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ORIGINAL RESEARCH

Coordinated active and reactive power management for enhancing PV hosting capacity in distribution networks

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Abstract

This paper proposes an operational planning model based on optimal active and reactive power control strategies to enhance solar photovoltaics (PV)' hosting capacity in distribution networks. Reactive power control is carried out through optimum static VAr compensators (SVCs) placement, while active power control is performed through flexible loads, particularly shiftable and interruptible loads. The first stage of the proposed two-stage stochastic model assigns decision-making regarding calculating PV hosting capacity at different nodes, in addition to the allocation and capacity of SVCs. In the second stage, the first stage decisions are assessed to ensure the power flow constraints under various uncertainties such as daily load and stochastic PV generation. The presented model is investigated through numerical analyses on modified IEEE 15-bus and IEEE 33-bus distribution systems considering different active-reactive strategy cases. While most previous works only rely on one type of active or reactive power control strategy, this study investigates the challenges of the respective application of active and reactive power control in various modes of fundamental practices. The obtained results prove the superiority of the proposed hybrid active-reactive control strategy for enhancing PV hosting capacity compared to respective active or reactive power controls.

1 | INTRODUCTION

The amount of solar photovoltaics (PV) connected to the distribution networks is rising, while the penetration of PV resources in low voltage distribution networks could affect the grid differently. Hosting capacity (HC) is the maximum capacity of PV generation that a distribution system can take in without violating operational constraints. Negative impacts of remarkable penetration of PV resources on distribution systems could be voltage amplitude violation, voltage imbalances, losses increment, harmonics, and feeders overloading [1–8]. A similar concept as renewable energy accommodation capacity (REAC) has been recently interested by researches. Both HC and REAC approaches focus on large integration of renewable energy sources (RESs) such as PVs while considering negative impacts due to high volatility [9, 10]. HC approach mainly serves for power systems from a planning perspective where maximum installed PV capacity is determined under power balance constraints and PV output constraints while REAC mainly serves for power systems from operational perspective [11] which may result in PV curtailment [12]. Anyway, optimal HC determination of PVs considering operational constraints is an essential issue in distribution systems [13, 14].

In addition to the problems above of high penetration of PVs in distribution systems, uncertainties in PV generation are another challenging issue that affects the operation of PV resources which should be considered in HC studies. PV generation is uncertain and depends on daily solar irradiation and climate conditions [15]. Both uncertainty sets, including PV generation and load, must be considered in the HC determination problem. The utilization of stochastic models could be a practical approach [16].

From another point of view, presented approaches to enhance the HC of PV can be categorized into active and reactive power control strategies. The active power control strategy is achieved through demand response (DR) which considers the potential of both shiftable and interruptible loads. There is no need to install extra devices in an active power control strategy or make the extra investment. It is noteworthy that utilizing the capabilities of flexible loads (FLs) is possible with limited measures and incentive payments to the consumers. Reactive power control strategies often require installing equipment and accepting extra investment costs. This paper investigates the optimality of the HC problem of PV resources through active and reactive power control strategies in separate and hybrid forms. This investigation aims to prove the superiority of hybrid active-reactive power control in various planning conditions and operational practices.

In order to maximize the HC of PVs in distribution systems, different methods have been presented in the previous research according to active and reactive control strategies. It has been shown that using reactive control devices positively impacts the enhancement of HC of PV while reducing the violations of power flow constraints. In [13], a coordinated approach has been presented based on reactive power control devices such as on-load tap changers (OLTC) and VAr sources to maximize the HC of PV resources considering uncertainties of PV generation. This research uses probability functions for the probabilistic operation of reactive control devices in different operational conditions. In [17], optimal placement of static VAr compensators (SVCs) is proposed to enhance the HC of PV. However, the uncertainties of PV generation and load are neglected, which could affect the accuracy of optimal results in operational conditions. Similarly, a two-stage stochastic operational planning model for enhancement of HC of PV has been proposed in [18], considering SVC installation's load and PV generation uncertainties. However, this study's presented approach did not consider the effects of active power control for HC of PV. Consideration of the distributed static compensator (DSTATCOM) in PV interfacing inverters for reactive power control is discussed in some researches such as enhancement of HC of PV with diverse inverter control schemes in [19]. Similarly, optimal distribution planning is discussed through hybrid integration of PVs and DSTATCOM in [20]. In [21], HC of RESs is investigated with integration of DSTATCOM and EVs.

As an active control strategy, DR can be effective for the optimal operation of power systems. In order to enhance the HC of PV in terms of optimizing energy loss, an optimization model for HC of PV is presented in [22], where the role of DR has been investigated. This work evaluates the possible utilization of DR in intelligent grids to enhance renewables' HC. However, load and renewable generation uncertainties are not considered in this research. The role of shiftable loads and energy storage systems (ESS) is explored in [23] to increase PV integration. In similar recent researches, role of ESS to enhance HC of PV is highlighted such as optimization of HC of distributed generations (DGs) by integration of ESS using loss sensitivity factor (LSF) approach in [24] or joint planning of DGs and ESS based on chaos optimization in [25]. In [26], it is shown that flexible loads can reduce the operation cost of microgrids and improve system stability. However, the effects of reactive loads and reactive control methods are not included. In [27], the impacts of electric vehicles (EVs) and PVs in the distribution network are investigated with and without applying shiftable loads. Beside load curtailment in case of interruptible loads in FLs, concept of active power curtailment (APC) of the PV generation can be considered an effective approach as well, but because it wastes energy (undistributed energy concept), it should be used with utmost precaution and extra measures. In [28], HC of PV is investigated through concept of APC via optimal oversized inverter.

Despite comprehensive and various studies concerning HC enhancement of PV, the presented methods in the previous studies often focused on only one active or reactive power control strategy. Although the challenging issue of PV outage due to voltage violation has been investigated in [29], considering the coordinated application of shiftable loads, SVC, and capacitor bank (CB), the presented model is far from real practice since the uncertainties of load and PV generation are neglected. Moreover, the objective function only minimizes the curtailed power and does not consider other aspects, such as the HC of PV or operation cost. Therefore, proposing a comprehensive scheme for HC enhancement of PV resources based on active and reactive power control strategies seems necessary. It is also interesting to investigate the control strategies' separate and combined effects on HC optimization. The pros of respective active, reactive, and hybrid power controls should be investigated in different real practices to adopt strategies in all practical case studies.

This paper presents an optimization model for maximizing the HC of PV resources in distribution systems using active and reactive power control strategies. The active power control is based on the capability of existing shiftable and interruptible loads in the network. At the same time, reactive power control is applied through SVC placement. This comprehensive optimization model is a two-stage stochastic operational planning problem based on hybrid active-reactive strategies. The objective function simultaneously maximizes the HC of PV resources while minimizing the operational planning costs of active-reactive control actions, including investment and operation costs of SVCs, incentive payment to the consumers for interruptible loads, and the cost of purchasing electricity from the wholesale market. It will be shown that the proposed hybrid control strategy is superior to respective active or reactive control strategies, which were used in most previous works. Challenges of respective application of active and reactive power control will be discussed in various real practices of network conditions such as PV penetration rates, daily load variation and stochastic PV generation. In summary, the original contributions of this paper can be listed as follows:

- A two-stage operational planning model is developed for PV hosting capacity problems in the distribution network, which considers both operational practice by enhancement of HC of PV and economical operational limits by minimization of total planning cost.
- A coordinated active and reactive power control strategy is proposed, where active power control is carried out through interruptible and shiftable load capacities while reactive power control is done by optimal SVC placement. It will

be shown that this proposed hybrid strategy has superiority in various planning conditions and all operational practices over respective active and reactive power controls used in most previous research.

The rest of the paper is organized as follows. Section 2 represents mathematical formulations of the proposed two-stage stochastic model based on hybrid active-reactive control. Section 3 devotes to simulation and numerical studies. Finally, the conclusion is presented in Section 4.

2 | PROBLEM FORMULATION

2.1 | Objective function

This paper presents a two-stage stochastic optimization framework to enhance the HC of PV resources throughout the distribution network while minimizing the total cost. The first stage variables are the installation node and capacity of SVCs and the installed capacity of PVs. It is noteworthy that these variables are independent of scenario realization and determined before the occurrence of stochastic PV generation. The second stage variables are operational decision variables dependent on the realized scenarios, such as injected or absorbed reactive power of SVCs, values of flexible loads (FLs) including shiftable loads and curtailable loads, and purchased active power from the wholesale energy market. It would be shown that the two-stage framework are linked to each other via the PV output factor matrix.

The primary objective function weighted combines the two purposes of maximizing the HC of PV resources while minimizing the system's total expected cost (EC) as planned in (1). The first term of the objective function assigns HC as the sum of PV capacities, as shown in (2). The second term in the primary objective function is the total EC of the system, including levelled investment cost and variable operational cost of SVCs, incentive payment for curtailable loads, and the cost of purchasing power from the wholesale electricity market as planned in (3),

$$Min\left\{-w^{HC}\times HC+w^{EC}\times EC\right\}, \tag{1}$$

$$HC=\sum_{m}E_{m}^{PV}, \tag{2}$$

$$\begin{aligned} EC=&\sum_{i}\eta C_{F}^{SVC}a_{i}^{SVC}\\ &+\sum_{s}\rho_{s}\sum_{i}\sum_{t}C_{V}^{SVC}a_{i}^{SVC}\left|q_{i,t,s}^{SVC}\right| \qquad ,\\ &+\sum_{s}\rho_{s}\sum_{i}\sum_{t}\left\{C^{INC}P_{i,t,s}^{Lcurt}+C_{i,t,s}^{grid}P_{i,t,s}^{grid}\right\} \end{aligned} \tag{3}$$

where $\eta=\frac{r(1+r)^{y}}{365[(1+r)^{y}-1]}$ is the daily recovery factor, r is the interest rate of the SVC device, and y is the SVC lifetime.

2.2 | Linear power flow modeling

In order to simplification of the load flow calculations, a linear power flow is employed in this paper according to the model presented in [30]. Active and reactive power balance equations have been planned in the following (4) and (5), respectively,

$$\begin{aligned} &p_{i,t,s}^{grid}+p_{m,t,s}^{PV}\\ &-\sum_{i'}\left[\left(P_{i,i',t,s}^{+}-P_{i,i',t,s}^{-}\right)+R_{i,i'}I2_{i,i',t,s}\right]=0 \end{aligned}, \tag{4}$$

$$\begin{aligned} &q_{i,t,s}^{grid}+q_{i,t,s}^{SVC}\\ &-\sum_{i'}\left[\left(Q_{i,i'\,t,s}^{+}-Q_{i,i'\,t,s}^{-}\right)+X_{i,i'}I2_{i,i'\,t,s}\right].\\ &+\sum_{i'}\left(Q_{i'\,i,t,s}^{+}-Q_{i'\,i,t,s}^{-}\right)-Q_{i,t}^{L}=0 \end{aligned} \tag{5}$$

Also, only one of the two positive auxiliary variables $\mathrm{P_{iits}}Q_{iits}$ can be zero each time, automatically satisfied according to the optimality. In addition, (6) and (7) restrict these variables through the maximum limit of the apparent power [30].

$$0\leq\left(P_{i,i'\,t,s}^{+}+P_{i,i'\,t,s}^{-}\right)\leq V^{Rated}I_{i,i'}^{max}, \tag{6}$$

$$0\leq\left(Q_{i,i'\,t,s}^{+}+Q_{i,i'\,t,s}^{-}\right)\leq V^{Rated}I_{i,i'}^{max}. \tag{7}$$

Equation (8) makes a voltage balance between two nodes. Equation (9) is employed to linearize the apparent power term's active and reactive power portions [30].

$$\begin{aligned} &V2_{i,t,s}-V2_{i'\,t,s}-Z_{i,i'}^{2}I2_{i,i'\,t,s}\\ &-2R_{i,i'}\left(P_{i,i'\,t,s}^{+}-P_{i,i'\,t,s}^{-}\right) \qquad ,\\ &-2X_{i,i'}\left(Q_{i,i'\,t,s}^{+}-Q_{i,i'\,t,s}^{-}\right)=0 \end{aligned} \tag{8}$$

$$\begin{aligned} &V2_{i}^{Rated}I\,2_{i,i'\,t,s}\\ &=\sum_{f}\left[\left(2f-1\right)\Delta S_{i,i'}\Delta P_{i,i'\,f,t,s}\right] \qquad .\\ &+\sum_{f}\left[\left(2f-1\right)\Delta S_{i,i'}\Delta Q_{i,i'\,f,t,s}\right] \end{aligned} \tag{9}$$

Equations (10)–(14) are associated with the piecewise linearization of the power flow model. Notably, the number of blocks for linearization of the second-order curve is assumed to be five according to [31], which makes an appropriate trade-off between accuracy and calculation burden. Further description and details of the employed linear power flow model can be found in [32–34].

$$P^{+}_{i,i' t,s} + P^{-}_{i,i' t,s} = \sum_{f} \Delta P_{i,i' f,t,s}, \tag{10}$$

$$Q^{+}_{i,i' t,s} + Q^{-}_{i,i' t,s} = \sum_{f} \Delta Q_{i,i' f,t,s}, \tag{11}$$

$$0 \le \Delta P_{i,i' f,t,s} \le \Delta S_{i,i'}, \tag{12}$$

$$0 \le \Delta Q_{i,i' f,t,s} \le \Delta S_{i,i'}, \tag{13}$$

$$\Delta\, S_{i,i'} = \frac{V^{Rated} I^{max}_{i,i'}}{F}. \tag{14}$$

2.3 | Constraints of PV hosting capacity

Equation (15) shows that HC is a non-negative variable,

$$E^{PV}_{m} \ge 0. \tag{15}$$

Also, to consider the uncertainty of PV generation, the output PV factor is defined as $\xi^{\mathrm{PV}}_{\mathrm{ts}} \in [0, 1]$, associated with the PV generation in bus m, and time t for specified scenario s based on the variation of PV generation according to daily hours and climate changes during a year. The relation between PV capacity in each bus and PV generation according to the PV output factor is expressed by (16). It is a linking time*scenario matrix which relates first-stage decision variables of capacity types to second-stage variables of real operational practices.

$$p^{PV}_{m,t,s} = \xi^{PV}_{t,s}\ E^{PV}_{m}. \tag{16}$$

2.4 | Constraints of optimal SVC planning

Equation (17) formulates the SVC capacity limits, while the total number of SVC limitations has been considered in (18),

$$0 \le Q^{SVC}_{i} \le \bar{Q}^{SVC}_{i}, \tag{17}$$

$$\sum_{i} a^{SVC}_{i} \le N^{SVC}_{inv}. \tag{18}$$

In addition, (19) to (25) describe the allowable support range of SVC reactive power. Variable $\tilde{q}_{\mathrm{its}}$ is equal to $|\mathrm{q}^{\mathrm{SVC}}_{\mathrm{its}}|$and $\mathrm{z}^{\mathrm{SVC}}_{\mathrm{i}}$is an auxiliary variable for replacement $a^{SVC}_{i} Q^{SVC}_{i}$, which results in faster convergence of the optimization problem [18].

$$\tilde{q}_{i,t,s} \ge q^{SVC}_{i,t,s}, \tag{19}$$

$$\tilde{q}_{i,t,s} \ge -q^{SVC}_{i,t,s}, \tag{20}$$

$$-a^{SVC}_{i} \bar{Q}^{SVC}_{i} + z^{SVC}_{i} \le 0, \tag{21}$$

$$a^{SVC}_{i} \bar{Q}^{SVC}_{i} - z^{SVC}_{i} \le 0, \tag{22}$$

$$-a^{SVC}_{i} \bar{Q}^{SVC}_{i} + z^{SVC}_{i} \le Q^{SVC}_{i} - \bar{Q}^{SVC}_{i}, \tag{23}$$

$$a^{SVC}_{i} \bar{Q}^{SVC}_{i} - z^{SVC}_{i} \le -Q^{SVC}_{i} + \bar{Q}^{SVC}_{i}, \tag{24}$$

$$-z^{SVC}_{i} \le q^{SVC}_{i,t,s} \le z^{SVC}_{i}. \tag{25}$$

2.5 | Constraints of flexible loads

In this paper, the curtailable and shiftable potential of the flexible loads are modelled from (26) to (29). Equation (26) shows shiftable load limits because only a limited portion of the load can be shifted. In addition, (27) ensures that the sum of shifted load in 24 hours of a day for each scenario must be equal to zero. The maximum potential of curtailable loads is planned in (28). The modified load at each time slot for a scenario can be obtained through (29),

$$-DR^{max}_{i} P^{L_{ini}}_{i,t} \le \Delta P^{L\text{-}DR}_{i,t,s} \le DR^{max}_{i} P^{L_{ini}}_{i,t}, \tag{26}$$

$$\sum_{t=1}^{24} \Delta\ P^{L\text{-}DR}_{i,t,s} = 0, \tag{27}$$

$$0 \le P^{L_{curt}}_{i,t,s} \le \alpha^{curt} P,^{L_{ini}}_{it}, \tag{28}$$

$$P^{L\text{-}fin}_{i,t,s} = P^{L_{ini}}_{i,t} + \Delta P^{L\text{-}DR}_{i,t,s} - P^{L_{curt}}_{i,t,s}. \tag{29}$$

The proposed two-stage stochastic optimization problem is a linear mixed-integer program (MIP) which can be solved by commercial MIP solvers such as CPLEX. This paper solves the proposed optimization problem in the GAMS software environment. In the following section, the numerical studies and simulation results are discussed. It is noteworthy that the hardware characteristics of the computer system are CPU 2.8 GHz Core i7 and RAM DDR4 16GB.

3 | SIMULATION RESULTS AND NUMERICAL STUDIES

3.1 | Input data

To show the effectiveness of the proposed model, the modified IEEE 15-bus has been selected as a test system. Further details of this system can be found in [35]. The value of rated apparent power and the nominal voltage of the network is 2.3 MVA and 11 kV, respectively. In this paper, candidate locations for installing PV are considered PV sites, as shown in Table 1 (Sites A are base case). Sensitivity of the PV locations on HC is examined for different candidate PV sites. It should be noted that the exact PV installed nodes and capacities would be obtained by

TABLE 1 Candidate locations for PV placement.

PV sites	Candidate location (bus)
Sites A	{4, 7, 9, 11}
Sites B	{4, 7, 9, 15}
Sites C	{4, 9, 11, 15}
Sites D	{4, 7, 11, 15}
Sites E	{7, 9, 11, 15}
Sites F	{3, 4, 7, 9}

TABLE 2 wholesale market prices [41].

Time (hour)	$C_{i,t,s}^{grid}$ ($/kWh)	Time (hour)	$C_{i,t,s}^{grid}$ ($/kWh)
1	0.040	13	0.043
2	0.037	14	0.042
3	0.034	15	0.044
4	0.034	16	0.048
5	0.033	17	0.053
6	0.036	18	0.061
7	0.042	19	0.061
8	0.049	20	0.059
9	0.053	21	0.054
10	0.053	22	0.050
11	0.050	23	0.046
12	0.048	24	0.043

the developed optimization program from the candidate locations in Table 1. In addition, a 15-year planning horizon has been considered, and the weighting factors in the objective function are both assumed to be 0.5. Weight factor analysis was not subject of the presented approach in this paper. Therefore, equal weight factor for both objective (HC and EC) is chosen that means the priority of the planning and operational optimization has the same value. In other words, both technical and economic aspects of the presented analysis have the same equal value. Any extension to the priority analysis of the respective objectives as weight factor analyses or meta-heuristic multi-objective analyses are left for the future studies. It is noteworthy that various normalization methods can be used for objective variables based on [36]. Different metric issues of objective variables are fully addressed by this reference. Also, interest rates (r) C_F^{SVC} and C_V^{SVC} are assumed to be 4%, 10000$, and 15$/hour according to real parameters of commercial SVCs (ranges between 100 kVar and 500 kVar), respectively [37–40]. Then, a comprehensive analysis is performed to investigate the impacts of PV penetration rate, number and capacity of installed SVCs, and contribution of FLs on the HC of PV units. The simulation results are analysed separately for different active and reactive power control strategies that will be explained in the following. It is noteworthy that the Nordic market has been very transparent for a long time; therefore, market clearing prices can be publicly accessed on Nord Pool. Hourly wholesale market prices ($C_{i,t,s}^{grid}$) are given in Table 2 according to [41].

It is noteworthy that uncertainties related to PV generation are modelled through ten scenarios according to historical data, as shown in Figure 1 [41]. According to the repeatability of each scenario, a probability is assigned to the generated scenarios based on [42].

Reactive and active power control strategies in order to enhance HC of PV units can be summarized as follows:

- The reactive power control strategy is performed through SVC placement in optimal locations, considering both SVC capacity and numbers. To minimize SVC installation cost and the challenges of reactive power injection, SVC reactive power must be optimally minimized. Note that the maximum capacity of SVC at each bus is considered being 0.05 p.u., while the maximum number of SVCs is 5.
- Active power strategy is applied through FLs. It is assumed that 10% of the initial load at each load point is curtailable and 10% of the initial load at each load point is shiftable. The value of the incentive payment to the consumers for load curtailment is presumed to be 0.04$/$kWh$.

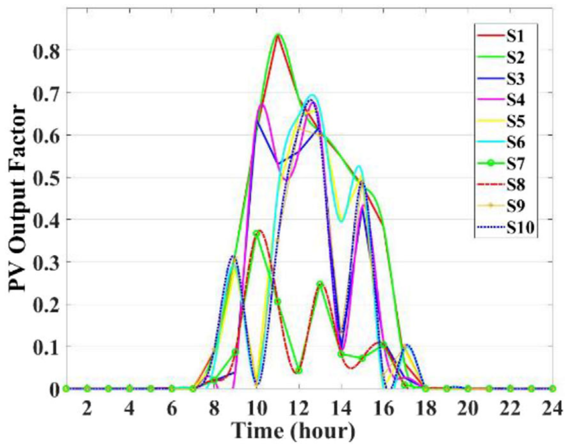

FIGURE 1 PV generation scenarios.

Four different case studies according to the employment of reactive and active power control are defined as follows:

- Case 1: This is the base case with no active or reactive power control.
- Case 2: This case assigns to the reactive power control strategy, where the impacts of SCV placement are investigated to enhance the HC of PV units.
- Case 3: This case is associated with the active power control strategy, where the impacts of FLs are investigated to enhance the HC of PV units.
- Case 4: In this case, the impacts of both reactive and active power control strategies are evaluated simultaneously.

The active and reactive power control strategy might be sensitive to the values of its main controlling parameters. Hence,

TABLE 3 Optimum PV hosting capacity in different case studies.

	PV location (bus)	PV size (p.u.)	PV hosting capacity (p.u.)	SVC location (bus)	Total cost ($)
Case 1	{4, 7}	{0.0528, 0.0352}	0.0881		2474.5
Case 2	{4, 7, 11}	{0.3527, 0.0760, 0.0451}	0.4739	{1, 7, 8}	2264.3
Case 3	{4}	{0.1976}	0.1976		2277.5
Case 4	{4}	{0.3398}	0.3398	{1}	2220.1

TABLE 4 Computation time and number of iteration for all four cases.

	Case 1	Case 2	Case 3	Case 4
Time (s)	12	27	14	23
Number of iterations	36263	40646	42153	46520

tunning of the input parameters is an important matter. In real practice, integration of the grid-tied PVs and control devices (e.g. SVCs) are usually done through three categories: small scale (such as residential generally less than 100 kW), medium scale (such as industrial or commercial between 100 kW and 5 MW) and large scale (such as utility generally between tens and hundreds of MW). Large-scale configuration has less per-unit cost (investment and operation) compared to medium-scale and small-scale configuration [43, 44]. Input parameters of the presented approach are selected according to medium-scale configuration.

The consequent results of all the above cases are discussed in detail in the following section.

4 | RESULTS AND DISCUSSION

4.1 | Optimal PV hosting capacity

Optimal PV hosting capacities for PV Sites A are compared for the defined cases in Table 3. As observed, the HC of PV units has different values for different cases. The lowest value of HC is obtained for Case 1 (with no control), and the highest value is for Case 2 (reactive power control). Further comparison between Cases 2 and 4 (hybrid active-reactive power control) demonstrates that the value of HC in Case 4 is obtained with lower cost and fewer SVCs. In addition, all the HC has been assigned to bus No. 4 in Case 4, while the HC is distributed among buses 4, 7, and 11 in Case 2, which can illustrate the superiority of Case 4 compared to Case 2. In addition, a comparison of computation time and iteration between all four cases is shown in Table 4.

4.2 | Effects of PV locations on hosting capacity

This section investigates the effects of PV candidate locations on HC. The simulation results are reported for the defined cases based on the PV sites given in Table 1. As it can be seen from

TABLE 5 Effect of PV candidate locations on PV hosting capacity in Case 1.

	PV placement (bus)	PV size (p.u.)	PV hosting capacity (p.u.)
Sites A	{4, 7}	{0.0528, 0.0352}	0.0881
Sites B	{7, 15}	{0.0354, 0.0527}	0.0881
Sites C	{15}	{0.0882}	0.0882
Sites D	{7, 15}	{0.0354, 0.0527}	0.0881
Sites E	{7, 15}	{0.0354, 0.0527}	0.0881
Sites F	{4, 7}	{0.0528, 0.0352}	0.0881

Tables 5–6, different PV locations do not affect HC because the PV costs are not included in the objective function. In addition, PV locations do not have impacts on different reactive and active power strategies (According to the SVC placement column in Tables 6 and 7 and the amount of curtailed load in Tables 7 and 8). However, comparisons of the results between these tables reveal some aspects of the effects of PV locations on HC as follows:

- The number of PV installations and PV capacity in each bus is entirely different for different PV candidate locations. It is noteworthy that, although four candidate buses have been considered for each PV Site in Table 1, the numbers of PV installations are different in each case. In addition, PV capacities for the same number of PV installations are different.
- While a different set of buses are considered in this study for all PV sites, some buses are more observable in both aspects of higher frequency and higher capacity (like buses No. 4, 7, 11, and 15); while some others are considered buses are not observed in the output results (like buses No. 3 and 9).
- A comparison between columns of SVC placement in Tables 6 and 7 shows that the hybrid strategy successfully minimizes the number of SVCs and consequently minimizes the total cost of HC enhancement in various conditions of PV placement.
- A comparison between the last columns of Tables 7 and 8 shows that the hybrid strategy successfully enhances the contribution of interruptible load and minimizes the total cost of HC enhancement in various conditions of PV placement.

TABLE 6 Effect of PV candidate locations on PV hosting capacity in Case 2.

	PV placement (bus)	PV size (p.u.)	PV hosting capacity (p.u.)	SVC placement (bus)
Sites A	{4, 7, 11}	{0.3527, 0.0760, 0.0451}	0.4739	{1, 7, 8}
Sites B	{4, 7, 15}	{0.1936, 0.0864, 0.1939}	0.4741	{1, 7, 8}
Sites C	{4, 11, 15}	{0.1585, 0.1215, 0.1939}	0.4740	{1, 7, 8}
Sites D	{4, 7, 11, 15}	{0.1585, 0.0767, 0.0447, 0.1939}	0.4740	{1, 7, 8}
Sites E	{7, 11, 15}	{0.0767, 0.2000, 0.1969}	0.4738	{1, 7, 8}
Sites F	{4, 7}	{0.3878, 0.0861}	0.4740	{1, 7, 8}

TABLE 7 Effect of PV candidate locations on PV hosting capacity in Case 3.

	PV placement (bus)	PV size (p.u.)	PV hosting capacity (p.u.)	Amount of curtailed load (p.u.)
Sites A	{4}	{0.1976}	0.1976	2897.2
Sites B	{15}	{0.1977}	0.1977	2897.5
Sites C	{15}	{0.1977}	0.1977	2897.5
Sites D	{15}	{0.1977}	0.1977	2897.5
Sites E	{15}	{0.1977}	0.1977	2897.5
Sites F	{4}	{0.1976}	0.1976	2897.2

TABLE 8 Effect of PV candidate locations on PV hosting capacity in Case 4.

	PV placement (bus)	PV size (p.u.)	PV hosting capacity (p.u.)	SVC placement (bus)	Amount of curtailed load (p.u.)
Sites A	{4}	{0.3398}	0.3398	{1}	4259
Sites B	{4, 15}	{0.1429, 0.1969}	0.3399	{1}	4259.5
Sites C	{4, 15}	{0.1429, 0.1969}	0.3399	{1}	4259.5
Sites D	{4, 15}	{0.1429, 0.1969}	0.3399	{1}	4259.5
Sites E	{11, 15}	{0.1427, 0.1969}	0.3397	{1}	4259.8
Sites F	{4}	{0.3398}	0.3398	{1}	4259

4.3 | Effects of PV penetration rate on hosting capacity

This section investigates the sensitivity of PV hosting capacity considering the maximum allowable PV penetration rate for the four defined cases. It should be noted that the PV penetration rate is defined as the ratio of the total amount of PV installed capacities at all buses to the system peak load.

PV hosting capacity versus the maximum allowable PV penetration rate and total operation cost versus the maximum allowable PV penetration rate are shown in Figures 2 and 3, respectively. As shown in Figure 2, there is no remarkable difference between Cases 2, 3, and 4 for low PV penetration rates (up to 30%). However, positive impacts of control strategies in Cases 2 and 4 are highlighted compared to Case 3 for higher PV penetration rates (more than 30%). Also, it can be observed that the increment of allowable PV penetration rate does not have a particular effect on PV hosting capacity

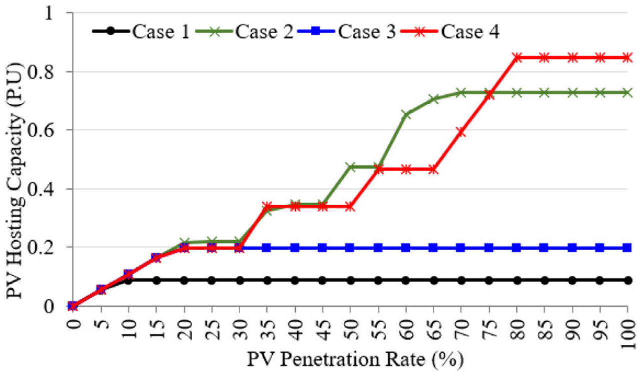

FIGURE 2 PV hosting capacity vs allowable PV penetration rate for the defined case studies.

for Cases 1 and 3. As shown in Figure 3, the increment of PV penetration rate results in total cost reduction for Cases 2, 3,

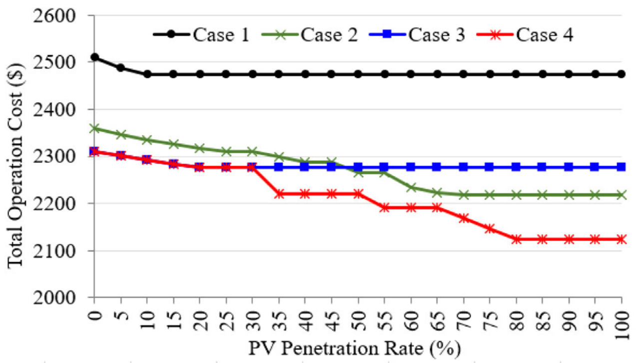

FIGURE 3 Total operation cost vs allowable PV penetration rate for the defined case studies.

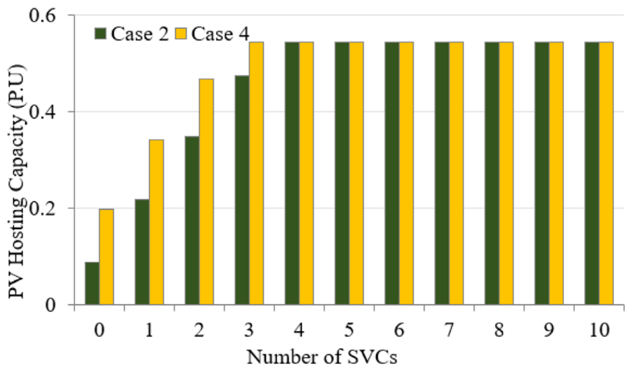

FIGURE 4 HC comparison versus the number of SVC for Cases 2 and 4.

and 4 compared to Case 1. It is worth to remind that exact calculation of penetration rate depends on sum of PV capacities that would be obtained by optimization program. Hence, fixed HC values for increasing penetration rate means that while maximum allowable penetration rate is increased but due to technical issues (power flow constraints), increase of HC is not possible (optimal).

Further comparison between Cases 2 and 3 reveals that active power control is more efficient than reactive power control for lower PV penetration rates. Reactive power control is more efficient for higher PV penetration rates (more than 35%). In addition, a comparison between all four defined cases verifies the higher efficiency of the hybrid active-reactive power control strategy versus other strategies.

4.4 | Effects of number and size of SVC on hosting capacity

In this part, the sensitivity of PV hosting capacity versus the number and size of SVC is investigated for Cases 2 and 4. PV hosting capacity versus the number of installed SVC is shown in Figure 4. In this investigation, the size of SVC is set at 0.05 as a fixed parameter. As seen from these figures, the maximum positive effect of the number of SVC on HC is equal to 3 for Case 4 and 4 for Case 2. For the lower number of SVCs, Case 4 has

TABLE 9 Effect of number of SVC-ON-SVC locations for Cases 2 and 4.

	SVC placement (bus)	
Num. of SVC	**Case 2**	**Case 4**
1	{1}	{12}
2	{1, 14}	{1, 12}
3	{1, 12, 14}	{1, 7, 8}
4	{1, 7, 8, 12}	{1, 7, 8, 12}
5	{1, 7, 8, 12, 15}	{1, 7, 8, 12, 15}
6	{1, 3, 7, 8, 12, 15}	{1, 6, 7, 12, 14, 15}
7	{1, 3, 7, 8, 10, 12, 15}	{1, 6, 7, 8, 12, 14, 15}
8	{1, 2, 3, 7, 8, 10, 12, 15}	{1, 3, 6, 7, 8, 12, 14, 15}
9	{1, 2, 3, 7, 8, 10, 12, 14, 15}	{1, 2, 3, 5, 6, 7, 8, 12, 15}
10	{1, 2, 3, 6, 7, 8, 10, 12, 13, 15}	{1, 3, 4, 6, 7, 8, 9, 12, 14, 15}

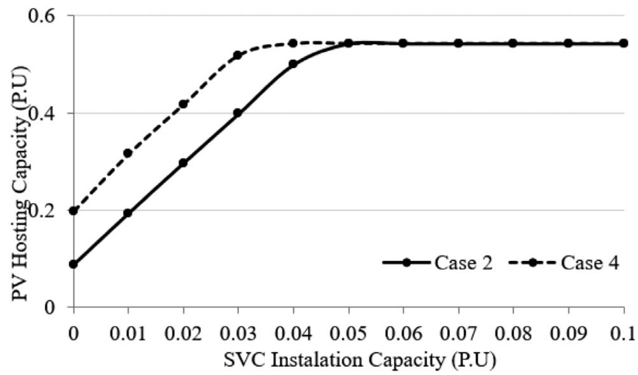

FIGURE 5 HC comparison versus SVC size for Cases 2 and 4.

reached its maximum HC. This shows that a hybrid strategy can enhance the HC of PV for a lower cost of SVC planning due to the potential of FLs. It can be observed that an additional number of SVC does not affect HC. In addition, the results of SVC placement for this study have been reported in Table 9. The contribution of FLs in Case 4 resulted in different SVC placements compared to Case 2. A comparison of PV hosting capacity versus SVC size is shown in Figure 5 for Cases 2 and 4. In this investigation, the number of SVC is set to 4 as a fixed parameter. This figure shows that Case 4 has reached the maximum HC value for the smaller SVC size. This proves the positive effect of combined active and reactive power control strategies for enhancing PV hosting capacity. In addition, SVC placement for this study is presented in Table 10. As can be observed, the contribution of FLs in Case 4 resulted in different SVC placements compared to Case 2.

4.5 | Effects of flexible loads

In this section, the effects of flexible loads, including shiftable and curtailable loads, are investigated on HC for cases of active power control strategies (Cases 3 and 4). Impacts of responsive load percentage on HC of PV units are shown in Figure 6 for

TABLE 10 Effect of SVC size on SVC locations for Case 2 and Case 4.

The capacity of SVC (p.u.)	SVC placement (bus)	
	Case 2	Case 4
0.01	{1, 2, 3, 13}	{8, 12, 13, 14}
0.02	{1, 2, 13, 14}	{1, 8, 12, 13}
0.03	{1, 12, 13, 14}	{1, 8, 12, 14}
0.04	{1, 12, 14, 15}	{1, 7, 8, 12}
0.05	{1, 7, 8, 12}	{1, 7, 8, 12}
0.06	{1, 7, 12, 15}	{1, 7, 8, 15}
0.07	{1, 7, 12, 15}	{1, 7, 12, 15}
0.08	{1, 7, 10, 15}	{1, 6, 7, 15}
0.09	{1, 2, 7, 15}	{1, 6, 7, 15}
0.10	{1, 2, 7, 12}	{1, 6, 7, 15}

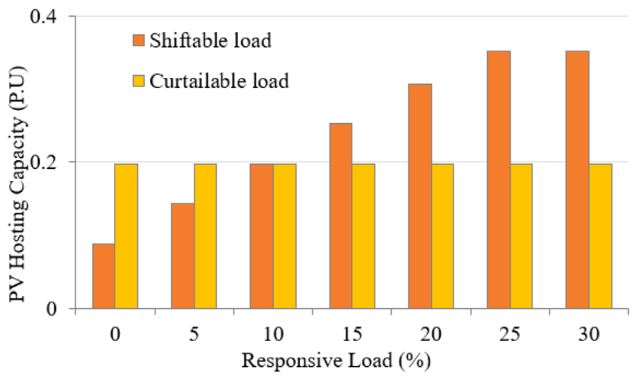

FIGURE 6 HC comparison for FL operations in Case 3.

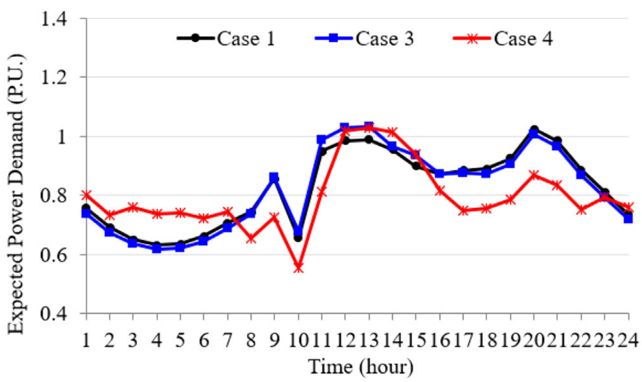

FIGURE 7 Final daily load curve after FL operations for Cases 3 and 4 (expected of all scenarios).

Case 3. It can be observed that shiftable loads have more impact on HC enhancement than curtailable loads in a higher percent of FL contributions. Moreover, the final modified daily load curves are compared for Cases 3 and 4 in Figure 7. As it can be observed from this figure, the positive effect of FL on adjusting the daily load curve is remarkable, particularly in Case 4. Reactive power control employment in Case 4 has resulted in a more effective contribution of FLs. Results are more distinguished in afternoon peak loads (16:00 to 22:00) when there is no PV generation. Effects of load curtailment according to variable PV generation (daylight hours and night hours) are discussed in [45]. Results of this study verify that while load curtailment faces some limits but has a positive impact on HC of PV. In [46], comparative investigation between integration of PVs and wind turbines (WTs) verifies challenging nature of PV daily output curve on HC of PV. Hybrid FL programs and SVC integration of the presented study achieves to alleviate this challenge.

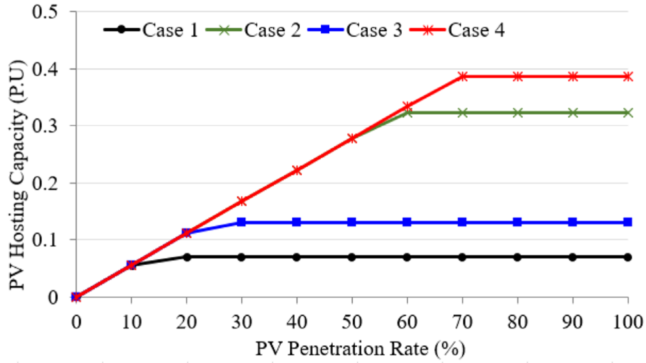

FIGURE 8 PV hosting capacity vs allowable PV penetration rate for the 33-bus test system control strategies.

4.6 | Validation

The proposed model's results are validated on this part's IEEE 33 bus distribution system. The detailed parameters of this test system can be found in [47]. Here, uncertainty scenarios and base parameters are the same as those in the previous section. Ten candidate locations are considered for the PV installation, that is, nodes 7, 8, 14, 19, 24, 25, 29, 30, 31 and 32. Also, the maximum allowable number of SVC placements is set to 10. The PV hosting capacity and computation running results are listed in Tables 11 and 12 for all four cases of control strategies, respectively. As it can be seen from Table 11, the same conclusions that were discussed in Table 3 for the 15-bus system are successfully repeated by the 33-bus system. Further comparison between Tables 4 and 12 shows that while expansion of the test system increases the computation running burden, it is still not a challenging issue in solving the process of the proposed model by the software.

In addition, the sensitivity of PV hosting capacity considering PV penetration rate is investigated for the four cases of control strategies like the 15-bus test system. PV hosting capacity versus maximum allowable PV penetration rate and total operation cost versus maximum allowable PV penetration rate are shown in Figures 8 and 9, respectively. These figures show that the same conclusions obtained for the 15-bus test system are achieved for the 33-bus test system. Summarily, a comparison between all four defined cases verifies the higher efficiency of the hybrid active-reactive power control strategy versus other strategies.

TABLE 11 Optimum PV hosting capacity in different case studies For the IEEE 33 bus distribution test system.

	PV location (bus)	PV size (p.u.)	PV hosting capacity (p.u.)	Total cost ($)
Case 1	{14, 32}	{0.05, 0.0202}	0.0702	5499.4
Case 2	{8, 14, 29, 30, 31, 32}	{0.05, 0.05, 0.0286, 0.05, 0.05, 0.05}	0.2786	5255.9
Case 3	{8, 14, 31, 32}	{0.0012, 0.05, 0.0295, 0.05}	0.1308	5306.6
Case 4	{8, 14, 29, 30, 31, 32}	{0.05, 0.05, 0.0286, 0.05, 0.05, 0.05}	0.2786	5064.2

TABLE 12 Computation Time and Number of Iteration for All Four Cases in the IEEE 33 bus Distribution Test System.

	Case 1	Case 2	Case 3	Case 4
Time (Second)	00′:41″	04′:25″	01′:00″	03′:14″
Number of iterations	71162	135949	107096	167741

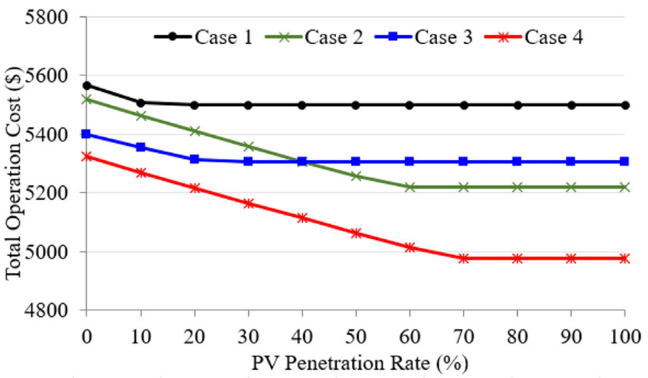

FIGURE 9 Total operation cost vs allowable PV penetration rate for the 33-bus test system control strategies.

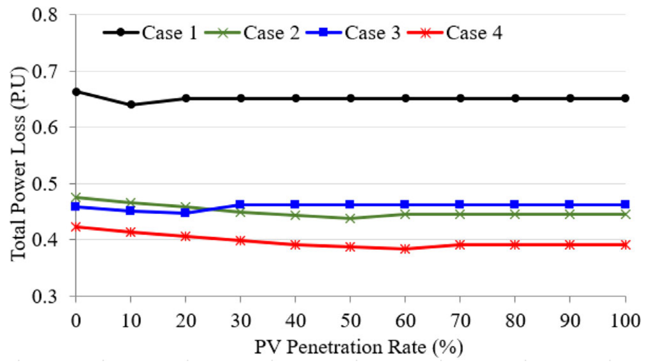

FIGURE 10 Total power loss of the 33-bus test system for all control strategies (expected of all scenarios).

The power loss of the network was not an issue in this study. This variable was not among the optimization objectives in the proposed model. However, values of the total power loss of the 33-bus test system are compared for all control strategies to investigate another aspect of the possible superiority of the proposed hybrid model. Results of the total power loss of the network for all expected scenarios are shown in Figure 10. It can be seen from this figure that, for all PV penetration rates, hybrid control (Case 4) is superior to other control cases in the aspect of power loss. It can also be seen that for lower PV penetration rates, Case 3 presents lower power loss than Case 2, while for higher PV penetration rates, this is vice versa. Again, this verifies the previously discussed conclusion. It is noteworthy that power loss conclusions are obtained while this was not an objective in proposed optimization model. In [48, 49], U-shaped trend of the network power loss in versus PV penetration rate is concluded. This trend can be observed for Cases 2 and 4 as well while the minimum optimal point is shifted from 50% in Case 2 to 60% in Case 4 (hybrid strategy achieves higher optimal PV penetration rate in power loss perspective).

The presented work of this study can be extended in real practices. Based on various presented sensitivity analyses, large optimal integration of grid-tied connection PVs can be achieved through coordinated management of active power control and reactive power control. Practical steps can be performed in different stages of medium-scale PV integration into distribution networks as follows:

- In early stages of incremental PV penetration, DR programs through shiftable loads and interruptible loads have the priority over SVC configuration (particularly in economic perspective).
- In middle stages of PV penetration, DR programs lose their benefits (in both technical and economic perspectives) over SVC configuration.
- Hybrid active power and reactive power control programs in high PV penetration (final stages more than 60%) has the definite superiority over respective active or reactive power control programs.

5 | CONCLUSIONS

This paper proposes a comprehensive operational planning model based on combined active and reactive power control strategies, while respective active or reactive power control are considered in previous works. Active power control was performed through flexible loads, particularly shiftable and curtailable loads, while reactive power control was carried out through SVC placement. The effectiveness of the proposed model was validated on the modified IEEE 15-bus test system and IEEE 33 bus distribution system considering different cases for active and reactive power control strategies. The results reveal that the hybrid strategy can minimize total operating costs compared to active and reactive power control. Also, it was shown that, in lower PV penetration rates, active power control is more optimal than reactive power control due to lower operational costs.

In comparison, in higher PV penetration rates, reactive power control shows superiority because of better HC enhancement. In addition, it was shown that the potential of FLs results in reduced operational cost due to the optimal placement of SVC in a hybrid strategy compared to reactive power control. While power loss was not among the objectives of the proposed model, the investigation of total power in different PV penetration rates also verified the presented analysis. Finally, it was shown that a hybrid strategy could better adjust the daily load curve due to the contribution of SVCs compared to respective active power control.

NOMENCLATURE

$i, i'/N$	Index/set of distribution nodes
m	Index of nodes with PV generation installation
$N^{PV}(i)$	Set of child nodes of node i with PV generation units
t/T	Index/set of time periods
s/S	Index/set of scenarios
f	Index of linear partitions in linearization
w^{HC}	The weighting factor of the PV hosting capacity
w^{EC}	The weighting factor of the expected cost, including SVC investment cost, SVC operation cost, curtailed load penalty cost, and purchased electricity costs from the wholesale market
C_F^{SVC}	Objective function coefficient associated with the fixed investment cost of SVC ($)
C_V^{SVC}	Objective function coefficient associated with the variable operating cost of SVC ($/h)
C^{INC}	Objective function coefficient associated with the incentive payment for the curtailed load ($/p.u.)
$C_{i,t,s}^{grid}$	Objective function coefficient associated with the purchased electricity cost from the wholesale market ($/p.u.)
ρ_s	Probability of scenario s occurrence
N_{inv}^{SVC}	Maximum allowed total SVC installation number
$\xi_{t,s}^{PV}$	PV output factor (ratio of PV hosting capacity) in period t and scenario s, $\xi_{ts}^{PV} \in [0, 1]$
V^{Rated}	Nominal voltage (V)
$I_{i,i'}^{max}$	The maximum current of a branch i, i' (A)
$Z_{i,i'}$	The impedance between nodes $i$and i' (Ω)
$R_{i,i'}$	The resistance between nodes $i$and i' (Ω)
$X_{i,i'}$	Reactance between nodes $i$and i' (Ω)
$\Delta S_{i,i'}$	The upper limit in the discretization of quadratic flow terms (kVA)
$P_{i,t}^{L\text{-}ini}$	Initial load demand at i^{th} node and t^{th} hour (p. u.)
DR_i^{max}	Maximum shiftable load factor (ratio of initial load demand), $DR_i^{max} \in [0, 1]$
α^{curt}	Maximum curtailable load factor (ratio of initial load demand), $\alpha^{curt} \in [0, 1]$
HC	The objective function associated with z PV hosting capacity
EC	The objective function associated with expected Cost
E_m^{PV}	PV hosting capacity allocated to node m
$p_{m,t,s}^{PV}$	PV output of unit m in period t and scenarios
a_i^{SVC}	binary decision variable flagging SVC installation at node i or not
Q_i^{SVC}	SVC installation capacity at node i
$q_{i,t,s}^{SVC}$	Reactive power support of SVC at node i in period t and scenario s
$P_{i,t,s}^{L\text{-}fin}$	Customers' demand after DR (p. u.)
$\Delta P_{i,t,s}^{L\text{-}DR}$	shifted load demand at node i in period t and scenario s (p.u.)
$P_{i,t,s}^{L\text{-}curt}$	Curtailed load demand at node i in period t and scenario s (p.u.)
$p_{i,t,s}^{grid}$	Purchased power from the wholesale market in period t and scenario s (p.u.)
$q_{i,t,s}^{grid}$	Supported reactive power from the wholesale market in period t and scenario s (p.u.)
P^+	Active power flows in downstream directions (p. u.)
P^-	Active power flows in upstream directions (p. u.)
$I, I2$	Current flow (p.u.), squared current flow (p.u.)
$V, V2$	Voltage (p.u.), squared voltage (p.u.)

AUTHOR CONTRIBUTIONS

Rezvaneh Golnazari: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software. **Saeed Hasanzadeh**: Conceptualization; investigation; methodology; software; supervision; validation; writing—original draft; writing—review & editing. **Ehsan Heydarian-Forushani**: Conceptualization; formal analysis; investigation; methodology; resources; software; writing—original draft; writing—review & editing. **Innocent Kamwa**: Conceptualization; investigation; methodology; software; supervision; validation; visualization; writing—original draft; writing—review & editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

CREDIT TAXONOMY

Rezvaneh Golnazari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Saeed Hasanzadeh: Conceptualization, Investigation, Methodology, Software, Supervision, Validation, Writing—original draft, Writing—review & editing, Ehsan Heydarian-Forushani: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Writing—original draft, Writing—review & editing, Innocent Kamwa: Conceptualization, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing

DATA AVAILABILITY STATEMENT

Research data are not shared.

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