absolute maximum voltage violation amount (in pu)

1) Category 1: Category 1 includes circuits 1, 2, and 3 (C1-C3). All three test circuits have voltage violations in the base case. Table III shows the test results from the proposed and benchmark loss reduction approaches.

When applying the benchmark approach (Cap only): for circuits 1 and 3, no capacitor switching action is available to improve both loss reduction and voltage violations or just correct voltage violations given its high priority; regarding to circuit 2, the capacitor switching action can achieve 20% loss reduction while improving the voltage profile by reducing the number of voltage violations and the maximum amount of the voltage violation. When applying the proposed approach (Cap+DER): comparing to the benchmark approach, the voltage violations are further improved for circuits 1 and 3 and completely eliminated for circuit 2. In addition more circuit loss reductions are
TABLE V

| Category 3: Test Results on Loss Reduction and Voltage Violation Correction |
|-----------------|-------------------|-------------------|
| Circuit        | Loss (kW)         | #VV               | Max[V]| |
| Base Case      | 49.9 (Reduction %)| 0                 | 0     | |
| Cap Only       | 45.5 (8.9%)       | 0                 | 0     | |
| Cap + DER      | 42.1 (16%)        | 0                 | 0     | |
| C7             |                   |                   |       | |
| C8             | 51.6              | 0                 | 0     | |
| Base Case      | 130               | 0                 | 0     | |
| C9             | 120.4 (7.3%)      | 0                 | 0     | |

Achieved: loss reduces 4.8% for circuit 1, 23% for circuit 2, and 7% for circuit 3.

The test results in this category demonstrate that the coordinated control among capacitors and DERs is able to further reduce loss while eliminating/improving voltage violations, comparing to the benchmark approach with capacitor control only.

2) Category 2: Category 2 includes circuits 4, 5, and 6 (C4-C6). Similar to the circuits in category 1, C4-C6 have voltage violations in the base case. Table IV shows the test results from the proposed and benchmark approaches.

When applying the benchmark approach (Cap only): for all three circuits, no capacitor switching action is available that can both correct voltage and reduce loss or just correct voltage violations. When applying the advanced approach (Cap + DER): given the high priority of the voltage correction over the loss reduction, voltage violations are improved (for circuits 5 and 6) or eliminated (for circuit 4) by sacrificing the system losses for all three circuits. Loss increases 34% for circuit 4, 8% for circuit 5, and 17% for circuit 6.

Test results in this category show that the voltage correction and loss reduction cannot be achieved concurrently due to the contradict impact of capacitor and DER var control on the two targets. Given the high priority of voltage correction, the coordinated control between capacitors and DERs is able to eliminate or improve voltage violation, while cap control only cannot achieve similar results.

3) Category 3: Category 3 includes circuits 7, 8, and 9 (C7-C9). Different from the circuits in the other two categories, C7-C9 have no voltage violation existing in the base cases. Table V shows the test results from the two approaches. Circuit 7 can achieve 8.9% loss reduction with the benchmark approach while 16% loss reduction with the proposed approach. Circuits 8 and 9 do not include any capacitors and can achieve 11% and 7.3% loss reduction with the proposed approach, respectively. Meanwhile, the test results show that proposed approach can reduce loss without incurring new voltage violation.

In summary, the test results from nine typical distribution utility circuits show that the involvement of DER var control and especially the optimally coordinated control among capacitors and DERs can achieve further loss reduction and voltage correction comparing to the approach with capacitor control only. In particular, when the impacts of the control action on the loss reduction and voltage violation do not contradict, the proposed approach can improve both aspects effectively. Otherwise, given the higher priority on the voltage correction, the proposed approach can better improve the voltage profile. When no voltage violation exists in the base case, the proposed approach can further reduce system loss without incurring new voltage violation.

C. Solution Performance

The solution performance is tested on a desktop computer with following configuration: Intel Core 2 Quad Processor Q9400@2.66 GHz, 4 GB RAM, Microsoft Windows XP operating system.

Tables VI and VII provide the solution runtimes on the nine test circuits based on two approaches, separately. Most of solution runtimes are less than or around three seconds. The solution runtime of circuit 5 is six seconds when applying proposed loss reduction approach. This circuit has relatively large dimension and number of controllable devices (four capacitors and eight DERs). Overall, the solution performance is suitable for online application to handle complex large-scale distribution circuits in the real world.

V. CONCLUSION

This paper presents an efficient and robust loss reduction approach based on the detailed multi-phase unbalanced distribution network modeling and advanced optimization technology. The proposed approach is tested with multiple representative real-world distribution system circuits. The test results demonstrate the effectiveness of the optimally coordinated capacitor and DER control in loss reduction and voltage violation correction. The solution performance proves the capability of the online application for large and complex systems. The future work will include the OLTC and voltage regulators as the additional controllable devices to facilitate voltage violation correction and further release the potential capability of capacitor and DER control in loss reduction. In addition, loss reduction over multiple time intervals (with varying generation and load levels) will be also investigated.
APPENDIX

The benchmark loss reduction problem formulation is derived based on the proposed approach as illustrated in (6)–(13). The benchmark approach only controls capacitor banks for loss reduction and voltage correction. The test results from this formulation are used as the reference to demonstrate the effectiveness of the advanced loss reduction approach. The detailed problem formulation is described in (16)–(22):

\[
\begin{align*}
\text{Min } f &= \sum_{i=1}^{n_e} \left( (I_i^+)^2 + (I_i^-)^2 \right) \cdot r_i \\
&+ \sum_{k=1}^{n_b} \left( V_k^+ + V_k^- \right) \cdot w_k \\
\text{s.t. } I_i^+ &= I_i^q(0) + \sum_{c=1}^{n_c} S_{ne}^{lc} \cdot u_c \\n&\quad i = 1, \ldots, n_b \\
I_i^- &= I_i^q(0) + \sum_{c=1}^{n_c} S_{ne}^{lc} \cdot u_c \\n&\quad i = 1, \ldots, n_b \\
(I_i^+)^2 + (I_i^-)^2 &\leq (I_i^{\text{ref}})^2 \\&\quad i = 1, \ldots, n_b \\
V_k - V_0 - V_k^+ + V_k^- + \sum_{c=1}^{n_c} S_{ne}^{lc} \cdot u_c \\&\quad k = 1, \ldots, n_u \\
V_{k}^{\text{MIN}} &\leq V_k \leq V_{k}^{\text{MAX}} \quad k = 1, \ldots, n_u \\
V_k^+ &\geq 0, V_k^- &\geq 0 \quad k = 1, \ldots, n_u.
\end{align*}
\]

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