Switchable Capacitor Bank Coordination and Dynamic Network Reconfiguration for Improving Operation of Distribution Network Integrated with Renewable Energy Resources

Ramin Borjali Navesi, Darioush Nazarpour, Reza Ghanizadeh, and Payam Alemi

Abstract—**Point of common coupling (PCC) arrays are the most prominent and widely-used intermittent distributed generations (DGs). Due to the right-of-way, environmental, economical and other restrictions, the connection of these types of DGs to the preferred point of the distribution network is very difficult or impossible in some cases. Therefore, because of non-optimal locations, they may cause a voltage rise at the PCC. In this paper, a coordinated design of switchable capacitor banks (SCBs) with dynamic reconfiguration of the distribution network is proposed to avoid low- and high-voltage violations. The distribution network reconfiguration is implemented to mitigate the voltage rise at PCCs and capacitor banks (CBs) to solve the low-voltage problem. A novel method is presented for determining the optimal size of CBs. The proposed capacitor sizing method (CSM) effectively determines the optimal values of reactive power for the given nodes. The optimal locations of SCB are determined using particle swarm optimization algorithm. The 24-hour reactive power curve optimized by the proposed method plays a pivotal role in designing SCBs. The simulation results show that the implementation of the dynamic network reconfiguration and the placement of SCB is required to maintain a standard voltage profile for better employment of DG embeded distribution networks.**

Index Terms—**Capacitor placement, distributed generation (DG), non-linear load, dynamic reconfiguration, switchable capacitor.**

I. Introduction

THE growing interest in the utilization of carbon/pollution-free energy sources has widely changed the traditional distribution networks into modern active distribution networks. Nowadays, the incorporation of distributed generations (DGs) and capacitor banks (CBs) into distribution networks seems unavoidable due to fast load growth and the obstacles in the construction of new substations [1]. DGs are able to provide voltage support, distribution congestion relief, power loss reduction, reliability improvement [2], [3], node voltage profile improvement, emission reduction, operation cost minimization and infrastructural or networks investment deferral [4]-[7]. Therefore, the optimal application of DGs is essential.

In the case of utility-owned DGs, it might be possible for distribution network operators to select the DG sites or optimally control their generations. Practically, if DGs are owned by customers, the operators cannot reallocate and resize the DGs. In addition, the placement of DGs is generally dictated by many other factors such as the land price, geographical restrictions of wind power and solar radiation and some other economical and/or technical issues. Therefore, these subjects are of theoretical importance. However, the analysis of the reactive power and network reconfiguration is totally valid both from the practical and academic points of view since SBs and networks are utility-owned.

It is worth mentioning that the benefits of DG integration are highly associated with their sites and sizes. In fact, the output power of DGs versus power losses leads to a U-shaped curve [8]. Therefore, the output power of DGs beyond a specific point may increase the power losses and violate voltage profile limits. Consequently, the non-optimal employment of DGs may generate counter-productive results. If a distribution network cannot accommodate the excessive power generation of DGs, it will encounter a voltage rise at the point of common coupling (PCC) and an increase in power loss. As a result, some corrective actions should be carried out. Otherwise, the expected benefits of DGs are not realized. This paper focuses on the optimal utilization of the existing DGs at non-optimal locations. To this end, the reconfiguration of the network in accordance with the generation and load levels is proposed. It is expected that the resultant dynamic configuration can alleviate voltage rise problem and reduce power losses.

When the output power of DGs is low due to insufficient wind speed or sunlight and preventive maintenance repairs,

Manuscript received: February 10, 2020; revised: June 22, 2020; accepted: October 26, 2020. Date of CrossCheck: October 26, 2020. Date of online publication: April 5, 2021.

R. B. Navesi, R. Ghanizadeh, and P. Alemi are with the Department of Electrical Engineering, Islamic Azad University, Urmia Branch, Urmia, Iran (e-mail: r.borjali.68@gmail.com; r.ghanizadeh@iaurmia.ac.ir; Payamalemi@gmail.com).

D. Nazarpour (corresponding author) is with the Faculty of Electrical and Computer Engineering, Urmia University, Urmia, Iran (e-mail: D.nazarpour@urmia.ac.ir).

DOI: 10.35833/MPCE.2020.000067

the network must be able to sustain a standard voltage profile without causing a low-voltage problem. Therefore, the employment of CBs as a cost-effective solution is necessary. Since CBs bring about voltage profile enhancement, the coordination of network dynamic reconfiguration and the placement of CB must be considered to avoid high-voltage deviation. To provide better coordination, switchable capacitor banks (SCBs) are used in this paper. Since the reactive power of the devices can be regulated, SCBs are increasingly integrated into distribution networks. Embedding SCBs in the distribution network is cost-effective to provide regulated reactive power support coordinated with dynamic network configuration [9]. To get the maximum benefits from SCBs, it is important to optimally locate and size them in distribution networks. To this end, some approaches are presented based on meta-heuristic algorithms to optimize the network using capacitor placement including the harmony search algorithm [10], the genetic algorithm [11], the ant colony algorithm [12], and the selective particle swarm optimization (PSO) algorithm [13]. Due to the simplicity and reasonable convergence speed of the PSO algorithm, the flower pollination algorithm [14] and discrete PSO [15] algorithm will be used in this paper for the placement of SCBs.

Based on the literature review, it can be found that, for the renewable energy sources such as wind and PV, the optimal siting and sizing should be substituted with their optimal utilization. Table I presents a classification of specialized literatures, which considers network configuration and capacitor placement, but not the problem of uncertainty and stochastic power generation of DGs. Thereby, in this paper, a dynamic network reconfiguration and a hybrid PSO capacitor sizing method (CSM) based placement of SCBs are proposed to overcome the voltage deviation problem in IEEE 33-bus and 69-bus distribution networks with varying loads and generations. To meet voltage constraints, the energy loss is minimized. Therefore, three different methods are employed to divide the main problem into three smaller sub-problems. The proposed solutions for the sub-problems are listed below.

TABLE I
CLASSIFICATION OF SPECIALIZED LITERATURES

Issue	Specialized literature					Proposed method
	Reference [2]	Reference [3]	Reference [11]	Reference [13]	Reference [15]	
Network condition	Dynamic configuration and load variation	Dynamic configuration and fixed loads	Fixed configuration and fixed loads	Fixed configuration and fixed loads	Fixed configuration and fixed loads	Dynamic configuration, load variation, fixed DG locations, DGs' uncertainties and voltage rise problem
CB/SCB sizing technique	Sensitivity analysis	Heuristics	Genetic algorithm	Selective PSO	Heuristics	Heuristics
Objective function	Energy loss reduction and voltage improvement	Power loss reduction and voltage improvement	Power loss reduction	Power loss reduction and voltage improvement	Power loss reduction and voltage improvement	Energy loss reduction and voltage improvement

1) Dynamic network configuration to mitigate voltage rise problem at PCCs.

2) The placement of PSO-based SCBs for voltage profile enhancement.

3) The determination of optimal value of reactive power using the proposed CSM for the maximum loss reduction.

Uniform voltage distribution reconfiguration algorithm (UVDRA) in [16] is used to determine the dynamic configuration scheme for 24-hour operation. Since SCBs will cause voltage increase, simultaneous placement of SCBs and network reconfiguration for decreasing voltage rise of DGs at PCCs is unessential. Therefore, the voltage rise problem due to excessive generation of WT and PV array at non-optimal locations is solved exclusively by the dynamic network reconfiguration. Moreover, the low-voltage problem of the network is solved by appropriate siting and sizing of SCBs. Hybrid PSO and CSM is used to minimize the energy loss and enhance the minimum voltage of the node up to the minimum allowable limit. The proposed CSM is used to determine hourly optimal reactive power curve, which is needed to minimize network energy loss during 24-hour operation, while the PSO algorithm is used simply to find optimal locations of SCBs, guaranteeing that the voltage constraints are met. Worst-case scenarios are considered to model the uncertainty of loads and generations. The proposed worst cases are chosen in a way that the majority of the probable operation scenarios are covered. Therefore, the operation scheme for the widely studied IEEE 33-bus distribution network is expected to be resilient and keep the operation indices within allowable limits under all other operation conditions.

The main contributions of this paper are as follows.

1) A CSM is proposed to determine the optimal value of reactive power that is accurate, fast and easy to implement.

2) A coordinated design of SCBs with dynamic network reconfiguration is conducted to reduce energy loss and avoid voltage limit violation for practical network operation.

3) Conservative worst-case scenarios are proposed to cover all probable uncertainties of demands and generations of WT and PV array in 24-hour operation.

4) A new method is proposed to design SCB by using the obtained hourly optimal reactive power curve.

II. Problem Formulation

A. Proposed CSM

The amount of optimal reactive power compensation is very much related to the places of capacitors in distribution networks. A modified version of optimal reactive power determination for a given node is introduced in this subsection. According to [17], the optimal reactive power to be injected by the CB which connects to a given node is determined by increasing the reactive power injection up to the value at which the node voltage magnitude in the modified load flow (load flow of the network without considering active parts of the loads) becomes 1 p. u.. This method requires repeated runs of the modified load flow program which increases the computation time. For instance, to determine the optimal sizing of a CB located at bus 6 of a IEEE 33-bus distribution network, 80 load flow runs are required [17], which leads to a heavy computation burden.

Inspired by [17], we present a method to determine the optimal sizing of CBs through a single run of a meshed network load flow. The details of the proposed method are presented as follows.

1) The active parts of the loads are removed, so we call it reactive load network (RLN).

2) The candidate locations for the installation of SCBs are considered as virtual slack nodes (VSNs) in the load flow program, which converts radial RLN into a meshed RLN.

3) A load flow program is executed for the resultant meshed RLN.

4) The reactive power value injected by VSNs is the optimal value of reactive power to be injected by SCBs.

Considering each candidate node as a VSN will create a loop between the main slack node and VSN. Therefore, it is required to implement a load flow program suitable for meshed distribution networks such as the Newton Raphson power flow, or a load flow program of weekly meshed distribution network [16]. Based on the method presented in this paper, only one load flow run is sufficient to determine the optimal value of the reactive power supplied by reactive power sources like CBs. Compared with [15], the proposed method avoids extra load flow runs and consumes the minimum computation time which is needed to obtain the optimal sizing of CBs. Meanwhile, the unnecessary formulations, modification of load flow program and complex programing codes are also avoided.

B. Objective Function

In this paper, we aim to minimize the energy loss of the distribution network with the priority of voltage profile within the prescribed 0.95 p.u. and 1.05 p.u. limits for all the operation scenarios including the worst cases. The energy loss minimization of the distribution network OB can be expressed as:

$$OB=\sum_{h=1}^{24}\left(\sum_{i=1}^{nL}R_i\left|I_i^h\right|^2\right)+PF \tag{1}$$

where R_i and I_i^h are the resistance and current magnitude of the i^{th} branch in the network at the h^{th} hour, respectively; n is the number of branches; L is the number of lines; and PF is the penalty factor. PF is calculated using the following constraints:

$$PF=\begin{cases}(0.95-V_{\min})\cdot 10^6 & V_{\min}<0.95\\(V_{\max}-1.05)\cdot 10^6 & V_{\max}>1.05\\0 & \text{otherwise}\end{cases} \tag{2}$$

where $V_{\min}$ and $V_{\max}$ are the minimum and maximum voltage magnitudes in the worst-case scenarios, respectively.

C. Uncertainty of Loads and Generations

According to [18], noticable errors may occur in the forecasting due to the uncertainties in the wind and PV outputs. Therefore, it is essential to implement an optimal voltage regulation scheme that can tolerate severe uncertainties and maintain voltage magnitude within the specified limits.

The probabilistic and stochastic methods to model load and generation uncertainties heavily rely on historical data. In contrast, robust optimization methods typically apply lower and upper limits of uncertain parameters. The planning solutions are offered by these methods which maintain the optimality for the worst-case scenarios. [19]. As a result, it is essential to consider the worst-case scenarios in the process of optimization to get a resilient operation solution. The cases of network operation optimization for the placement of SCBs coordinated with dynamic reconfiguration are listed as follows.

1) Case 1: voltage rise condition. The loads decrease to 90% and the generations of WTs and PV arrays increase 110% of the typical values.

2) Case 2: base case. Loads and generations are in accordance with the time profile of a typical day.

3) Case 3: low-voltage condition. The loads increase up to 110% of typical load profile while WTs and PV arrays are disconnected to get the repair or preventive maintenance. The objective is to keep the maximum and minimum voltage magnitudes of the distribution network within the operation limits in all of the above cases. The operation limits are set to be 1.05 p.u. and 0.95 p.u. for upper and lower bounds so that the voltage is within the normal range.

D. PSO Algorithm

As a robust optimization algorithm, PSO is a population-based algorithm inspired by the foraging behavior of swarms. In PSO, each solution x_i^t has the memory of the position where it gets the best performance (local best) of the population Gb^t (global best), and these pieces of information are used to update its position by (3) and (4).

$$v_i^{t+1}=v_i^t+C_1r_1(Gb^t-x_i^t)+C_2r_2(Lb_i^t-x_i^t) \tag{3}$$

$$x_i^{t+1}=x_i^t+v_i^{t+1} \tag{4}$$

where C_1 and C_2 are the acceleration coefficients between 0 and 4; r_1 and r_2 are the random variables between 0 and 1; t is the iteration index; and v_i^t is the speed of particle movement. The particles, i.e., solutions of the problem, change according to (4) and (5). A detailed explanation of the PSO algorithm can be found in [20].

E. A Review on UVDRA

In this paper, UVDRA [16] is a meta-heuristic reconfiguration algorithm, which uses the uniform voltage distributions of ending nodes. It starts from a sub-network (a small part of the network) and expands to the source nodes.

In the process of load increment, a load flow program is executed for the sub-network. Then, the candidate node with the highest voltage magnitude is added to the main node group and its downstream node/nodes is/are added to the candidate node group. This process is continued until two identical nodes are obtained, i.e., twin nodes, which emanates from different main nodes. In this stage, one of the open switches is determined. Obviously, one of the twin nodes is excessive. Therefore, the one with the lower-voltage magnitude is removed and its upstream branch is stored in the list of open switches.

Figure 1 shows the flowchart of UVDRA. A detailed explanation of UVDRA can be found in [21]. Note that the method used for network reconfiguration is not restricted to UVDRA and can also be employed by other method.

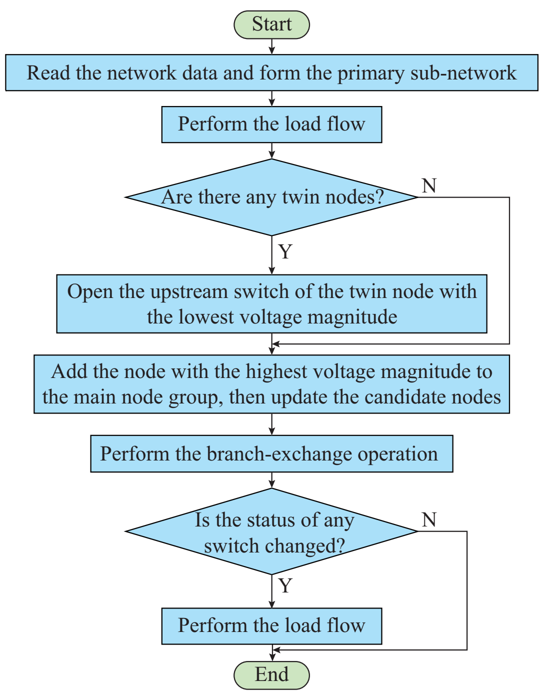

Fig. 1. Flowchart of UVDRA.

III. Solution Method

To deeply explore the obtainable solutions of the optimization problem, it is necessary to reduce the search space of the problem. Hence, three different procedures for each optimization variable are specified. Three proposed optimization techniques for the optimal configuration of the network, optimal siting and sizing of CBs include the UVDRA, the PSO algorithm and the proposed CSM. Firstly, the correction of voltage profile, which is of great importance in the network operation, is divided into two sub-problems, i.e., over-voltage and low-voltage problems. For the over-voltage problem, the network reconfiguration is proposed. Thus, the dynamic configuration scheme of the network with non-linear loads along with intermittent output power of WT and PV arrays must be calculated using the UVDRA. The objective of the network reconfiguration is to reduce the energy loss and mitigate the voltage rise at PCCs. The voltage rise can be mitigated by providing better paths for the generated active power to flow in the distribution network.

For the low-voltage problem and loss reduction, the combination of PSO and the proposed CSM is suggested. The optimal sizing of SCB is related to its placement and network configuration. Fortunately, the proposed CSM can accurately determine the optimal curve of reactive power to be injected by SCBs during 24-hour operation, which has to be well-matched to the dynamic configuration of the network and varying loads and generations. Considering hourly optimal reactive power injection to the nodes, the PSO algorithm deals only with the placement of SCBs. Thereby, the heavy computation burden for both siting and sizing of SCBs at each hour of the operation time is reduced by only computing the placement of SCBs. As a result, the obtained solutions are expected to be global or near global optima. Figure 2 shows the flowchart of the instruction of the proposed CSM for energy loss reduction, which makes the network resilient to the worst operation circumstances, where i_t, i_t^{max}, and I_t are the iteration number, the maximum iteration number, and the total iteration number, respectively.

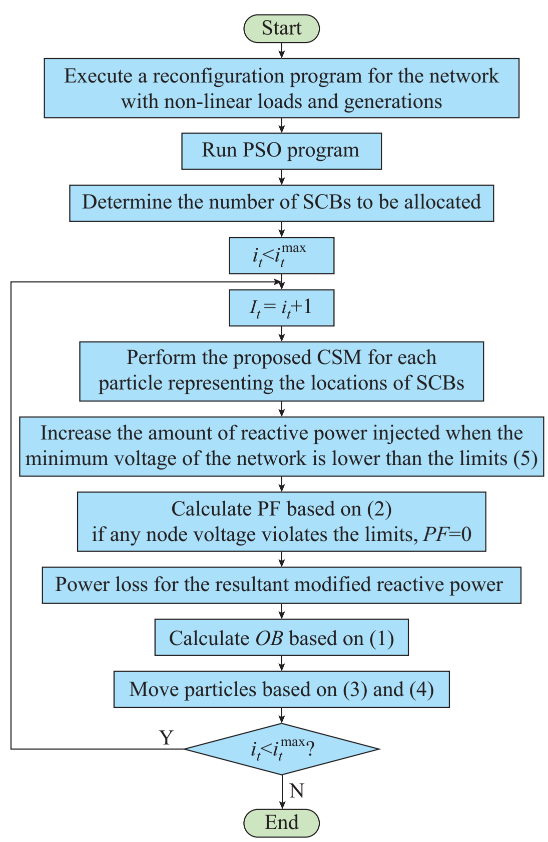

Fig. 2. Flowchart of instruction of proposed CSM.

IV. Simulation Result and Discussion

To improve the network operation, the proposed dynamic network reconfiguration and the placement of SCB are applied to a IEEE 33-bus distribution network shown in Fig. 3.

The open switches are S33, S34, S35, S36, and S37. This network has a total load of 3.72 MW and 2.3 Mvar, and the details of the data are given in [22].

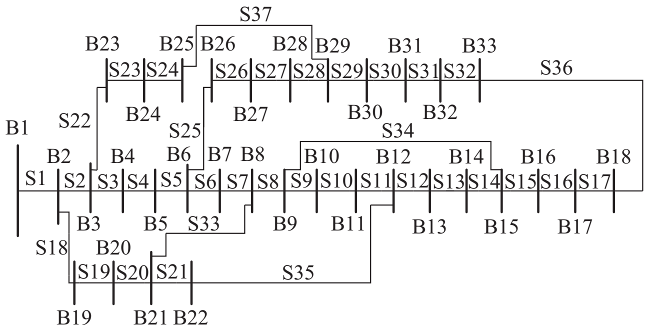

Fig. 3. IEEE 33-bus distribution network.

The capability of the proposed CSM in finding the optimal sizing of capacitors at the given nodes is evaluated. For this purpose, the results in [23] are selected for the same case study. Table II shows the results of comparison between the proposed CSM and those of [23]. The locations of CBs are chosen to be the same as those of [23], so that the power loss depends only on the sizing of CBs.

TABLE II
REACTIVE POWER ALLOCATION RESULTS FOR IEEE 33-BUS DISTRIBUTION NETWORK

No. of CB units	Method	Location	Capacity (kvar)	Total capacity (kvar)	Power loss (kW)
1 CB unit	[23]	30	1190	1190	151.54
	CSM	30	1273	1273	151.39
2 CB units	[23]	13	405	1457	141.97
	CSM	13	393	1473	141.94
	[23]	30	1052	1457	141.97
	CSM	30	1080	1473	141.94
3 CB units	[23]	13	383	1769	138.65
	CSM	13	369	1828	138.55
	[23]	25	386	1769	138.65
	CSM	25	428	1828	138.55
	[23]	30	1000	1769	138.65
	CSM	30	1031	1828	138.55
Original network				0	211.00

The sizing of three CB units is considered for this purpose, i.e., 1 CB unit, 2 CB units, and 3 CB units.

As shown in Table II, for 1 CB unit and 3 CB units, the amount of power loss reduction by the proposed CSM is fairly better than that of [23]. For 2 CB units, the performance of both methods is almost the same. It can also be noticed that the total capacity of the required reactive power in the proposed CSM slightly exceeds the results of [23], where it has better performance in loss reduction. The same scenario is applied to a IEEE 69-bus distribution network. The data of this distribution network are given in [24].

As presented in Table III, the results of power loss are almost the same for all of three methods. However, the proposed CSM detects the same or lower power loss with the minimum total capacity, which could be an indication of better combination of capacities between the selected nodes for CBs.

TABLE III
REACTIVE POWER ALLOCATION RESULTS FOR IEEE 69-BUS DISTRIBUTION NETWORK

No. of CB units	Method	Location	Capacity (kvar)	Total capacity (kvar)	Power loss (kW)
1 CB unit	[17]	61	1310	1310	152
	CSM	61	1285	1285	152
2 CB units	[17]	61	1224	1580	147
	CSM	61	1233	1578	147
	[17]	17	356	1580	147
	CSM	17	1080	1578	147
	[25]	61	1169	1435	147
	CSM	61	1237	1582	146
	[25]	18	266	1435	147
	CSM	18	345	1582	146
3 CB units	[17]	61	1210	1756	145
	CSM	61	1204	1735	145
	[17]	21	226	1756	145
	CSM	21	207	1735	145
	[17]	12	230	1756	145
	CSM	12	324	1735	145
	[25]	61	1232	1875	145
	CSM	61	1194	1792	145
	[25]	21	230	1875	145
	CSM	21	230	1792	145
	[25]	11	413	1875	145
	CSM	11	367	1792	145
Original network				0	225

As stated before, the time duration of the proposed CSM is equal to one load flow run, while the sizing in [17] requires multiple load flow runs to reach the intended voltage magnitude.

Reference [25] applies a combination of analytical and two meta-heuristic algorithms to find the optimal siting and sizing. The meta-heuristic algorithms have population and iterations to search for possible solutions. Therefore, they are time-consuming algorithms. It could become even more complicated or time-consuming when the number of capacitors increases.

However, the proposed CSM does not depend on the number of capacitors as it only impacts on the number of slack nodes (substation nodes) in the load flow, and one load flow run is always enough to determine the size of capacitors. Therefore, the proposed CSM is simple and involves less computation complexity, which requires less computation time compared with the other methods.

Furthermore, as shown in the comparison results, the results of the proposed CSM are quite satisfying since the same or less power loss is achieved by using less total reactive capacity.

To investigate a more realistic operation of a distribution network, it is necessary to consider the variation of loads and generations. The typical 24-hour forecasted levels of the output power of WTs, PV arrays and demands under study are adopted from [23] and shown in Table IV.

TABLE IV
TYPICAL 24-HOUR FORECASTED LEVELS OF OUTPUT POWER OF WTS, PV ARRAYS AND DEMANDS

Time (hour)	WT	PV	Demand	Time (hour)	WT	PV	Demand
1	0.815	0	0.719	13	0.945	0.516	0.875
2	0.880	0	0.674	14	0.776	0.475	0.868
3	0.886	0	0.624	15	0.673	0.418	0.851
4	0.880	0	0.588	16	0.591	0.254	0.875
5	0.881	0	0.582	17	0.487	0.050	0.951
6	0.881	0	0.588	18	0.466	0	1.000
7	0.953	0	0.600	19	0.373	0	0.981
8	0.987	0.008	0.633	20	0.339	0	0.948
9	0.985	0.050	0.644	21	0.339	0	0.900
10	0.962	0.125	0.730	22	0.372	0	0.875
11	1.000	0.418	0.793	23	0.393	0	0.801
12	0.979	0.511	0.844	24	0.339	0	0.722

It is considered that due to some geographical or technical restrictions, there are no other available locations to connect WT and PV array except the non-optimal locations 18 and 12. The rated output power values of WTs and PV arrays are considered to be 1.5 WM and 1 MW, respectively.

Figure 4 shows the voltage violation of IEEE 33-bus distribution network in cases 1-3. Under the operation conditions of cases 1 and 2, both high- and low-voltage problems arise in some of the operation hours. Moreover, under the operation condition of case 3, there is a low-voltage problem in all of the operation hours. Obviously, it is not feasible to supply power to the customers by the existing non-standard voltage.

$$Q^h_{modified} = Q^h_{optimal} K \cdot (0.95 - V^h) \tag{5}$$

where $Q^h_{modified}$ and $Q^h_{optimal}$ are the resultant modified and optimal hourly reactive power compensations, respectively; and V^h is the hourly voltage.

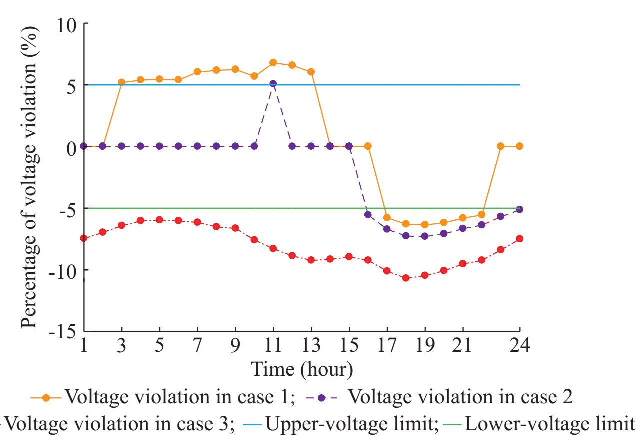

Fig. 4. Voltage violation of IEEE 33-bus distribution network in cases 1-3.

According to the proposed solution, the first step is to solve the over-voltage problem using dynamic network reconfiguration. Accordingly, UVDRA is applied to the system to find the hourly optimal configuration for varying loads and generations. The proposed configurations are summarized in (6). To upgrade the existing system to an active network with the capability of dynamic network reconfiguration, only switches 15 and 13 need remote control technology.

$$N_{ob} = \begin{cases} [7\ 9\ 13\ 34\ 37] & 8 \le t \le 17 \\ [7\ 9\ 15\ 34\ 37] & \text{else} \end{cases} \tag{6}$$

where N_{ob} is the number of open branches.

It is worth mentioning that extra and redundant switching actions are avoided to make the operation plan cost-efficient and feasible. To achieve the minimum switching actions, the operation indices such as the maximum and minimum voltage and power loss of new and existing configurations are compared in two successive hours.

Figure 5 shows hourly values of reactive power injection for the optimal curve, modified curve and designed SCB, which are based on three ways to supply reactive power. The first way is to inject the optimal reactive power (ORP) obtained by the proposed CSM; the second way is to inject modified reactive power (MRP); and the third way is to use SCB, which is designed to approximate MRP curve.

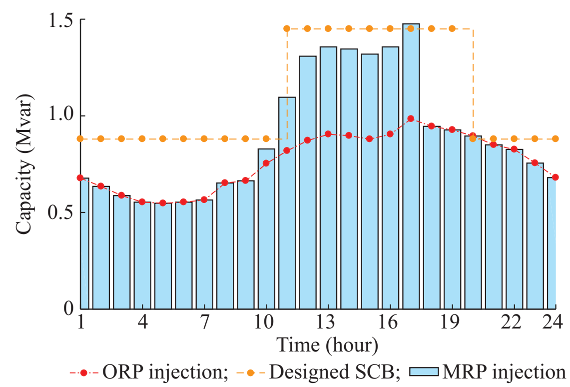

Fig. 5. Hourly values of reactive power injection for optimal curve, modified curve and designed SCB.

As shown in Fig. 6, ORP injection leads to the lowest energy loss. However, it does not necessarily enhance the minimum node voltage up above the minimum voltage limit. Therefore, a modification is applied to the hourly optimal reactive power curve to increase the minimum voltage up to the minimum voltage limit. At any hour when the minimum network voltage violates the lower limit, the value of ORP increases based on (5). In Fig. 5, it is apparent that at some hours of the operation time, the MRP injection curve differs from the ORP curve. In these hours, the values of the minimum network voltage fall below the lower limit as shown in Fig. 6.

Even though the deviation from the ORP resulting in extra power loss, it is crucial for the sake of voltage profile improvement. Moreover, the variation of reactive power near its optimal point results in only a slight increase in the power loss.

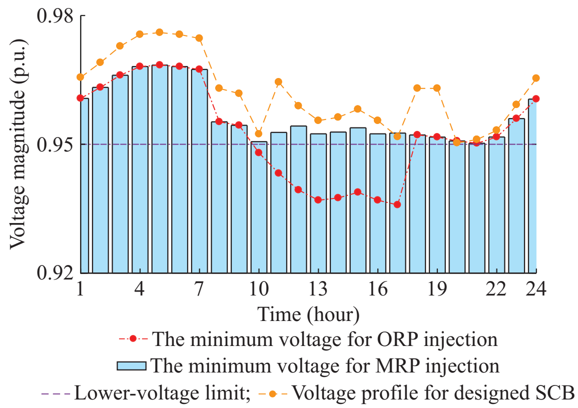

Fig. 6. Hourly values of the minimum network voltage.

The power loss differences are shown in Fig. 7 for the three ways of reactive power supply. The ORP obtained by the CSM results in the minimum power loss for all of the operation hours. Nevertheless, other methods also reduce the power losses nearly close to ORP.

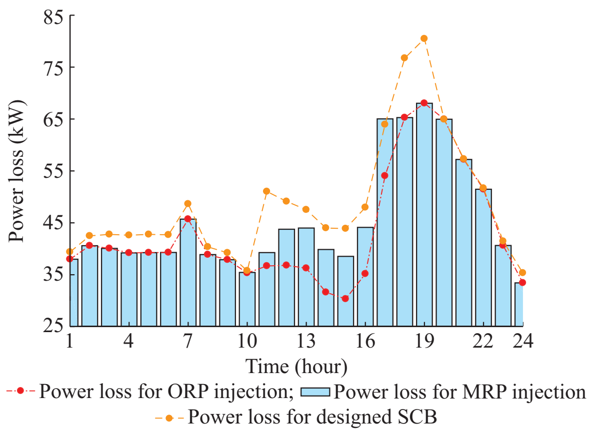

Fig. 7. Hourly values of power loss difference.

Figure 8 shows the maximum network voltage when operating in case 1. It is apparent that the ORP and MRP curves are well below the upper-voltage limit. However, the designed CSM slightly violates the maximum allowable voltage limit. This is because when the network is operating in case 3, it is required to inject extra reactive power to avoid low-voltage violation at hours 10 and 20. Additionally, when the network is operating in case 1, the lower-level designed SCB will lead to a high-voltage violation.

Therefore, it might be reasonable to increase the levels of SCB to avoid this slight voltage violation and approximate the MRP curve more closely, which doubles the switching actions and increases the associated costs.

Figure 9 shows the hourly values of MRP curves and SCB. The MRP curve for node 14 is almost constant. Therefore, it is modeled with a fixed capacitor bank (FCB) with a capacity of 250 kvar. According to the MRP curve for node 30, an SCB is needed to resemble the curve. Two levels of SCB are designed considering no decline from the values of MRP at the hours when voltage magnitude for MRP is very close to the minimum allowable voltage.

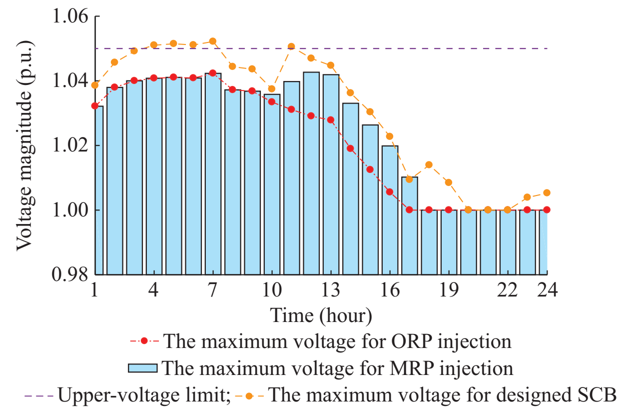

Fig. 8. Hourly values of the maximum network voltage.

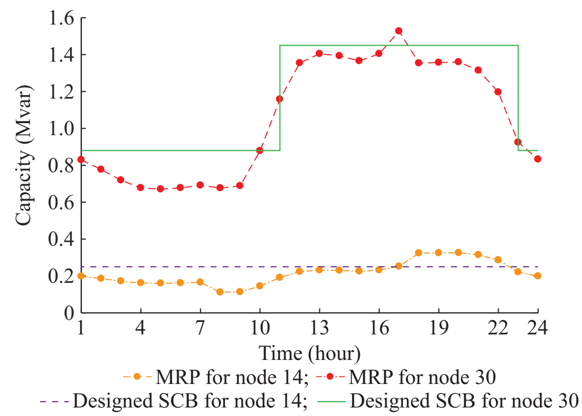

Fig. 9. Hourly values of MRP curves and SCB.

The maximum and minimum network voltages of the network operating in cases 1 to 3 are shown in Fig. 10. Figure 10 illustrates that the system equipped with an RCS, FCB and SCB can maintain voltage magnitude within the desired levels even in worst-case situations.

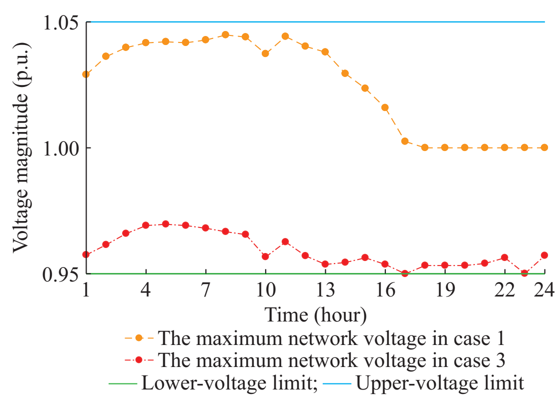

Fig. 10. The maximum and minimum voltages in cases 1 to 3.

Table V shows a summary of the simulation results for the operation optimization of the IEEE 33-bus distribution network. The total energy loss of the original network is 2753 kWh for a typical day. Both high- and low-voltage violations occur in the original network. In scenario 1, only the proposed dynamic network reconfiguration scheme (6) is applied to the system. The high-voltage violation problem is solved and 39% of power loss is reduced.

TABLE V
SUMMARY OF SIMULATION RESULTS FOR OPERATION OPTIMIZATION OF IEEE 33-BUS DISTRIBUTION NETWORK

Scenario	Reactive power injection	Proposed locations by PSO	The maximum voltage of case 1 (p.u.)	The minimum voltage of case 3 (p.u.)	Total daily energy losses of case 2 (kWh)	Energy loss reduction (%)
Scenario 1			1.024	0.8900	1674	39.2
Scenario 2	Optimal curve	33	1.042	0.9359	1036	62.4
	Modified curve	33	1.043	0.9503	1090	60.4
	SCB (750-1620 kvar)	33	1.053	0.9502	1172	57.4
Scenario 3	Optimal curve	14-30	1.039	0.9353	918	66.7
	Modified curve	14-30	1.039	0.9506	991	64.0
	SCB and CB (250 kvar)	**14**	**1.044**	**0.9500**	**1043**	62.1
	SCB and CB (880-1450 kvar)	**30**	**1.044**	**0.9500**	**1043**	62.1
Scenario 4	Optimal curve	14-24-30	1.038	0.9346	869	68.4
	Modified curve	14-24-30	1.038	0.9506	946	65.6
	2 SCBs and CB (250 kvar)	14				
	2 SCBs and CB (300-500 kvar)	24	1.044	0.9500	1001	63.6
	2 SCBs and CB (600-1450 kvar)	30				
Original network			1.062	0.9100	2753	0

Nevertheless, the condition of the minimum node voltage has been worsened compared with the original network. In scenario 2, node 33 is chosen by the PSO for reactive power injection. The ORP curve obtained by CSM results in the minimum power loss for this scenario. However, the minimum voltage of case 3 falls below the allowable limit. The MRP curve best satisfies the operation restrictions and reduces the energy loss by up to 64%. There is a need for advanced power electronic devices such as distribution static synchronous compensator to supply the desired reactive power in accordance with the MRP curve. An alternative solution is to use SCB. As shown in Table V, the maximum voltage magnitude is 1.053 p.u. (slightly more than the limit) and the minimum network voltage in case 3 is 0.95 p.u., which is acceptable. The energy loss reduction is 57.4%.

Similarly, in scenario 3, ORP curves are not acceptable since they will cause low-voltage violations. MRP curves meet the voltage constraints, and the modern power electronic devices are required. The practical cost-efficient solution is to implement the combination of FCB and SCB as depicted in Fig. 8. Even though the reactive power supplied by SCB and FCB differs from that by MRP, it still satisfies the operation constraints and reduces energy loss by up to 62.1%. The reduction in energy loss from 2753 to 1043 kWh means a daily energy saving of 1710 kWh, which is a noticeable value.

In scenario 4, the results are not that much different and the rate of improvement is not that significant. The percentage of energy loss reduction in this scenario is only 0.4% more than that of scenario 3. Therefore, the practical and cost-efficient solution for the operation improvement of the IEEE 33-bus distribution network is to implement an FCB and SCB, as shown in scenario 3 (bold).

The same procedure is applied to IEEE 69-bus distribution network. The original data of the network are given in [25]. The standard IEEE 69-bus distribution network is modified by adding WTs and PV arrays at buses 18 and 63. The rated output power values of WTs and PV arrays are 3 MW and 2 MW, respectively.

Figure 11 shows the voltage violation of the modified IEEE 69-bus distribution network during 24-hour operation. In cases 1 and 2, the high-voltage problem arises in some hours of the operation time and for all of the cases that the low-voltage problem exists.

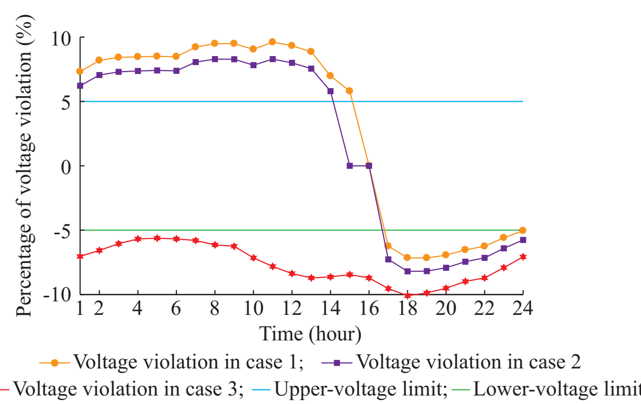

Fig. 11. Voltage violation of modified IEEE 69-bus distribution network in cases 1-3.

At first, UVDRA is applied to the system to find the hourly optimal configuration for varying loads and generations. The proposed configurations are summarized in (7). Only switches 19 and 70 need to be switched once in the operation hours of a day.

$$N_{ob}=\begin{cases}[14\ \ 19\ \ 58\ \ 61\ \ 69] & 8\le t\le 17\\ [14\ \ 70\ \ 58\ \ 61\ \ 69] & \text{else}\end{cases} \tag{7}$$

The summary of the simulation results for the operation optimization of the IEEE 69-bus distribution network is shown in Table VI. The total energy loss of the original network is 4950 kWh for a typical day.

Applying the proposed dynamic network reconfiguration scheme in scenario 1, the high-voltage violation problem is solved and 35.4% of energy loss is reduced. Nevertheless, the condition of the minimum node voltage still exists. In scenario 2, node 61 is chosen by the PSO for reactive power injection. The ORP and the MRP curves both satisfy the operation restrictions and are identical in all of the scenarios. In this scenario, the energy loss reduces by up to 42.7%. The curve is approximated by a SCB with levels of 670 and 950 kvar. By applying the SCB, it is possible to reduce the energy loss by up to 42.6%. In scenarios 3 and 4, the same scheme for SCB is proposed while another CB is used to improve the operation conditions. However, the results in scenario 4 are not that much different from scenario 3 and the rate of the improvement is insignificant. In this paper, scenario 3 is selected as the best solution, which may change if other parameters such as CB or SCB capital costs, maintenance costs, operation costs and other related factors are analyzed. However, these aspects of the study are beyond the scope of this paper.

TABLE VI
SUMMARY OF SIMULATION RESULTS FOR OPERATION OPTIMIZATION OF IEEE 69-BUS DISTRIBUTION NETWORK

Scenario	Reactive power injection	Proposed locations by PSO	The maximum voltage of case 1 (p.u.)	The minimum voltage of case 3 (p.u.)	Total daily energy losses of case 2 (kwh)	Energy loss reduction (%)
Scenario 1			1.0491	0.9495	3199	35.4
Scenario 2	Optimal curve	61	1.0491	0.9634	2834	42.7
	Modified curve	61	1.0491	0.9635	2843	42.6
	SCB (680-950 kvar)	61	1.0491	0.9635	2843	42.6
Scenario 3	Optimal curve	61-65	1.0491	0.9656	2725	44.9
	Modified curve	61-65	1.0491	0.9656	2725	44.9
	SCB and CB (340 kvar)	**65**	**1.0491**	**0.9610**	**2737**	44.7
	SCB and CB (670-950 kvar)	**61**	**1.0491**	**0.9610**	**2737**	44.7
Scenario 4	Optimal curve	61-64-66	1.0491	0.9656	2702	45.4
	Modified curve	61-64-66	1.0491	0.9656	2702	45.4
	SCB and 2 CBs (300 kvar)	66				
	SCB and 2 CBs (260 kvar)	64	1.0491	0.9610	2716	45.1
	SCB and 2 CBs (670-950 kvar)	61				
Original network			1.0875	0.9092	4950	0

V. CONCLUSION

Instead of the optimal siting of DGs, we propose the optimal exploitation of intermittent PV and wind energy resources. The non-optimal locations of these DGs together with their excessive generation may cause a problem of voltage rise. On the contrary, during the reparation when DGs are disconnected from the network, a low-voltage problem may occur. We propose the operation optimization of such a network with varying loads and generations. Dynamic network reconfiguration is used to alleviate the problem of voltage rise. Meanwhile, the design procedure of SCBs coordinated with dynamic network reconfiguration is proposed to overcome the low-voltage violation problem in the network. For this purpose, we propose a robust CSM that is exceptionally fast and accurate in finding the ORP value at a given node. Using CSM, the ORP curve for the given node is obtained. An MRP curve is proposed to prioritize voltage improvement over energy loss reduction. Therefore, the MRP curves have to be used for the design of SCBs because these curves are completely coordinated with loads, generations, and the given configurations. By using these curves, it is possible to design the desired levels of SCBs or FCBs that best approximate their associated curves.

The proposed method is applied to a IEEE 33-bus distribution network with varying loads and generations of WTs and PV arrays located at non-optimal nodes 12 and 18. It is shown that the dynamic operation of the IEEE 33-bus distribution network based on the proposed configuration solely saves 39% of energy loss and mitigates the problem of voltage. By using the proposed CSM and the designed SCB and an FCB, the energy loss of the network can be reduced from 2753 kWh to 1043 kWh, while the non-standard voltage profile of the system is also improved and retained within the prescribed limits. The designed network is resilient to the worst-case scenarios. The same procedure is applied to IEEE 69-bus distribution network to further analyze the effectiveness of the proposed CSM and the obtained results.

In summary, the salient contributions of this paper are summarized as follows.

1) A novel method for allocating reactive power for any given location is proposed based on the load flow run of one simple meshed network. The proposed CSM is proven to be effective and capable of finding better solutions compared with the most recent approaches. This methodology is solely of great importance in the research area of capacitor placement in distribution networks.

2) A design procedure for the determination of the levels of SCB is presented based on the MRP curve that meets the operation voltage limits with the most possible energy loss reduction.

3) The dynamic network operation, and the design and placement of SCBs are presented in this paper for the improvement of network operation. The coordination of these tools enables them to solve the voltage violation problem and reduce energy losses.

4) Most conservative uncertainties of loads and generations are considered to achieve a network resilient to the worst-case situations.

REFERENCES

[1] A. R. Jordehi, "Optimisation of electric distribution systems reviews," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1088-1100, Nov. 2015.

[2] S. Das, D. Das, and A. Patra, "Operation of distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors," *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109219, Oct. 2019.

[3] F. Iqbal, M. T. Khan, and A. S. Siddiqui, "Optimal placement of DG and DSTATCOM for loss reduction and voltage profile improvement," *Alexandria Engineering Journal*, vol. 57, no. 2, pp. 755-765, Jun. 2018.

[4] J. M. Home-Ortiz, Ozy D. Melgar-Dominguez, M. P. *et al*., "A stochastic mixed-integer convex programming model for long-term distribution system expansion planning considering greenhouse gas emission mitigation," *International Journal of Electrical Power & Energy Systems*, vol. 100, pp. 178-192, Sept. 2018.

[5] A. K. Basu, S. P. Chowdhury, S. Chowdhury *et al*., "Microgrids: energy management by strategic deployment of DERs, a comprehensive survey," *Renewable and Sustainable Energy*, vol. 15, pp. 4348-4356, Mar. 2011.

[6] O. D. Montoya, W. Gil-González, and L. F. Grisales-Noreña, "Relaxed convex model for optimal location and sizing of DGs in DC grids using sequential quadratic programming and random hyperplane approaches," *International Journal of Electrical Power & Energy Systems*, vol. 115, p. 105442, Feb. 2020.

[7] Q. Zhao, S. Wang, K. Wang *et al*., "Multi-objective optimal allocation of distributed generations under uncertainty based on D-S evidence theory and affine arithmetic," *International Journal of Electrical Power & Energy Systems*, vol. 112, pp. 70-82, Nov. 2019.

[8] V. M. Quezada, J. R. Abbad, and T. G. S. Roman, "Assessment of energy distribution losses for increasing penetration of distributed generation," *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 533-540, Jun. 2006.

[9] A. Ameli, A. Ahmadifar, M. H. Shariatkhah *et al*., "A dynamic method for feeder reconfiguration and capacitor switching in smart distribution systems," *International Journal of Electrical Power & Energy Systems*, vol. 85, pp. 200-211, Feb. 2017.

[10] E. S. Ali, S. M. A. Elazim, and A. Y. Abdelaziz, "Improved harmony algorithm and power loss index for optimal locations and sizing of capacitors in radial distribution systems," *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 252-263, Sept. 2016.

[11] M. Kalantar and R. Dashti, "Combination of network reconfiguration and capacitor placement for loss reduction in distribution system with based genetic algorithm," in *Proceedings of 41st International Universities Power Engineering Conference*, Newcastle upon Tyne, UK, Oct. 2006, pp. 308-312.

[12] M. J. Kasaei and M. Gandomkar, "Loss reduction in distribution network using simultaneous capacitor placement and reconfiguration with ant colony algorithm," in *Proceedings of Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Chengdu, China, Apr. 2010, pp. 1-4.

[13] T. M. Khalil, A. V. Gorpinich, and G. M. Elbanna, "Combination of capacitor placement and reconfiguration for loss reduction in distribution systems using selective PSO," in *Proceedings of 22nd International Conference and Exhibition on Electricity Distribution (CIRED)*, Stockholm, Sweden, Jun. 2013, pp. 1-4.

[14] V. Tamilselvan, T. Jayabarathi, T. Raghunathan *et al*., "Optimal capacitor placement in radial distribution systems using flower pollination algorithm," *Alexandria Engineering Journal*, vol. 57, no. 4, Dec. 2018, pp. 2775-2786.

[15] A. Elsheikh, Y. Helmy, Y. Abouelseoud *et al*., "Optimal capacitor placement and sizing in radial electric power systems," *Alexandria Engineering Journal*, vol. 53, no. 4, pp. 809-816, Dec. 2014.

[16] A. Bayat, "Uniform voltage distribution based constructive algorithm for optimal reconfiguration of electric distribution networks," *Electric Power Systems Research*, vol. 104, pp. 146-155, Nov. 2013.

[17] A. Bayat and A. Bagheri, "Optimal active and reactive power allocation in distribution networks using a novel heuristic approach," *Applied Energy*, vol. 232-234, pp. 71-85, Jan. 2019.

[18] M. Bollen and F. Hassan, *Integration of Distributed Generation in the Power System*. New Jersey: John Wiley & Sons, May 2011.

[19] A. Ehsan and Q. Yang, "State-of-the-art techniques for modelling of uncertainties in active distribution network planning: a review," *Applied Energy*, vol. 239, pp. 1509-1523, Apr. 2019.

[20] J. Kennedy and R. C. Eberhart, "Particle swarm optimization," in *Proceedings of IEEE International Conference on Neural Networks*, Piscataway, USA, Jun. 1995, pp. 1942-1948.

[21] A. Bayat, A. Bagheri, and R. Noroozian, "Optimal siting and sizing of distributed generation accompanied by reconfiguration of distribution networks for maximum loss reduction by using a new UVDA-based heuristic method," *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 360-371, Mar. 2016.

[22] A. M. Zin, A. K. Ferdavani, A. B. Khairuddin *et al*., "Reconfiguration of radial electrical distribution network through minimum-current circular updating mechanism method," *IEEE Transactions on Power Systems*, vol. 27, no, 2, pp. 968-974, May 2012.

[23] E. Hooshmand and A. Rabiee, "Robust model for optimal allocation of renewable energy sources, energy storage systems and demand response in distribution systems via information gap decision theory," *IET Generation, Transmission & Distribution*, vol. 13, no. 4, pp. 511-520, Apr. 2019.

[24] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401-1407, Apr. 1989.

[25] E. S. Ali, S. M. A. Elazim, A. Y. Abdelaziz *et al*., "Capacitors allocation in distribution systems using a hybrid formulation based on analytical and two metaheuristic optimization techniques," *Computers & Electrical Engineering*, vol. 85, p. 106675, Jul. 2020.

Ramin Borjali Navesi received the B.S. degree in electrical engineering from the Tabriz Branch-Azerbayjan University, Khoy, Iran, in 2011. He received the M.S. degree from Shabestar Branch-Islamic Azad University Shabestar, Shabestar, Iran, in 2015 and now he is a Ph.D student in Urmia Branch, Islamic Azad University, Urmia, Iran. His research interests include smart grid, transmission line and power systems stability.

Daryoosh Nazarpour received the B.Sc. degree from the Iran University of Science and Technology, Tehran, Iran, in 1982, and the M.Sc. and Ph.D. degrees from the Faculty of Engineering, University of Tabriz, Tabriz, Iran, in 1988 and 2005, respectively, all in electrical power engineering. Currently, he is a Professor in Urmia University, Urmia, Iran. His research interests include power electronics and flexible AC transmission system.

Reza Ghanizadeh received the B.S. degree in electrical engineering from the Ardabil Branch-Islamic Azad University Ardabil, Ardabil, Iran, in 2009. He received the M.S. and the Ph.D. degrees from University of Birjand, Birjand, Iran, in 2013 and 2017, respectively. He is currently an Assistance Professor in the Faculty of Electrical Engineering at Urmia Branch, Islamic Azad University, Urmia, Iran. His research interests include power quality, microgrids control, power electronics, high voltage, power system stability and fact devices.

Payam Alemi received the B.S. degree from the University of Tabriz, Tabriz, Iran, in 2005, and the M.S. degree from the Science and Research Branch, Islamic Azad University, Tehran, Iran, in 2008, and the Ph.D. degree in electrical engineering, from Yeungnam University, Gyeongsan, Korea, in 2014. Then he joined Simon Fraser University korea, Canada, for his post-doctoral program until 2016. Currently he is an Assistant Professor in the Department of Electrical Engineering, Islamic Azad University, Urmia Branch, Urmia, Iran. His current research interests include the control of multilevel power converters, power loss analysis for converters, LCL filters and machine drives, DC-DC converters.