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ORIGINAL RESEARCH PAPER

Optimal stochastic scheduling of reconfigurable active distribution networks hosting hybrid renewable energy systems

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Abstract

Renewable energy sources (RESs) have a remarkable role in advancing the goals of restructured power systems to reduce greenhouse gas emissions and increase the level of reliability. However, due to the non-uniform utilisation of these resources in various sectors of power grids, a major part of the generated renewable energies is spilled to satisfy the power system constraints. Motivated by this challenge, the role of the reconfiguration mechanism in maximising the utilisation of RESs in active distribution networks (ADNs) is investigated herein. To this end, a two-stage stochastic model is presented for optimal scheduling of reconfigurable distribution networks in the presence of high-power hybrid wind/photovoltaic systems. The main goal of the presented model is to maximise the hybrid system owner's profit. In the first stage of the presented structure, the optimal hourly bilateral dispatches between the hybrid system and the ADN in the day-ahead electricity market are determined to maximise the hybrid system owner's profit. In the second stage, the power spillage of the hybrid renewable energy systems are minimised using reconfiguration technology in the real-time electricity market. For practical implementation, the proposed operational strategy is applied to the modified 33-bus and 69-bus distribution test systems, and is solved using GAMS software. The simulation results indicate that the proposed strategy can considerably reduce renewable power spillage, increase the hybrid system owner's profit, and decrease total active power loss of the ADN. According to the obtained results in the 33-bus test system, the profit of the hybrid system owner is increased by up to 6.8% as well as the total active power loss being decreased by up 75.58% through the presented structure.

1 | INTRODUCTION

1.1 | Motivation

Nowadays, one of the most efficient approaches to meet demand in active distribution networks (ADNs) is renewable sources. The installed capacity of renewable energy sources (RESs) in distribution networks in many countries such as China, Germany, and Denmark has been increased rapidly [1]. In the meantime, the share of wind turbines (WT) and photovoltaic (PV) systems is indisputable for supplying needed energy in the form of a hybrid system [2]. However, according to some strong evidence, ADNs do not have sufficient infrastructure (such as line capacity) for using high penetration levels of RESs [3]. Thus, the renewable energy spillage rate in ADNs has increased over the past years [4, 5]. In the absence of proper planning for using high-power RESs, serious problems such as line congestion and voltage deviation may occur in ADNs. For more efficient use of RESs in distribution networks, innovative concepts such as energy storage systems (ESSs) [6], load management technique [7], and reconfigurable systems [8] have been presented. In the meantime, those technical approaches that are designed and operated based on reliable, economical, and environmentally friendly qualities, are especially favoured by the power system operator and distributed generation unit owners. Having these in mind, it is necessary to provide a comprehensive approach for the optimum utilisation of RESs in order to assess the technical and economic challenges, as well as to satisfy the technical constraints of ADNs.

1.2 | Background and related works

As stated in the literature, the optimal energy trading approaches in the power markets with consideration of the high-power RESs have attracted much attention from the researchers' perspective [9, 10]. There are various studies that have addressed the challenges of utilising high-power RESs in medium-voltage smart grids considering the role of ESSs. The authors of [11] suggested a stochastic approach to maximise the utilisation of RESs by considering the frequency-based pricing mechanism in a pump-storage hydro plant. In [12], a multi-criteria approach has been proposed for optimal dispatch of the hybrid renewable energy systems by relying on the ESSs. The optimisation problem has been solved by the ε-constraint method and a hybrid WT/PV/fuel cell/ESS system has been used to carry out the simulations. In [13, 14], the optimal operation of ESSs in the presence of RESs has been modelled and the effect of integrated systems on networks' operational costs has been investigated. In [15], efficient stochastic energy management has been presented to solve the challenges posed by the use of high-power RESs in ADNs with respect to up-to-date ESSs. In [16], a scenario-based model has been presented to determine the optimal sitting of ESSs in ADNs. The proposed method has been developed using a dynamic linearisation model of the optimal power flow to achieve different goals, including (i) harvesting higher wind energy, (ii) managing line congestion, and (iii) decreasing voltage deviation. In [17], a feasible solution has been presented to reduce wind power curtailment using heat storage. The strategy has been implemented in a standard distribution test system and the simulation results showed that wind power curtailment is decreased by 3% in the test system. None of the mentioned papers considered the role of the reconfiguration mechanism as a technical tool for the efficient exploitation of ADNs and increasing the utilisation of RESs.

Another solution to alleviate power spillage of renewable sources is the expansion of reconfigurable networks. The reconfiguration mechanism has the potential to enable distribution networks to deal with the system anomalies, for example, a reduction in the duration of power outages [18], minimisation of active and reactive power losses, minimisation of voltage deviation, and enhancement of power quality [19]. Some studies have employed the reconfiguration method for ADN planning and operation in the presence of ESSs and RESs to improve the distribution system's performance using traditional objective functions [20, 21]. The authors of [22] solved a multi-objective stochastic mixed-integer problem to reduce the distribution system's operational costs. They presented a new mechanism to increase the level of RESs with simultaneous use of ESS and network reconfiguration approach. In [23], a stochastic energy management strategy aimed at the sustainable operation of ADNs has been presented in the presence of WTs and reconfiguration mechanism. Moreover, the uncertainty in the output power of WTs has been modelled using a risk-averse strategy. The authors of [24] examined the role of the hourly reconfiguration in coordination with renewable energy sources to improve the performance of distribution networks in terms of loss reduction. In [25], a day-ahead energy-trading model has been provided for the efficient exploitation of ADNs in the presence of high-power RESs by relying on the reconfiguration mechanism. Moreover, in [26], a deterministic procedure has been proposed for the optimal operation of distributed energy sources in the ADNs. In addition, the seasonal reconfiguration mechanism has been used to satisfy network security constraints. The utilised procedure in this work has been formulated as a mixed-integer linear programming model and the simulation results demonstrated that this model could improve the performance of the ADNs. All these studies consider the optimisation problem from the distribution company's viewpoint and aim to improve the technical parameters of the distribution network. Table 1 summarises the combination of the proposed solutions in the literature to improve the performance of ADNs.

Nevertheless, none of the mentioned studies takes into account the interests of the hybrid system owner in solving optimisation problems. The main goal from the perspective of hybrid system owners is to maximise the profit through maximum participation in electricity markets. Thus, the concern about RES power spillage should also be studied from the hybrid system operator's point of view. In this regard, due to the high degradation cost of ESSs, as well as operations and maintenance (O&M) costs, the conventional ESSs are not an economical solution to solve the power spillage issue. Hence, the reconfiguration mechanism is used herein as an economical solution to deal with renewable power spillage as well as to improve the performance of ADNs.

1.3 | Contributions

An extended version of the preliminary study presented in [27] is given. Herein, the proposed operational strategy is explained in more detail. Moreover, more comprehensive case studies by making reference to a modified 69-bus distribution test system are used to verify the performance of the proposed strategy. The impacts of the hybrid renewable energy systems on the technical parameters of ADNs are examined with and without the presence of the reconfiguration mechanism. The main contributions are summarised as follows:

- A holistic two-stage stochastic model is presented to simultaneously optimise significant objectives from the perspective of the ADN operator and hybrid system owner. In the proposed structure, the role of technical and economic challenges is intended in stochastic programming.
- A complete model for the optimal hourly reconfiguration of the ADNs is used to harvest higher wind and PV energies.
- The impacts of the uncertainties of electricity market price and high-power RESs on the technical and economic parameters are investigated within the context of the reconfigurable ADN.

TABLE 1 Comparing the proposed structure with different studies

References	Type of technical tool	Uncertainty	Problem-solving perspective
[11–16]	ESSs	Yes	ADN operator
[17]	ESSs and load management technique	No	ADN operator
[20, 21]	ESSs and reconfiguration mechanism	Yes	ADN operator
[22–24]	Reconfiguration mechanism	Yes	ADN operator
[25, 26]	Reconfiguration mechanism	No	ADN operator
Proposed model	Reconfiguration mechanism	Yes	ADN operator and hybrid system owner

Abbreviations: ADN, active distribution network; ESS, energy storage system.

1.4 | Structure

The structure of the proposed method and mathematical formulations are given in Section 2. Simulations and numerical results are discussed in Section 3, and finally, the conclusions are summarised in Section 4.

2 | SYSTEM MODEL AND PROBLEM FORMULATION

Figure 1 demonstrates the proposed two-stage framework. The proposed stochastic model is solved from the perspective of the hybrid renewable energy system owner and ADN operator to improve the performance of the distribution network as well as to maximise the benefit of the hybrid system owner by providing wind and solar energies in the day-ahead and real-time electricity markets. To this end, the reconfiguration strategy is used to maximise the utilisation of the hybrid system in ADN as well as to minimise the renewable power spillage. As shown in Figure 1, the input parameters are the forecasts of WT and PV power generation, load demands, and electricity price. The uncertainties of market prices and renewable power generation are modelled using the scenario-based stochastic method. The output of the first stage is the optimal bilateral dispatches between the hybrid renewable energy system and ADN in the day-ahead electricity market. Then, this variable is used to calculate the hybrid system's profit in the second stage based on the participation rate in the real-time electricity market. The formulation of the proposed strategy is presented in the following sub-sections.

2.1 | Objective function

The proposed two-stage model is formulated as a stochastic mixed-integer non-linear programme with the aim of profit maximisation as in (1).

- Maximise:

$$EPF = \sum_{t=1}^{24}\left(\lambda_t^{D} \times \sum_{i=1}^{NB} PC_{i,t} + \left(\sum_{s=1}^{NS} \pi_s \times RE_{t,s}\right) - CO_t\right) \quad (1)$$

$$RE_{t,s} = \lambda_{t,s}^{R} \times \left(\sum_{i=1}^{NB}\left(P_{i,t,s}^{PV} + P_{i,t,s}^{wind} - PC_{i,t} - P_{i,t,s}^{spill}\right)\right) \quad (2)$$

$$CO_t = \lambda^{SW} \times \sum_{(i,j)=1}^{NB} \left|\alpha_{ij,t} - \alpha_{ij,t\text{-}1}\right| \quad (3)$$

The objective function is composed of two stages. In the first stage, the optimal bilateral dispatches are determined. It should be noted that this variable is independent of the scenario-based stochastic model. The second stage indicates stochastic programming and is influenced by different scenarios. Equation (2) describes the stochastic process. According to Equation (2), the revenue of hybrid system performance from the power provided to the distribution network in the real-time market is determined based on the stochastic programming. The revenue of the hybrid system in the real-time electricity market can be zero, negative, or positive amounts. The zero amount represents the supply of the hybrid system energy only in the day-ahead market, and also the positive amount represents the supply of the hybrid system energy in both day-ahead and real-time markets with different rates of participation. The negative value can be derived from the imbalance cost for each scenario or hybrid system power spillage due to network constraints. $P_{i,t,s}^{spill}$ shows the amount of power spilled in each scenario. Finally, the last term (CO_t) refers to the cost of switching operations and can be calculated using Equation (3). After offering the production schedule by hybrid renewable energy systems in the electricity market, the ADN operator will change the network topology for maximum utilisation of RESs based on the capacity of each line. Therefore, switching costs should be paid by the hybrid system owner.

2.2 | Problem constraints

The following constraints have been considered for the optimisation model:

- Bilateral dispatches constraint: According to Equation (4), the traded power of the hybrid system at each hour in the day-ahead electricity market should not exceed the maximum capacity of the existing renewable sources in each hybrid unit.

$$0 \le PC_{i,t} \le PH_i^{max}, \quad \forall t \in NT,\ i \in NB \quad (4)$$

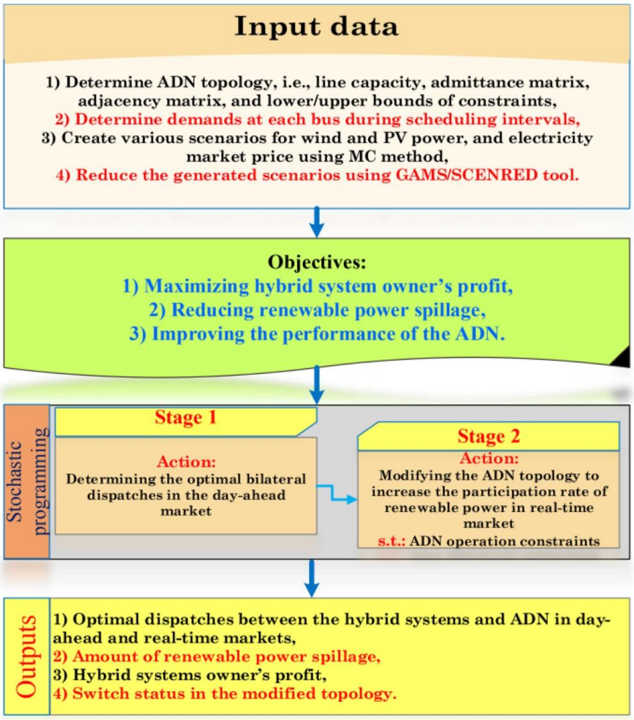

FIGURE 1 The proposed framework for maximising hybrid system profit

- Distribution power flow constraints: Inequalities (5)–(8) indicate the active and reactive power flow models for ADN [28]. These equations are modified to contemplate the influential support of the reconfiguration mechanism in the distribution networks. In these equations, when the line between buses i and j is connected, the binary variable ($\alpha_{ij,t}$) will be equal to 1. On the contrary, when the line between buses i and j is disconnected, the binary variable ($\alpha_{ij,t}$) will be equal to 0.

$$P_{ij,t,s} - Y_{ij}\left[V_{i,t,s}^{2} cos\left(\theta_{ij}\right) - V_{i,t,s}V_{j,t,s}cos\left(\theta_{ij} + \delta_{i,t,s} - \delta_{j,t,s}\right)\right] \leq M\left(1 - \alpha_{ij,t}\right),\ \forall t \in NT,\ i,j \in NB, s \in NS \tag{5}$$

$$P_{ij,t,s} - Y_{ij}\left[V_{i,t,s}^{2} cos\left(\theta_{ij}\right) - V_{i,t,s}V_{j,t,s}cos\left(\theta_{ij} + \delta_{i,t,s} - \delta_{j,t,s}\right)\right] \geq -M\left(1 - \alpha_{ij,t}\right),\quad \forall t \in NT, i,j \in NB, s \in NS \tag{6}$$

$$Q_{ij,t,s} - Y_{ij}\left[V_{i,t,s}^{2} sin\left(\theta_{ij}\right) - V_{i,t,s}V_{j,t,s}sin\left(\theta_{ij} + \delta_{i,t,s} - \delta_{j,t,s}\right)\right] \leq M\left(1 - \alpha_{ij,t}\right),\ \forall t \in NT,\ i,j \in NB, s \in NS \tag{7}$$

$$Q_{ij,t,s} - Y_{ij}\left[V_{i,t,s}^{2} sin\left(\theta_{ij}\right) - V_{i,t,s}V_{j,t,s}sin\left(\theta_{ij} + \delta_{i,t,s} - \delta_{j,t,s}\right)\right] \geq -M\left(1 - \alpha_{ij,t}\right),\ \forall t \in NT,\ i,j \in NB, s \in NS \tag{8}$$

- Power balance constraints: The active and reactive power balance constraints for the distribution network can be described by Kirchhoff's first law, which are presented in Equations (9) and (10). These equations guarantee the active and reactive power balance at all buses during each scheduling interval.

$$P_{mg,t,s}^{G\_I} - P_{mg,t,s}^{G\_S} + P_{i,t,s}^{wind} + P_{i,t,s}^{PV} - PC_{i,t} - P_{i,t,s}^{spill} = P_{i,t,s}^{Load} + \sum_{(i,j)=1}^{NB} P_{ij,t,s},\quad \forall t \in NT, i \in NB,\ s \in NS \tag{9}$$

$$Q_{mg,t,s}^{G\_I} - Q_{i,t,s}^{Load} = \sum_{(i,j)=1}^{NB} Q_{ij,t,s}, \forall t \in NT, i \in NB, s \in NS \tag{10}$$

- Voltage and line flow constraints: Inequalities (11)–(13) demonstrate the limits of acceptable voltage at each bus and allowable active and reactive power flow at each distribution feeder.

$$V^{min} \leq V_{i,t,s} \leq V^{max},\quad \forall t \in NT, i \in NB, s \in NS \tag{11}$$

$$\alpha_{ij,t} \times P_{ij}^{min} \leq P_{ij,t,s} \leq \alpha_{ij,t} \times P_{ij}^{max} \tag{12}$$

$$\alpha_{ij,t} \times Q_{ij}^{min} \leq Q_{ij,t,s} \leq \alpha_{ij,t} \times Q_{ij}^{max} \tag{13}$$

- Reconfiguration and network radiality constraints: Equations (14)–(17) are constraints related to the radiality of the distribution network. These equations assure that all system buses except the substation bus (mg) have at least one route to other nodes. α_{ij} determines the status of each line. α_{ij} is equal to 1 if bus i is connected to bus j and 0 otherwise. To keep the radial structure of the distribution network, the number of closed switches per loop must be equal to the number of nodes minus 1. Finally, according to Equation (18), the number of switching actions must be less than its maximum possible bound.

$$\sum_{(i,j)=1}^{NB} \alpha_{ij} = N_{bus} - 1,\ \forall t \in NT \tag{14}$$

$$\alpha_{ij} = \alpha_{ji},\quad \forall i,j \in NB, t \in NT \tag{15}$$

$$\sum_{j=1}^{NB} \alpha_{ij} \geq 1,\quad \forall t \in NT, i \in NB \tag{16}$$

$$\alpha_{mg,j} = 1,\quad \forall t \in NT \tag{17}$$

$$\sum_{t=1}^{NT} \left|\alpha_{ij,t} - \alpha_{ij,t-1}\right| \leq SW^{max} \quad \forall (i,j) \in NB \tag{18}$$

3 | CASE STUDY AND NUMERICAL RESULTS

3.1 | Modified 33-bus distribution test system

3.1.1 | Assumptions

The presented structure is implemented on the 33-bus distribution network. The topology of the modified test system is illustrated in Figure 2. The required data, including line info and limitation of power flow about this test system, are available in [29]. The system has a rated voltage of 12.66 kV, and the base value of power is equal to 100 MVA. Also, the voltage variation ranges for the system's buses are between 0.9 and 1.05 p.u. The hourly active and reactive demands, as well as the share of each bus from the system's power consumption, are given in [29]. Two hybrid renewable energy systems, hybrid systems 1 and 2, are assumed to be installed in buses 21 and 29. It should be noted that the specified locations for installing hybrid renewable systems were determined experimentally and based on the hypotheses presented in the previous studies. Each of these hybrid systems includes one WT and one PV source. The installed capacity of WT and PV sources is equal to 3.5 and 1.5 MW, respectively. The appropriate scale of day-ahead market prices at BZN UK on Thursday, June 28, 2018 [30] has been used in an optimisation problem for all scenarios. These amounts are shown in Figure 3. According to the available data in [31], 100 scenarios for PV and wind power generation, and the real-time market price were generated using the Monte Carlo approach. After that, the generated scenarios along with the probability of each scenario should be entered into the GAMS/SCENRED tool as the input parameters [32]. This tool is based on the scenario tree approach, in which various parameters such as the number of leaves and nodes of the tree as well as the number of time steps must be determined in the GAMS environment. Then, the command to start the scenario reduction process ($libinclude scenred.gms) must be executed by specifying the number of scenarios intended as the output of the process. The uncertainties of PV and wind power generation, and the real-time market price are modelled through the three scenarios shown in Figures 3 and 4. The probability of occurrence for each scenario is equal to one in three.

The maximum allowable number of switching operations ($SW^{\max}$) is assumed to be 10 times per day to use the ability of the reconfigurable distribution network. Also, the cost of each switching action ($\lambda^{\max}$) is set to be $1.

The proposed structure for reconfigurable distribution networks is formulated as a mixed-integer convex programming (MICP) optimisation problem and is solved using MOSEK under the general algebraic modelling system (GAMS) software. To achieve the optimal solution the relative gap and the solution time limits are adjusted to 0.1% and 10,000 s. The computational time of the proposed optimisation problem for the 33-bus distribution test system and 69-bus distribution test system is about 72 s and 116 s, respectively.

3.1.2 | Simulation results

In order to show the effectiveness of the proposed structure to increase the hybrid system owner's profit and decrease wind and PV power spillage in ADNs, two different case studies are addressed as follows:

In ***case 1***, scheduling is performed only in the presence of the hybrid system, regardless of the reconfiguration method.

In ***case 2***, the effect of the reconfiguration method on the system's scheduling in the presence of RESs is considered.

I) Hourly optimal bilateral dispatches (first-stage)

The hourly optimal bilateral dispatches between the hybrid renewable energy system and the ADN in the day-ahead electricity market for two cases and each type of the hybrid system located at bus 21 and bus 29 is shown in Figure 5. Also, the hourly optimal bilateral dispatches are not related to stochastic programming, and are the same for all scenarios.

The hourly scheduled power levels for participation in the day-ahead market should be less than the hybrid system capacity; the maximum capacity of hybrid systems is assumed here to be 5 MW. As can be seen from Figure 5, the sum of the scheduled power to sell in the day-ahead market for both hybrid systems in case 1 is equal to 80.388 MW, while this amount in case 2 is equal to 91.176 MW. The results show that using the reconfiguration method, the hybrid system can be more involved in the day-ahead electricity market.

II) Decreasing wind-PV power spillage and increasing hybrid system profit (second-stage)

According to the generated scenarios, the wind and PV power spillage in the real-time electricity market for each case is shown in Figure 6. In case 1, the amount of the spilled power from both hybrid systems in scenarios 2 and 3 is equal to 3.75% and 12.89% of the total forecasted power, respectively. In case 2, the hybrid system power spillage issue only occurs in scenario 3 and the spilled power amount has reached 1.58% of the total forecasted power. According to Figure 4, the amount of power generation in all scenarios in the time intervals [20-01] is greater than the other intervals, so the highest power spillage belongs to this range.

Table 2 shows the open switches, where remotely controlled switch numbers 2, 22, 35, and 36 are in the open state during every 24 h period.

The optimal results of the earned profits by the hybrid renewable energy system owner for participating in the day-ahead and real-time electricity markets are summarised in Table 3. It is observed that in case 2, the profit of the hybrid system owner increases by 6.7% in comparison with case 1.

Furthermore, to evaluate the effect of the proposed structure on the ADN's parameters (such as average voltage and active power loss), the simulation results have been compared with the base model of the distribution network (without the hybrid system and reconfiguration method) and have been provided in Table 4. To this end, the active power loss can be calculated by Equation (19). All of these variables ($P_{ij,t,s}$, $Q_{ij,t,s}$, $V_{i,t,s}$) are calculated through constraints (5)–(13) during the scheduling period.

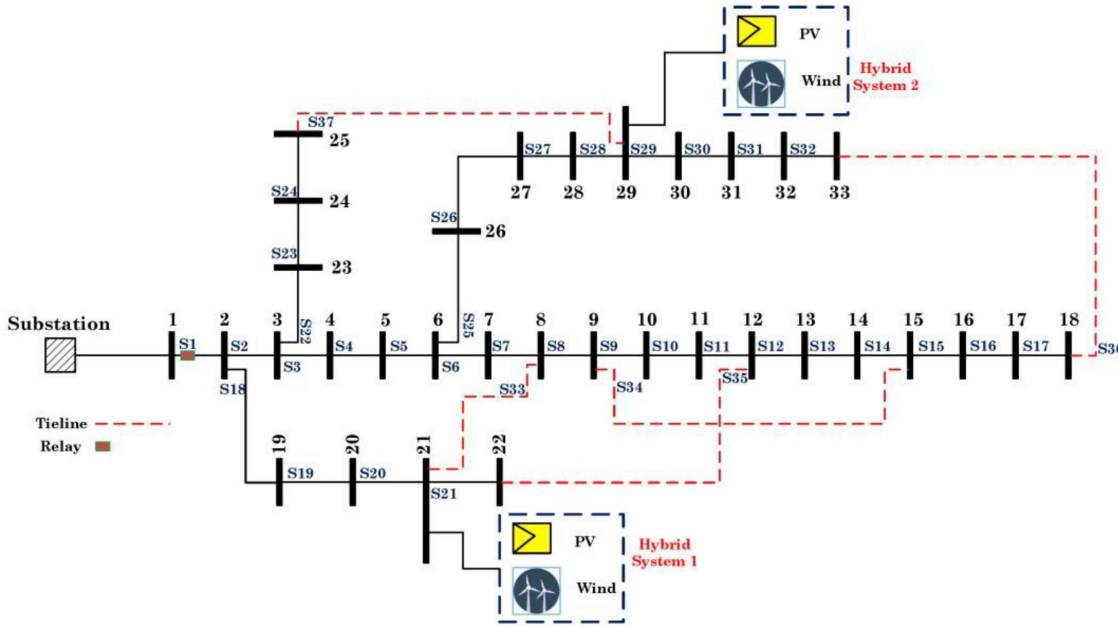

FIGURE 2 Topology of the modified 33-bus distribution test system

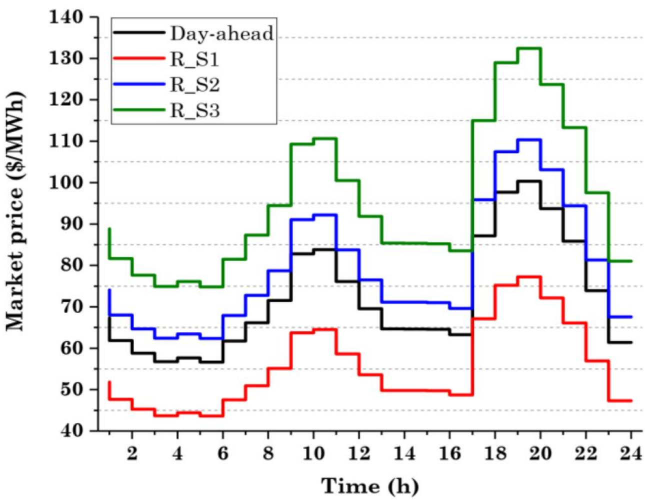

FIGURE 3 Day-ahead and real-time market prices for each scenario

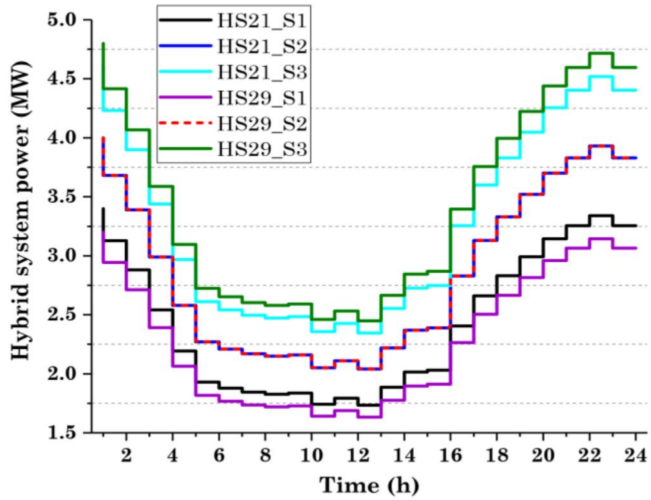

FIGURE 4 PV and wind power generation scenarios

$$P_{loss} = \sum_{t=1}^{NT} \sum_{i=1}^{NB} \sum_{j=1}^{NB} r_{ij} \cdot \left(\frac{P_{ij,t,s}^2 + Q_{ij,t,s}^2}{V_{i,t,s}^2} \right), \ \forall s \in NS \quad (19)$$

The results of this table confirm the effectiveness of the proposed method in improving the distribution grid's performance.

3.2 | Modified 69-bus distribution test system

The modified 69-bus distribution test system is considered to evaluate the presented stochastic strategy in a large-scale power system. The single-line diagram of the modified test system is illustrated in Figure 7. The test system includes 68 sectionalising switches shown by solid lines and five tie switches shown by dotted lines. The system has a rated voltage of 12.66 kV, and the base value of power is equal to 100 MVA. Also, the voltage variation ranges for the system's buses are between 0.9 and 1.05 p.u. The required data of the 69-bus distribution test system are given in [33]. Four hybrid renewable energy systems are assumed to be installed in buses 47, 59, 23, and 35. Each of these hybrid systems includes one WT and one PV source. The installed capacity of each renewable source and the day-ahead and real-time electricity market prices are considered to be similar to the 33-bus test system. In addition, the previously defined case studies for the modified 33-bus test system are included in this test system.

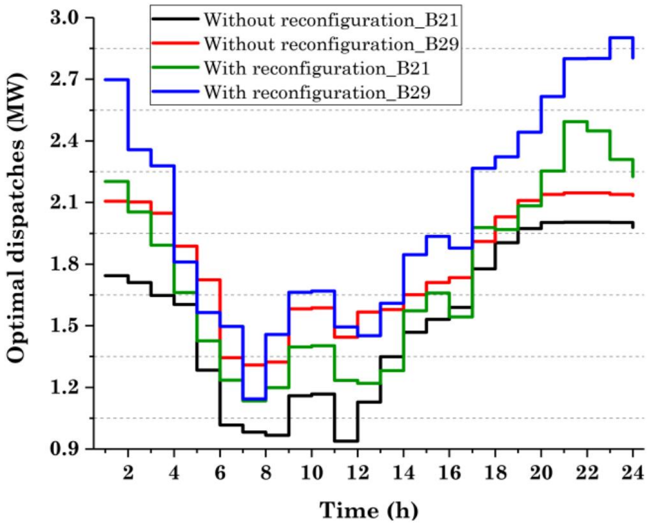

FIGURE 5 Optimal bilateral dispatches in the day-ahead electricity market

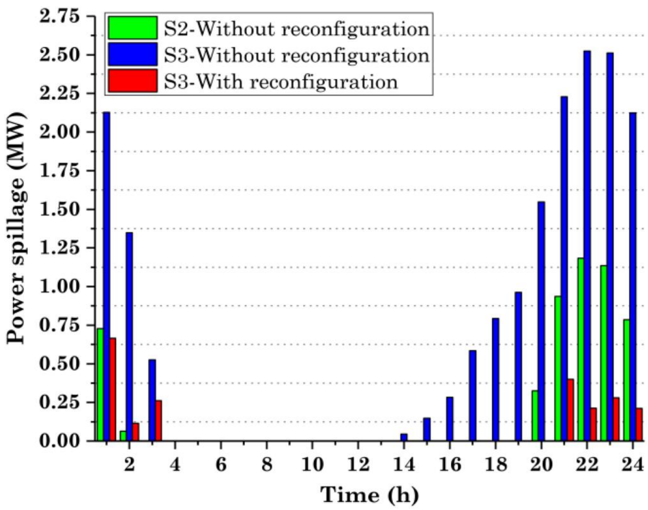

FIGURE 6 Hybrid system power spillage for each scenario

The economic and technical impacts of the use of high-power renewable sources in the coordination with the reconfiguration mechanism from the perspective of the hybrid system owner and ADNs operator are given in Tables 5 and 6. The simulation results show that the optimal utilisation of the hybrid renewable energy systems under the reconfiguration mechanism increases the hybrid systems owners' profit. Furthermore, according to Table 6, a comparison of the different conditions indicates that employing the hybrid renewable energy system (i.e. considering the high-power wind turbines and PV systems) can decrease the active power loss from 8.836 MW up to 5.042 MW as well as improve the average voltage magnitude from 0.924 up to 0.943 depending on the various renewable power generation scenarios. Meanwhile, the use of the reconfiguration mechanism in the framework of the presented stochastic strategy can significantly decrease the active power loss up to 3.101 MW as well as improve the average voltage magnitude up to 0.969.

TABLE 2 Opened switches in the reconfiguration process in the 33-bus test system

Hour	Open switches
1–5	S2, S22, S35, S36, S13
6–8	S2, S22, S35, S36, S14
9–12	S2, S22, S35, S36, S13
13–24	S2, S22, S35, S36, S14

TABLE 3 Hybrid system owner's profit in different cases in the 33-bus test system

	Case 1	Case 2
Sold power in day-ahead market ($)	5863.504	6682.433
Sold power in real-time market ($)	3992.696	3841.567
Switching cost ($)	–	7
Profit ($)	**9856.2**	**10,517**

3.3 | Sensitivity analysis

The sensitivity of the hybrid system owner's profit to the amount of installed capacity of RESs in case study 2 is shown in Figure 8. Accordingly, the initial installed capacity of RESs, which is equal to 5 MW in the 33-bus test system and 10 MW in the 69-bus test system, is multiplied by the coefficients change from 0.4 to 1.6 applying 12 equal steps. As can be seen from this figure, the hybrid systems' profit is increased linearly up to values close to the 1.2 of the initial capacity. However, there are no changes in the hybrid systems' profit by increasing the amount of installed capacity to more than 1.2 of the initial capacity. These results indicate that the 33-bus and the 69-bus test systems can host approximately 6.5 and 12 MW of RESs, respectively, based on the specified demand and physical characteristics of ADNs.

4 | CONCLUSION AND FUTURE WORK

A stochastic architecture is proposed herein for the joint allocation of high penetration levels of hybrid renewable energy systems, including wind farms and PV systems, and reconfigurable ADNs. The proposed structure was evaluated using different case studies from the perspective of the ADN operator and also the hybrid system owner in which the profit of the hybrid system owner was maximised and technical parameters of the ADN were improved. Numerical results show that the proposed model was able to maximise the system owner's profit by minimising renewable power spillage. In addition to the positive impact of the optimal reconfiguration method on the hybrid system owner's profit, important features of the distribution network such as active power loss and average voltage were also improved. The key findings from the simulation results can be summarised as follows.

The experimental results of the 33-bus distribution test system show that: (a) the reconfiguration mechanism is effective in reducing renewable power curtailment. The total renewable power curtailment was reduced from 22.914 MW to 2.148 MW. (b) The profit of the hybrid system owner was increased by up to $10,517 in the framework of the presented structure compared to the case without the reconfiguration mechanism, which had a total profit of $9856.2. (c) In the situation that the proposed stochastic strategy was employed, the total active power loss was decreased by up to 75.58% compared to the initial status of the ADN. (d) The sensitivity analysis proved that the optimisation results were significantly influenced by the installed capacity of the WT and PV source.

TABLE 4 Evaluating the effect of the proposed structure on ADN's features in the 33-bus test system

	Base case	S. no.	Case 1	Case 2
Active power loss (MW)	4.214	S1	2.817	**1.029**
V_{avg} (p.u.)	0.949		0.966	**0.987**
Active power loss (MW)	4.214	S2	3.069	1.198
V_{avg} (p.u.)	0.949		0.961	0.982
Active power loss (MW)	4.214	S3	3.381	1.672
V_{avg} (p.u.)	0.949		0.958	0.976

Notes: The bold numbers are related to the best case study that has improved system performance.

Abbreviation: ADN, active distribution network.

The experimental results of the 69-bus distribution test system show that: (a) the profit of the hybrid system owner was increased by up to 15.17% in the presence of the reconfiguration mechanism compared to case study 1. (b) The total active power loss was decreased by up to 3.101 MW using the presented structure compared to the initial status of the ADN, which had a total power loss of 8.836 MW.

The proposed stochastic optimisation programme could be extended by considering the demand response programmes as a decisive tool in advancing the targets of the distribution network operator based on the technological activities of subscribers. It should be mentioned that the reliability indices were ignored due to the particular emphasis on economic issues, but the role of reliability analysis on the proposed structure could be examined in future studies.

In order to make the proposed design more practical, it is necessary to use the phase coordinates model to take into account the unbalanced nature of ADNs. By doing so, the distribution network operator will be able to incorporate various protection issues such as short-circuit current calculation, protection coordination, and reliability requirements within the proposed structure. Although the use of the phase coordinates model will help the technical analysis of the AND, the development of the proposed structure to form an unbalanced network will greatly increase the complexity of the optimisation programme. Protection issues cannot be easily incorporated into optimisation models, therefore, in order to

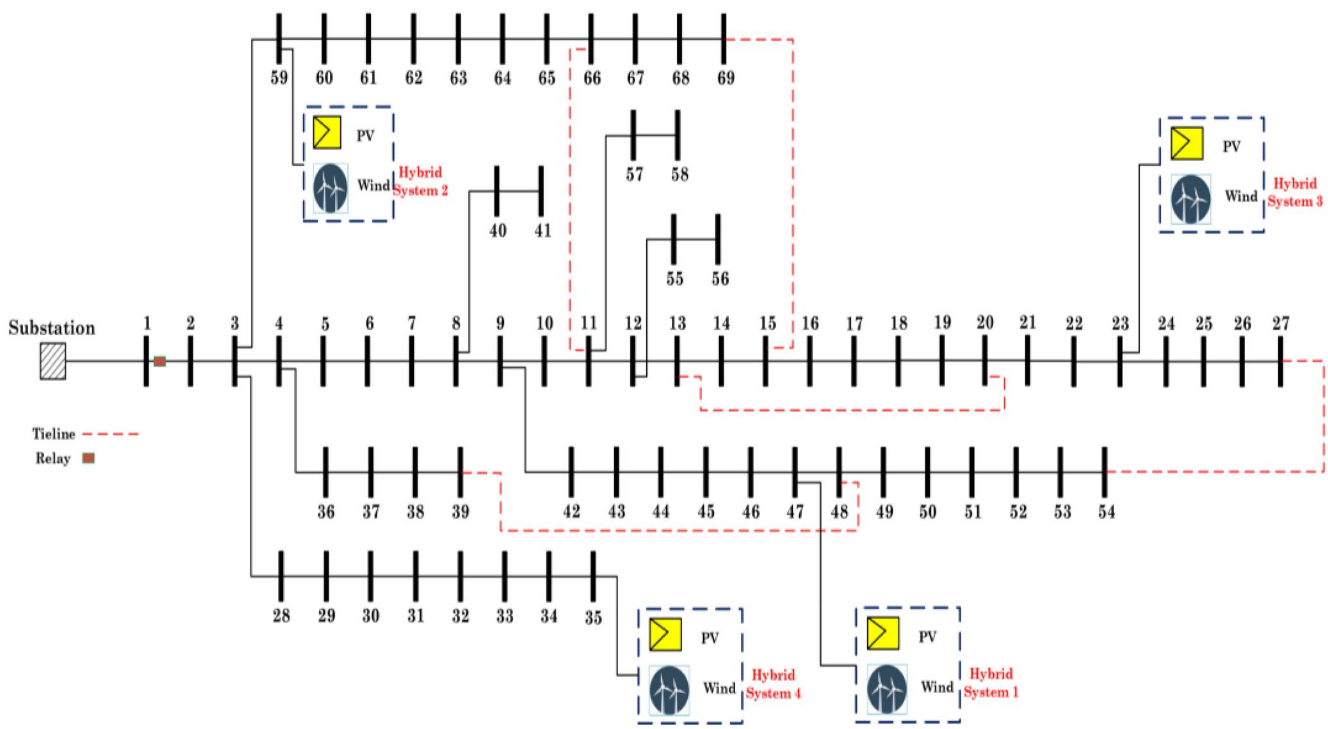

FIGURE 7 Topology of the modified 69-bus distribution test system

TABLE 5 Hybrid system owner's profit in different cases in the 69-bus test system

	Case 1	Case 2
Sold power in day-ahead market ($)	21,812.234	27,197.502
Sold power in real-time market ($)	14,963.675	15,166.107
Switching cost ($)	-	10
Profit ($)	**36,775.909**	**42,356.609**

TABLE 6 Evaluating the effect of the proposed structure on ADN's features in the 69-bus test system

	Base case	S. no.	Case 1	Case 2
Active power loss (MW)	8.836	S1	5.042	**3.101**
V_{avg} (p.u.)	0.924		0.943	**0.969**
Active power loss (MW)	8.836	S2	6.796	3.574
V_{avg} (p.u.)	0.924		0.935	0.961
Active power loss (MW)	8.836	S3	6.017	4.08
V_{avg} (p.u.)	0.924		0.94	0.955

Notes: The bold numbers are related to the best case study that has improved system performance.

Abbreviation: ADN, active distribution network.

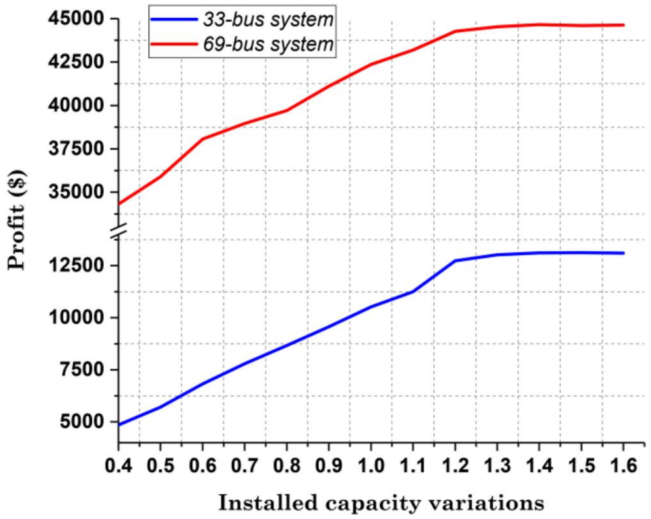

FIGURE 8 Sensitivity of hybrid systems' profit to the installed capacity of renewable energy sources in case study 2

extend the proposed structure in the form of the unbalanced ADN, the nature of the optimisation problem in general must be changed.

NOMENCLATURE

Indices (sets)

i, j (NB) Indices of buses. Note that '*mg*' is substation bus.
s (NS) Index of scenarios;
t (NT) Index of time horizon.

Parameters:

M Large positive number;
PH_i^{max} Maximum capacity of hybrid system at bus i (MW);
$P_{i,t,s}^{pv}$ Hourly power production of PV system at bus i in s-th scenario (MW);
$P_{i,t,s}^{wind}$ Hourly power production of wind turbine at bus i in s-th scenario (MW);
$P_{i,t,s}^{load}$, $Q_{i,t,s}^{load}$ Hourly active/reactive power consumption at bus i in s-th scenario (MW/MVAr);
P_{ij}^{max} Upper limit of active power between bus i and j (MW);
P_{ij}^{min} Lower limit of active power between bus i and j (MW);
Q_{ij}^{max} Upper limit of reactive power between bus i and j (MVAr);
Q_{ij}^{min} Lower limit of reactive power between bus i and j (MVAr);
SW^{max} Maximum number of switching operations;
V^{max} Upper limit of voltage magnitude;
V^{min} Lower limit of voltage magnitude;
Y_{ij} Magnitude of admittance between bus i and j;
λ_t^D The day-ahead market price at time t ($/MWh)
$\lambda_{t,s}^R$ The real-time market price at time t in s-th scenario ($/MWh);
λ^{SW} Price of each switching operations ($);
$\prod_s$ Probability of each scenario;
θ_{ij} Phase of admittance between bus i and j.

Variables and functions:

$CO_{t,s}$ The hourly cost of switching operations in s-th scenario ($);
$P_{i,t,s}^{spill}$ Hourly power spillage of hybrid system at bus i in s-th scenario (MW);
$P_{mg,t,s}^{G\_S}$ Hourly active power sold to substation bus in s-th scenario (MW);
$P_{ij,t,s}$, $Q_{ij,t,s}$ Active/reactive power flow of line ij at time t in s-th scenario (MW/MVAr);
$P_{mg,t,s}^{G\_I}$, $Q_{mg,t,s}^{G\_I}$ Hourly active/reactive power purchased from substation bus in s-th scenario (MW/MVAr);
$PC_{i,t}$ Hourly optimal bilateral dispatch at bus i (MW);
$RE_{t,s}$ Hourly revenue of power sold to distribution network in s-th scenario ($);
$V_{i,t,s}$ Voltage magnitude of bus i at time t in s-th scenario.
V_{avg} The average voltage level of the ADN during the scheduling period.

$\delta_{i,t,s}$	Phase angle of bus i at time t in s-th scenario.
$a_{ij,t}$	Binary variable; 1 if the line ij is connected, and 0 otherwise;
EPF	Expected profit of hybrid system.

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