Capacitor Allocation in Order to Maximize the Loss Reduction Benefit and Improve the Voltage Profile Based on NSGA-II

Mortaza Farsadi[1], Tohid Sattarpour Dizaji[1], and Hadi Hosseinnejad[2]
[1] Urmia University, Urmia, Iran
m.farsadi@urmia.ac.ir, t.sattarpur@yahoo.com
[2] Department of Electrical Power Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran
h.hosseinnejad@iaurmia.ac.ir

Abstract

For many years, using capacitor as generally was one of the big challenges in electrical industrials. Some of these problems refer to economical and other ones are based on technical limits. Capacitor placement is a challenge that define as the base of capacitors problems, is considered in this paper. In this paper, in order to maximizing the loss reduction benefit and voltage profile improvement simultaneously, considering different percentages of peak load and electricity prices have been studied. Also, a probabilistic load model at each load state is assumed in this paper instead of utilizing time-series based models. Moreover, optimum numbers of capacitors should be used in each load state in order to optimizing the problem. Therefore, it is used non-dominated genetic algorithm version II (NSGA-II) to solve the problems under study. NSGA-II is used for a typical network by considering possibilities. The effectiveness of the proposed scheduling approach verified on IEEE 33-bus distribution test system over the planning period. Here the most important part is modeling the probability of load, which can say the load's behavior is most of the time follow that.

1. Introduction

Locating capacitors and other kind of electrical stuffs are used many years as a main part of every electrical network. Most used methods for this goal are genetic algorithm [1], PSO [2] and other meta heuristic algorithms [3]. Therefore, dissimilar kinds of Intelligent Electronic Devices (IED) that used for many years in power systems, such as smart meters and Distribution Remote Terminal Units (DRTUs) and some other devices developed to profit an online and efficient control on diverse parts of networks [4, 5]. Different types of consumer such as commercial and industrial consumers can contribute in demand request. The policy is supply in two bases including time-based programs and motivation-based programs [6, 7]. Time based programs, with different electricity prices for different peak loads of day ahead hours, are generally used for encourage consumers to use in the best way, but behind all this policies it is important to use some IED to have stability and more certainty.

In this paper the using shunt capacitors is aimed to reach a various kind of proposes consist on loss reduction benefit and voltage profile improvement. Shunt capacitors are popular to solve some problems in distribution network [8, 9]. Except reduction in power losses, the shunt capacitors improve the voltage profile, power factor, voltage stability of the system and some others [10]. Using capacitors in distribution networks in most of the papers and plans are a way to reach some golden goals. Some kinds of energy sources such as Distribution Generation (DG) and Energy Storage System (ESS) have been used with capacitors in distribution networks in order to different goals. For example in paper [11], the authors used a multi-objective method for locating DGs like wind power generation in the distribution network. In paper [12] the Differential Evolutionary (DE) algorithm has been used. In paper [13], the method that used is wavelet transform and hybrid principal component network analysis.

Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Dynamic Programming (DP) are popular methods in most of the papers for optimization. GA that is a sort of probabilistic heuristic algorithms produces a way for optimization problems by using methods motivated by natural evolution in nature such as legacy, mutation, mixture, and crossover [14]. PSO is one of other methods for optimization that is a computational algorithm to optimize by iteratively trying to progress a contestant solution. PSO optimizes a problematic by having a population of first fortuitous solutions [15]. DP as another way is a method for solving a difficult problem by breaking it down into an assembly of simpler sub-problems [16].

The most important thing which must consider is that each of the prior methods has some problems, for example GA and PSO aren't sufficient for solving the multi-objective problems and the DP might finally effect on the sizes of the problem, thus requiring giant calculations.

The method that is used in this paper is Non-dominated Sorting Genetic Algorithm version II (NSGA-II) [17]. The most important thing about NSGA-II is that can sort last answers in a way that the best answers can compete between each other in every moment and it can reach multi goals together. By using NSGA-II for locating capacitors as a main part we decided to use capacitors in order to maximize the loss reduction benefit and improve the voltage profile considering different load states, electricity prices for each state and also considering the probability of each state during the planning period. After this step it's important to get the number of capacitors that are online in each load state and in duration of planning period. The effectiveness of the proposed method verified on a 33-bus distribution test system over the planning period.

This paper is organized in 6 sections. The NSGA-II algorithm is presented in section 2. Section 3 is prepared to describe the methodology. Evaluate the Objective Functions and Simulation results are provided in section 4 and 5 respectively. Eventually, conclusion is presented in section 6.

2. NSGA-II Algorithm

NSGA-II that is used in this paper as the main algorithm, is a relative of Genetic Algorithm .GA as an intelligent algorithm reproduces the natural selection manner. In this method, the most qualified parentages would be luckier to replace their genetic code to the future descendants. This procedure known as evolution process employed by specific operators namely crossover, mutation, selection etc. By this method, GA would be proper to carefully inquiry the search space and then find the optimal answers [18, 19].

NSGA is an algorithm from the family of the GA for multiple objective function optimizations. It is related to other evolutionary Multiple Objective Optimization (MOO) methods such as Strength Pareto Evolutionary Algorithm (SPEA), and Pareto Archived Evolution Strategy (PAES). The updated and currently canonical form NSGA is its version II [19].

The first aim is to minimize the function as it's mentioned in equation (1):

$$\begin{aligned}&\min F(x)=\{f_i(x),\ldots,f_n(x)\}\\&s\,t:\ g(x)\le 0,\ \ h(x)=0\\&x\subset\Re\end{aligned}\tag{1}$$

In this equation, *F(x)* is main function that consist *i* parts. $f_i(x)$ is the *i-th* function that is going to optimize by multi-objective algorithm. *g(x)* and *h(x)* are limits that *g(x)* is related to non-equal limits and *h(x)* is equality limits. The "Fig. 1" shows a multi-objective algorithm with two typical functions.

In "Fig. 1", it's obvious that A and B are better than C as an answer to optimization and minimization. But, which between A and B are better than other one is not clear. So, it's defined a subject with the name of "dominate". When it is said X_1 dominate X_2, it means X_2 in no aspect is better than X_1. After non-dominating sort of answers, the second part is defining "Pareto Front". The "Fig. 2", shows the "Pareto Front" for a typical function consists two sub-functions.

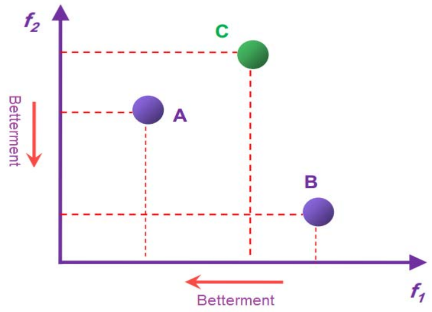

Fig. 1. A multi-objective algorithm with two function.

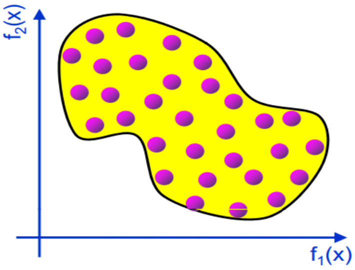

Fig. 2. Pareto Front for a typical problem.

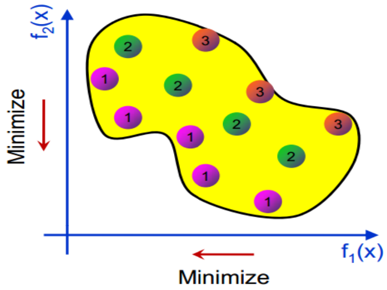

Fig. 3. Grouping answers.

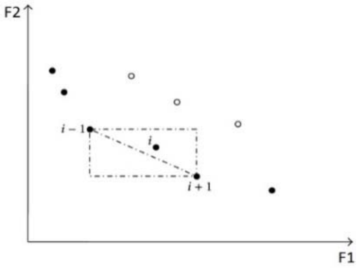

Fig. 4. Crowding distance calculation.

As it's showed, the border around the answers is "Pareto Front" which appears and as a simple explanation, it's the feasible answers which can happen and use by considering limits and other conditions. The next step is defining and sorting answers to groups (for example in 3 groups). This part will cut our answers to 3 parts, *F1*, *F2*, and *F3*.

The next step in "Fig. 3" algorithm will omit the answers which excess than population size. Then it's important to calculating crowding distance that showed in "Fig. 4".

In equation (2) the "Crowding Distance" can be seen which separate the best answer. The "Crowding distance" is a concept that omits the answers near to each other and keep the answer that are various in one or more aspect to have a vast gamut of answers. The incensement of *dj(k)* shows the improvement of answer because of distance between them. For example as it's shown in "Fig. 4", the particle (answer) *i-th's* relativity between *i-1* and *i+1* is shown in equation (2). The end step in algorithm applies crossover and mutation on answers that give the best answers as it's in GA.

$$d_j(k)=\sum_{i=1}^{n}\frac{f_i(k-1)-f_i(k+1)}{f_i^{\max}-f_i^{\min}}\tag{2}$$

3. Methodology

In this section, the general methodology employed in this paper is presented. The loading at each bus is assumed to follow the load shape. The load data has been clustered into 10 distinct load states. The loading levels, electricity prices, and the probabilistic models of load during the planning period for each state are given in "Fig. 5". As shown in this figure, electricity prices are different for each load state. For example, at maximum peak load state the electricity price is 0.031 $/kWh and the probability of this state is 1% (0.01).

The outputs of this methodology are the optimal location of the capacitors in the distribution network and also the

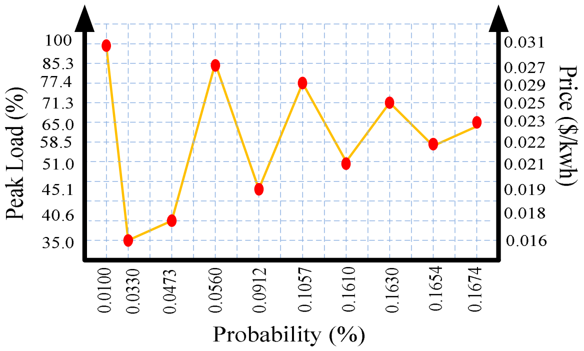

Fig. 5. Structure of the proposed methodology

optimum numbers of capacitors in each load state in order to optimize the objective functions.

The proposed methodology is based on the following assumptions:

- The network is balanced during the planning period.
- There is limited budget for placing of capacitors and totally, two kinds of capacitors have been selected, 300 Kvar capacitors and 600 Kvar capacitors.
- The capacitors have been controlled online for switching the optimum number of capacitors in each load state.
- There are five capacitors in this study. Three capacitors are 300 Kvar and two capacitors are 600 Kvar.
- Duration of planning period is one year.

4. Evaluation of Objective Functions

Capacitors are considered to be installed at different buses for injecting reactive power to the network. Capacitors, due to their excellent capabilities, could utilize to attain several objectives such as power losses minimization and voltage profile improvement. Herein, the most important purpose is to maximize the loss reduction benefits and improvement of voltage profile in the network represented as follows in equation (3) and equation (4):

$$OF1 \quad LRB = 8760 \times \sum_{Ls} \rho_{LS} \times C_{LS} \times (P_{Loss}^{WithoutC} - P_{Loss}^{WithC}) \tag{3}$$

$$OF2 \quad VPI = \sum_{LS} (\Delta V_{WithoutC}^{LS} - \Delta V_{WithC}^{LS}) \tag{4}$$

Where, LRB represents the loss reduction benefit, Ls is the load states index, ρ_{LS} and C_{LS} are the probability and electricity price for each load state respectively, and $P_{Loss}^{WithoutC}$ and P_{Loss}^{WithC} represents the total power losses for each state without and with capacitor, respectively. VPI, is the second objective function that represents the voltage profile improvement in the network under study. $\Delta V_{WithoutC}^{LS}$ and ΔV_{WithC}^{LS} represents the sum of total buses voltage profile without and with capacitor at load states (*LSes)*, respectively.

The sum of total buses voltage profile is represented by equation (5):

$$\Delta V^{LS} = \sum_{i=1}^{Nbus} (V_s - V_i)^2 \tag{5}$$

Where, V_s is the voltage of substation that is assumed equal to 1 (Vs =1), and V_i is the voltage of *i-th* bus. Note that ΔV^{LS} is the total buses voltage profile for load state *LS*.

The problem constraints such as load flow balances, and voltage limits, for each combined load-capacitor state (*Ls*), are presented as follows in equation (6) and (7):

$$P_{g_{i,Ls}} - P_{L_{i,Ls}} = \sum_{j \in \Omega_i} P_{ij}(V_{i,Ls}, V_{j,Ls}, Y_{ij}, \theta_{ij}) \tag{6}$$

$$Q_{g_{i,Ls}} + Q_{C_{i,Ls}} - Q_{L_{i,Ls}} = \sum_{j \in \Omega_i} Q_{ij}(V_{i,Ls}, V_{j,Ls}, Y_{ij}, \theta_{ij}) \tag{7}$$

Where, $Q_{C_{i,Ls}}$ is reactive power generation by capacitor at bus i and state Ls respectively. $P_{L_{i,Ls}}$ and $Q_{L_{i,Ls}}$ represents active and reactive powers of distribution network feeders at each load state respectively, $V_{i,Ls}$ and $V_{j,Ls}$ are bus voltages at bus i and bus j at each load state respectively, finally Yij and θ_{ij} are the magnitude and phase angle of feeder's admittance, respectively.

$P_{g_{i,Ls}}$, $Q_{g_{i,Ls}}$ are active and reactive power generate in each bus and P_{ij}, Q_{ij} respectively are active and reactive powers which transmits between bus *i* and *j*.

Proper constraints are required to assurance the voltage magnitude to be kept at permissible range at each bus.

$$V_{\min} \le |V_{i,Ls}| \le V_{\max} \tag{8}$$

Where, V_{min} and V_{max} are minimum and maximum limits of bus voltages for each load state respectively and i is indices of buses.

5. Simulation results and discussion

The system used for the case study is IEEE's 33-bus radial distribution system, as shown in "Fig. 6".

The rated active and reactive power ranks of the load points as well as the feeder data are taken from [20]. The system's active and reactive powers in peak load state are 3.715 MW and 2.3 MVA, respectively. For this case study the bus 1 is connected to the sub transmission network and is assumed as the substation.

NSGA-II has been applied with various crossovers and mutations in each iteration. The best results are obtained with population size of 100, recombination rate equal with 0.5 and mutation factor accustomed at 0.01, respectively. Note that NSGA-II and its parent GA, as one of the heuristic algorithms, does not guarantee the same answer even after running the same problem numerous times but they are all acceptable. Consequently, in this study NSGA-II's run was repeated 15 times and saved optimal solution results. This section summarizes optimum results of this study, optimal siting of capacitor units in order to achieve maximum loss reduction benefit and voltage profile improvement. The impact of allocated capacitors is studied in this section through comparing in two different conditions: evaluating the network condition with capacitors and without capacitors, also selecting the optimum numbers of capacitors in each load state.

"Table.1" gathers the power loss for each load state and finds the obtained results for the first and second objective functions. As shown in this table, loss reduction benefit considering the probability of each state and their electricity prices, is 4874$ during a year. In addition, the power losses for each load state with and without capacitors are shown in this table. Moreover, the optimum results for the second objective function are given in this table too.

"Table .2" shows the optimum location and numbers of capacitors at each load state. As shown in this table, bus 13 and

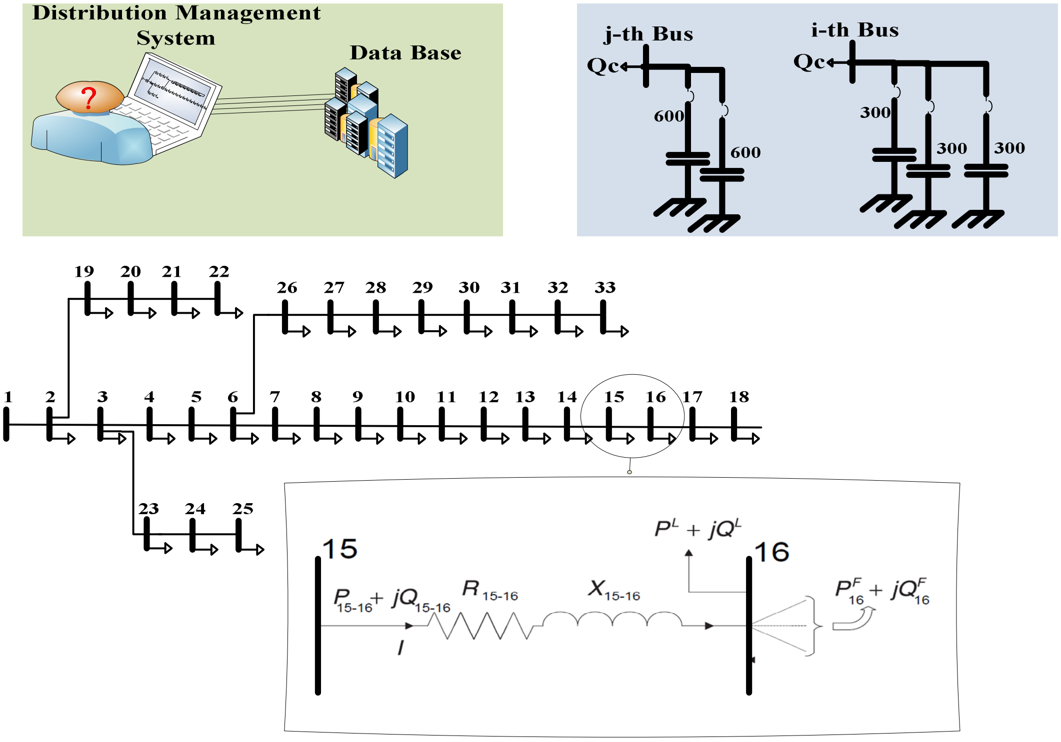

Fig. 6. The schematic diagram of the IEEE's 33-bus radial distribution system

Table 1. Optimal results for test system.

$OF1 \quad LRB = 8760 \times \sum_{Ls} \rho_{LS} \times C_{LS} \times (P_{Loss}^{WithoutC} - P_{Loss}^{WithC})$			4874 $	Objective Functions			
$OF2 \quad VPI = \sum_{LS} (\Delta V_{WithoutC}^{LS} - \Delta V_{WithC}^{LS})$			1.1177	Objective Function 1		Objective Function 2	
Load State Num.	Peak Load (%)	Probability (ρ_{LS}) (%)	Price (C_{LS}) ($/kWh)	$P_{Loss}^{WithoutC}$ (kW)	P_{Loss}^{WithC} (kW)	$\Delta V_{Without\ C}$	$\Delta V_{With\ C}$
01	35.0	3.30	0.016	23.3973	18.1021	0.0147	0.0079
02	40.6	4.73	0.018	31.7341	23.5905	0.0347	0.0195
03	45.1	9.12	0.019	39.4120	34.2541	0.0595	0.0354
04	51.0	16.10	0.021	50.8320	35.8047	0.0916	0.0479
05	58.5	16.54	0.022	67.6272	46.6933	0.1343	0.0671
06	65.0	16.74	0.023	84.3106	58.0783	0.1875	0.0933
07	71.3	16.30	0.025	104.2559	72.1993	0.2534	0.1282
08	77.4	10.57	0.027	121.8549	85.0019	0.3305	0.1592
09	85.3	5.60	0.029	149.8646	104.0404	0.4253	0.1883
10	100	1.00	0.037	210.9862	157.7679	0.5591	0.2261

30 are the optimum place for 300 Kvar and 600 Kvar capacitors respectively. Also, in the maximum peak load state, because of maximum power losses with maximum electricity prices, the numbers of capacitors must be equal to maximum number of them.

The acceptable range for voltage magnitudes in all buses and each load state has been determined to be between 0.95 p.u and 1.05 p.u respectively. "Fig. 7" and "Fig. 8", depict the voltage profile for the test system without and with capacitors, respectively. As it is seen, voltage profiles of the test system without capacitors are not in acceptable ranges but with capacitors are limited in the allowable ranges.

In "Fig. 9", the "Pareto Front" as it's described, illustrated for load state 10. This load state is the maximum peak load which it is the most important load state for showing NSGA-II effect on decreasing the power losses cost and improving the voltage profile. It is mention again that first function should increase by an increment in difference between power loss cost with capacitors and without them. The last and best answers for both functions are highlighted by a circle in this figure.

Table 2. Optimum site and numbers of capacitors in each load state.

Optimal Capacitor Site	Bus 13 (300 Kvar)	Bus 30 (600 Kvar)
Load State Number.	Numbers of 300 Kvar	Numbers of 600 Kvar
1	0	1
2	0	1
3	1	0
4	1	1
5	1	1
6	1	1
7	1	1
8	2	1
9	2	2
10	3	2

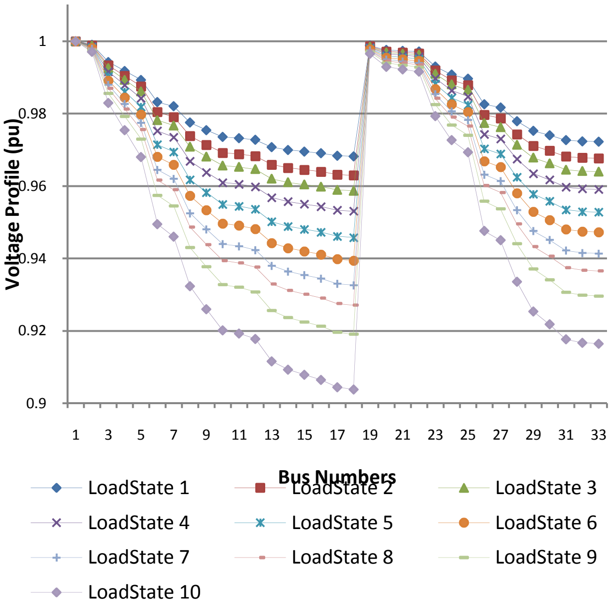

Fig. 7. Voltage profile without capacitor.

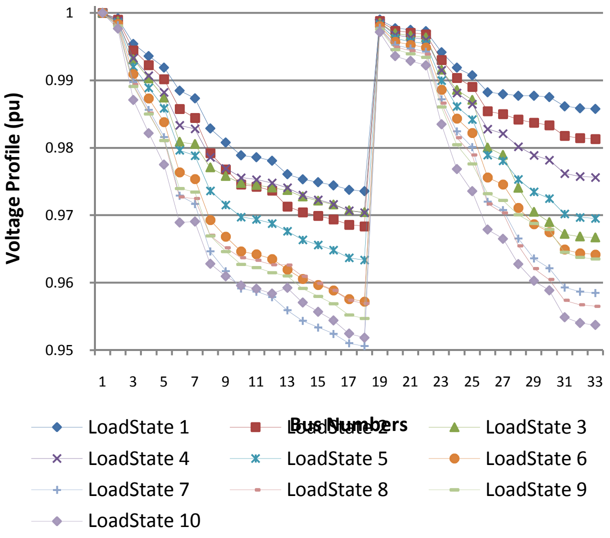

Fig. 8. Voltage profile with capacitor.

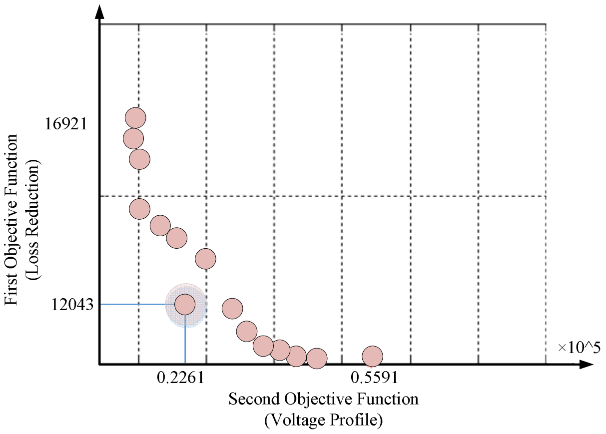

Fig. 9. Pareto Front for load state 10.

6. Conclusion

In this paper, by presenting a comprehensive mathematical formulation, concurrent allocation of two types of capacitors has been modeled based on NSGA-II. Capacitor allocation is one of the important problems in the distribution networks, which is presented in this paper.

This paper proposed the methodology by considering the probability of load states with their special electricity prices during the planning period in order to maximizing the loss reduction benefits and voltage profile improvement, simultaneously. It was shown that applying capacitor units which results in higher reactive power support, would have a considerable effect on voltage profile and energy losses cost. By this way, the optimal numbers of capacitors at each state have been assigned as well. NSGA-II method has been used to solve the problems under study. The value of the proposed scheduling method has been confirmed on IEEE 33-bus distribution test system. Consequently, it is necessary for distribution network operators to consider the numbers of capacitors in the expansion planning problems as well as siting and sizing issues in the future smart distribution networks.

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