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Two-Level Optimisation and Control Strategy for Unbalanced Active Distribution Systems Management

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ABSTRACT This article proposes a new approach to the operation of unbalanced Active Distribution Systems (ADS) using an economic dispatch optimisation model for Active Distribution Systems Management (ADSM). The model proposes a two-level control strategy. The first one poses an optimisation problem with the objective of minimising total active power losses in the ADS and the second one proposes an algorithm that controls the position of the taps of three-phase on-load tap-changer (OLTC) transformers to ensure compliance with the technical constraints imposed by the Distribution System Operator (DSO). The optimisation problem is solved by MATLAB® and DIgSILENT PowerFactory® for power systems static simulations. This paper includes a novel peer to peer communication framework between MATLAB®/DIgSILENT®. The control and optimisation strategy is validated on the IEEE 34-Node Distribution Test Feeder. This network incorporates balanced and unbalanced three-phase loads, single-phase loads in the different phases, and two-phase loads. In this scientific paper, photovoltaic (PV) and wind power generation (WT) have been integrated to test feeder operation, with the support of battery energy storage systems (BESS). The correct operation of the proposed ADSM is demonstrated using numerical simulation on five scenarios considering several configurations of the renewable generation units and the batteries. The strategy has also been validated in a more extensive distribution network, proving its good performance.

INDEX TERMS Distributed generation, active distribution systems, active distribution systems management, economic dispatch.

NOMENCLATURE

ACRONYMS

ADS	Active Distribution System
ADSM	Active Distribution System Management
BESS	Battery Energy Storage System
DER	Distributed Energy Resources
DR	Demand Response
DSO	Distribution System Operator
ED	Economic Dispatch
ESS	Energy Storage Systems
DG	Distributed Generation
PV	photovoltaic unit
OLTC	On-Load Tap-Changer
OPF	Optimal Power Flow
RES	Renewable Energy Systems
WT	Wind Turbine
SOC	State Of Charge

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PARAMETERS

C_t^{Ext}	Operation and maintenance cost of external grid at time t
C_t^{BESS}	Power generation cost of battery at time t
I_{max}^{kj}	Maximun current of branch kj
P_{max}^{i}	Maximum generation capacity of unit i
P_{min}^{i}	Minimum generation capacity of unit i
P_{max}^{c}	Maximum charging rate of the BESS
P_{max}^{d}	Maximum discharging rate of the BESS
SOC_{max}^{i}	Maximum state of charge of the BESS i
SOC_{min}^{i}	Minimum state of charge of the BESS i
η_c	Battery charging efficiency
η_d	Battery discharging efficiency
P_t^{Dem}	Power demanded at time t

VARIABLES

P_t^i	Power given by unit i at time t
SOC_t^i	State of charge of the BESS i at time t
P_t^{Loss}	Power losses at time t
V_t^k	Voltage of node k at time t
I_t^{kj}	Current of branch kj at time t

I. INTRODUCTION

A. MOTIVATION

In recent years, there has been a greater awareness among the world's population of the need for public administrations to develop more sustainable economic development models for their countries [1]. This demand is justified by the growing demand for energy for domestic use and economic activities related to trade, industry and transport [2], causing an increase in greenhouse gas emissions and the depletion of fossil fuels [3]. As a consequence of these policies, electric power systems are making a transition from a centralised network, composed of large, controllable power plants, which transport electric power over long distances and downwards, to a decentralised grid based on increasing the penetration of renewable energy systems (RES) [4], [5]. This process introduces a new paradigm in the future of the electricity sector in favour of decarbonisation [6]. Currently, 20% of total electricity generation in the world is obtained from non-conventional or alternative energy sources [7]. In this context, the transformation of existing electricity grids into the intelligent electricity grids of the future depends to a large extent on the level of deployment of generation and storage resources distributed within the electricity systems [8], [9]. The specialised literature recognises this new approach to generating and transporting electrical energy, as Distributed Generation (DG) [10]. Although the concept of DG has been used repeatedly in different scientific publications, its definition is still a matter of discussion. It has been described as a small-scale generation, mainly from renewable energy sources and close to the load it feeds [8], [11]. Other authors argue that it can include conventional generation on a larger scale, connected to any part of the Distribution System [12]. The European Union (EU) distinguishes between DG and Distributed Energy Resources (DERs). The first refers to generation plants connected to the Distribution System [13], [14] and the second comprises DG, demand response (DR) and energy storage systems (ESS) [15]. Therefore, due to the widespread deployment of distributed energy resources and the liberalisation of the electricity market, traditional distribution networks are undergoing a transition to Active Distribution Systems (ADSs) [16]–[19]. There are multiple benefits attributed to the presence of the DERs in the operation of these grids, environmental benefits associated with a reduction of greenhouse gas emissions [20], [21], by using renewable energy sources, reduction of losses in the grid [22], [23], if the DG is connected close to consumption, improvement in the voltage profile [24], [25], especially in long lines due to the contribution of active power from these sources, among others. It should be noted that these technical services to the network can only be obtained by selecting the size, type of technology, volume and optimal location of the generation and storage resources. On the other hand, when considering the radial nature of medium voltage distribution grids, the impacts produced by the DERs are fundamentally due to the modification suffered by power flows, both in magnitude and direction, causing problems of a technical and regulatory nature, associated with losses, investments, voltage profile, quality of service, stability, etc [10]. Currently, the increasing installation of renewable energy sources, such as wind and photovoltaic energy, with energy storage systems, makes the management of ADSs even more complicated, due to the variable nature of renewable energy resources, which causes increased volatility in the electricity system [26], and therefore imposes significant technical and regulatory challenges in the future.

Currently, the electricity sector regulation does not allow the DSO to own or operate generation or storage resources in the networks. However, it is clearly accepted that it is necessary to provide the DSO with the capacity to operate the generation and storage resources in its networks, either through specific bilateral contracts, or through the installation of its own resources in duly justified cases (reinforcement of the grid), in order to maximize the penetration of RESs in the distribution networks [27]. This paper assumes that the DSO has control over the storage devices present in the ADS.

This paper proposes an economic dispatch (ED) optimisation model for ADSMs, to achieve the integrated management of the DERs and the control means available to the DSO in an active unbalanced real-time network with high penetration of RESs and BESSs. The main objective is to minimise the losses in the unbalanced ADS making use of the control resources available, including storage devices, while increasing the penetration of distributed renewable energies by enforcing compliance with operating limits [28]. Note that the objective may change to minimise the cost of imported energy from the main grid at the PCC (point of common coupling) in the case of the microgrid operator.

B. RELATED WORK

Distribution System Operators (DSO) are currently paying more attention to optimal energy management in medium and low voltage networks [29]. ADSMs participate in the optimal operation of both controllable and renewable distributed generation sources and energy storage systems, following an economic criterion, while satisfying the technical limitations of the network and energy resources.

Optimal operation of the ADSs can be programmed in a time interval, generally from one to three days ahead, depending on forecasts of the RESs, load demand and taking into account economic and technical aspects [30]. In the approach to the optimisation problem, minimising the total cost of purchasing electricity is generally considered as an objective [31], [32]. Following this criterion, it can be observed that most mathematical formulations propose to maximise the share of RESs in the total energy consumption, as one of the main objectives in the operation of ADSs, [33]–[35].

However, in medium and low voltage networks, the ratio R/X is high, which implies a greater sensitivity of voltage fluctuations to active power injections of distributed generation resources [36]. For this reason, the mathematical formulation of the problem also incorporates the objective of minimising power losses avoiding at the same time violations of voltage limits [37]–[39]. The fact that RESs participate in voltage regulation and cost minimisation, causes DSOs to alter the traditional operation of distribution networks to an active operation approach (ADSs) [40], [41]. For this purpose, objective functions are proposed to minimise, in addition to losses, the total operating costs of the ADSs [42], [43]. A different approach is proposed in [44], where a stochastic control of the reactive power injection of the inverters of the photovoltaic (PV) generators is proposed to help minimise losses. To do this, it proposes an auxiliary voltage regulation market, where PV owners receive financial incentives for providing reactive power support. Other studies suggest optimisation models based on gains in which uncertainties are taken into account [45], [46].

Therefore, from the above comments, it can be stated that the operation of ADSs simultaneously and optimally manages active and reactive power flows in the daily schedule, incorporating constraints (and penalties in the objective function), for the minimisation of active power losses, the cost of electricity imported from the main grid, operating costs or the minimisation of greenhouse gas emissions [29], [47]. Some authors propose a two-stage programming method. In the first stage, the aim is to minimise the total cost of electricity generation in order to meet demand. In the second stage, corrective scheduling is proposed to enforce the technical constraints of ADS [28], [48]. This approach enables the DSO to facilitate the participation of DG owners in the daily and intra-day electricity market and, therefore, maximise the profits of the distribution company [49]–[51]. In the literature review carried out, it can be seen that the Optimal Power Flow (OPF) and the Economic Dispatch are among the most used tools to analyse the planning, operation and future development of the ADSs [30]. According to [52], most of the proposed optimisation models, due to the nonlinear characteristics of the power flow equations and the non-linearity of the fuel cost curves of the unconventional generation units are posed as a mixed-integer nonlinear programming problem (MINLP). The multiple decision variables and restrictions increase the difficulty to solve this type of problem. To address them, the main optimisation methods used can be divided into two categories: numerical methods and heuristic algorithms. [52]. The most used traditional optimisation algorithms, using numerical methods are: quadratic programming [53], Newton Raphson [54], Interior Point Methods [33], [55]. Mathematical optimisation techniques include: Semi-definite Programming (SDP) [56], the Second-Order Cone Programming (SOCP) [57], among others. The use of numerical method based software packages, CPLEX®, GUROBI® are adopted in [37], [58]. Heuristic algorithms mainly include Genetic Algorithms [32], [42], Tabu Search [59], Particle Swarm Optimisation [39], etc.

C. CONTRIBUTIONS

The main contribution of this paper regarding previous proposals is a new ED optimisation approach for ADSM based on a two-level control strategy and its validation using different DERs penetration scenarios.

Other contributions are:

- The goal of maximising social welfare [60] in ADSM schemes is taken into account in several recent publications. Within this framework, this paper proposes the use of ED with the aim of minimising the active power losses of ADS, while maximising the power delivery of the available DERs and therefore decreasing the contribution of the external grid.
- A dynamic OLTC control algorithm is incorporated, which means that the voltage per phase in the secondary of the two OLTCs can be treated as a decision variable and not as a fixed parameter.
- The ED approach for ADSM is implemented in a joint simulation platform MATLAB®-DIgSILENT®, using Peer-to-Peer communication between them.
- Validation in the IEEE 34-Node Test Feeder Model. RESs and BESSs are incorporated, which transform this network into an ADS. The power system under study is modelled in DIgSILENT®, and the optimisation algorithm is implemented in MATLAB® using a nonlinear convex optimisation algorithm.

D. PAPER ORGANISATION

The rest of the paper is organised as follows: Section II provides an explicit formulation and discussion of the optimisation and control strategy for ADSM, while section III focuses on developing the electrical model considered for each of the components of the system. Section IV provides an

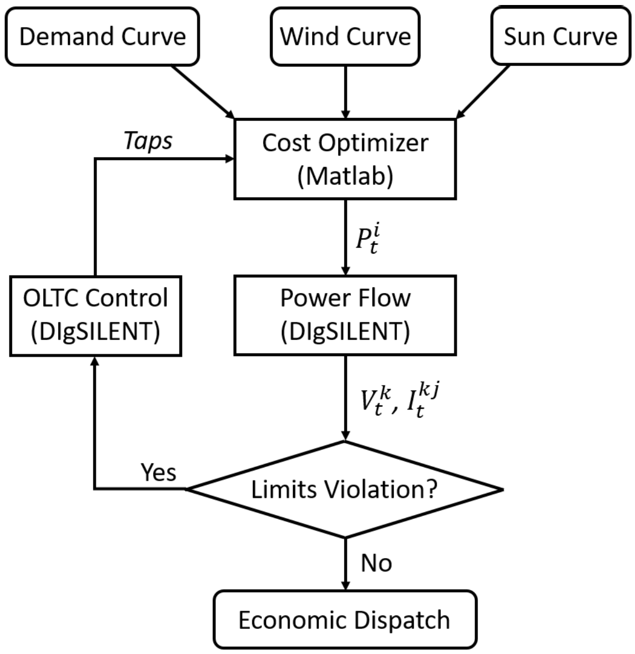


FIGURE 1. Optimal active power planning strategy flowchart.

application of the proposed method to the IEEE 34-Node Test Feeder under different DG penetration scenarios, showing the level of improvement obtained in each case. Conclusions are summarised in section V.

II. OPTIMISATION AND CONTROL STRATEGY

Based on the discussions mentioned above, this article explores optimal energy management in distribution networks that operate in medium voltage. The electrical power systems generally operate radially [61] and with the presence of imbalances in voltages and currents, caused by the uneven distribution of load between the phases [62]. Imbalances are worsened by the presence of DERs (RESs and EESs) [29], [63]. Renewable energy sources are affected by weather conditions and cause intermittent operation. The changes that are currently taking place in Medium Voltage (MV) networks to become ADS, make their operation even more complex. For this reason, the DSO currently pays more attention to the control of the MV networks.

A. MODELING APPROACH

This paper proposes a new ED approach for ADSMs based on a two-level control and optimisation strategy. The proposed model is formulated to schedule DSO load sharing between available generation resources, external grid, RESs and BESSs, while satisfying technical and economic constraints, over a 15 minutes time horizon. The flowchart of the proposed optimal active power planning strategy is shown in Figure 1.

The proposed two-level control scheme has been implemented in a joint simulation platform of two Matlab-DIgSILENT PowerFactory software applied to IEEE 34-Node Test Feeder, which is shown in Figure 2. The first, proposes an optimisation problem to minimise ADS active power losses by enforcing the technical constraints of the network avoiding overloads, voltage problems, by phase. The optimisation problem is formulated in equation (2) and is subject to the constraints imposed by equations (7)-(15). The equation (7) represents the power balance. The maximum and minimum power limits of the generation units, external network, BESSs, PVs and WT are represented by the equations from (8) to (11). The maximum and minimum limits of the state of charge of the BESSs (SOC) are imposed on (12) and SOC is defined by (13). Additionally, in the equations (14) and (15) the technical restrictions of network operation are expressed, associated with the voltages at the nodes and the currents in the lines.

The decision variables at this level are the power injected by the external network and the BESSs. This control level considers as input variables the most probable demand and generation of the photovoltaic and wind generators installed in the grid, in 15 minutes.

Hierarchically, this is the highest level. Below this, another level of control is implemented to ensure that losses in the network are kept to a minimum and that the phase voltages are kept within the operating ranges acceptable to the DSO. Control variables at this level are the on-load tap positions of two three-phase transformers (OLTC) present in the network. Figure 2 also shows the flow of information between the two levels of control. The first level transfers the results to the second level and this changes the TAPS of the two transformers, based on the solution provided by the simulation of unbalanced power flows. The first level was implemented in MATLAB® and the second level using PowerFactory DPL language in DIgSILENT®. Peer-to-peer communication is used between both platforms.

B. OBJECTIVE FUNCTION

Based on the proposals presented in [29] and [64], this study formulates the optimisation problem with the aim of minimising the total active power losses in ADS. This objective aims at maximising the use of RESs and BESSs, either to satisfy local demand or to export energy from ADS [33]. The problem is formulated with the equation expressed in (1).

$$min\left(P_t^{Loss}\right) = min\left(P_t^{Ext} + P_t^{BESS_i} + P_t^{PV_i} + \right. \\ \left. + P_t^{WT} - P_t^{Dem}\right) \quad \forall t \in [1, 96]. \quad (1)$$

To minimise losses, costs must be assigned to power terms, which are control variables. In this work, the generation costs of the external grid $\left(C_t^{Ext}\right)$ and the operation costs of the BESS $\left(C_t^{BESS}\right)$ at interval time t, are considered. In this sense, the external grid can be a transmission network, or a higher voltage distribution network. Neither the generation costs of the RESs nor the operation costs of the OLTCs are considered. Therefore, the objective function to optimise in this problem is to minimise the costs of total active power losses. The cost

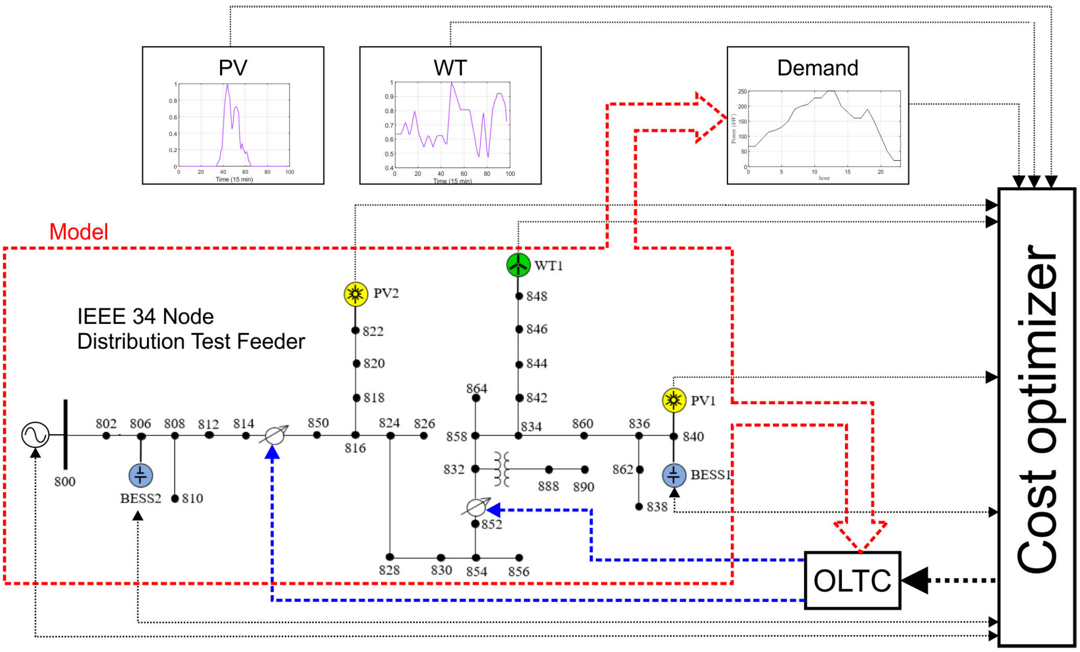


FIGURE 2. Optimisation and control strategy.

function is defined as (2).

$$min\ C_t^{Loss} = C_t^{Ext} + C_t^{BESS} \tag{2}$$

Two main components are considered in this cost function: the cost of energy associated with the external network and the costs of battery energy storage systems (BEES).

$$C_t^{Ext} = C_{Ext}\left(P_t^{Ext}\right) \tag{3}$$

$$C_t^{BESS} = C_{BESS}\left(P_t^{BESS}\right) \tag{4}$$

The cost of the energy imported from external network C_{Ext}, is considered proportional to the average power at the interval time t, P_t^{Ext}, and the cost of the BESSs, C_{BESS} is assumed as in [65]. The problem is formulated as a non-linear programming problem and is solved with an Interior Point Methods algorithm.

C. OLTC CONTROL ALGORITHM

The algorithm for changing the taps (**Algorithm 1**) is executed for each transformer and each phase. The OLTC control modifies the taps if the voltages exceed a value of V_{max} or are lower than V_{min}.

The variables of the first control level are optimised without considering the operational constraints. The second level of control (OLTC) improves the optimisation by controlling the voltages at the nodes by adjusting taps on various power flows. This control algorithm is very fast in decision making and has a low computation cost, and no additional resources are used other than those of the network. This allows the distributed implementation of the second level of control in local controllers (PLCs, etc.). In [66], a more advanced algorithm has been proposed, which controls the voltages, by injecting reactive power from capacitors and inverters. In that case, the authors formulated a non-convex optimisation problem and generally NP-Hard with a large number of variables, avoiding a high computational cost, by using a DRL technique. However, in that case, additional resources are required (capacitor banks and inverters), in addition to a great effort of design and time, highly dependent on the nature and configuration of each network in which it is applied.

Algorithm 1 OLTC Control Algorithm

while *Vcheck=0* **do**
  if $V < V_{min}$ **then**
    if $TAP < TAP_{max}$ **then**
      TAP=TAP+1;
      make Power Flow;
    else
      Vcheck=1;
  if $V > V_{max}$ **then**
    if $TAP > TAP_{min}$ **then**
      TAP=TAP-1;
      make Power Flow;
    else
      Vcheck=1;
  if $V \geq V_{min}$ **then**
    if $V \leq V_{max}$ **then**
      Vcheck=1;

D. PEER-TO-PEER MATLAB®-POWERFACTORY® COMMUNICATION

This article presents the Peer-to-peer (P2P) method for joining MATLAB® and DIgSILENT® PowerFactory, using an

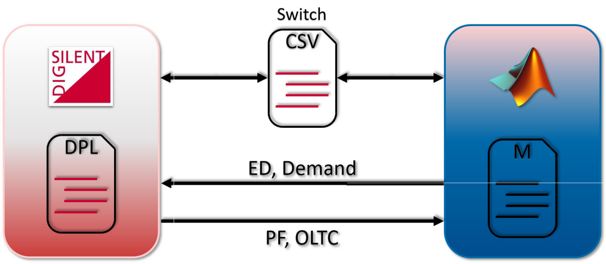


FIGURE 3. Automatic data exchange between MATLAB® and DigSILENT®.

TABLE 1. Priority order of integration of RESs and BESSs.

DERs installation priority			Bars to install DERs	Type DERs	
Branches (i)	$P_{Load,i}$ (p.u.)	$\frac{P_{Load,i}}{P_{Dem}}$ (%)	Node	three-phase	single-phase
834-848	0,62	34,81	848	WP	
834-840	0,36	20,10	840	PV1 BESS1	
816-822	0,1715	9,71	822		PV2
			806	BESS2	

interface where each tool places and stores *csv* files, allowing the exchange of data files between both. The power system under study is modelled in PowerFactory and the optimisation algorithm is implemented in MATLAB®, getting voltage and current values from DIgSILENT® after power flow analysis.

The real-time optimisation is carried out by MATLAB® and DigSILENT®. Initially, MATLAB® should get the initial values of voltages and currents of each bus bar. Then, an optimisation process starts running in MATLAB®, iteratively checking the values of voltages/currents by means of a power flow calculation in DIgSILENT®. When the optimisation process finishes, the value (calculate by MATLAB®) is given to DIgSILENT®. The process is shown in Figure 3.

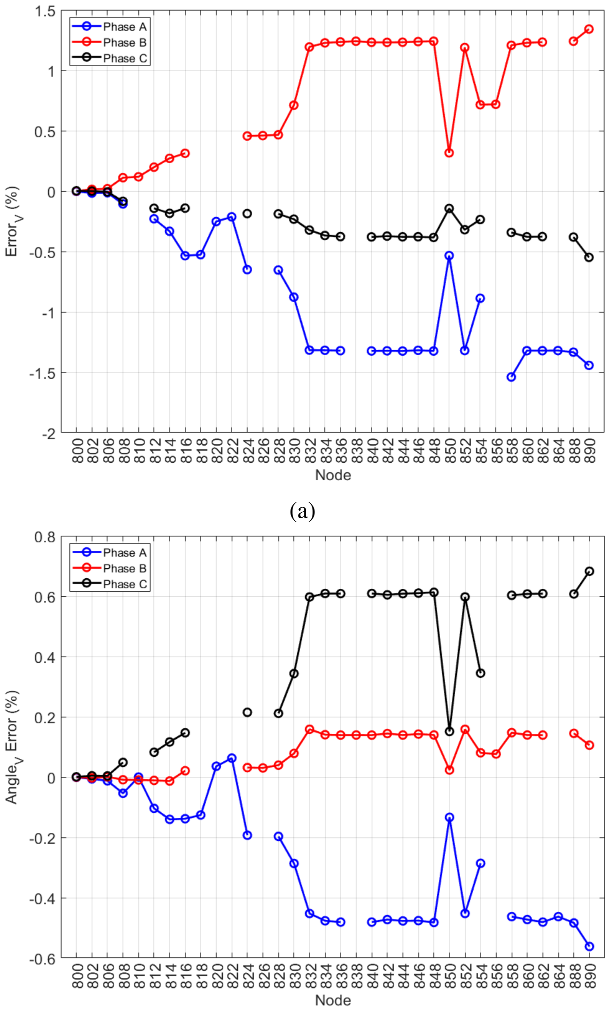
III. SYSTEM MODELING

This section presents the data and characteristics of the MV distribution network used as a case study, which does not originally have DERs. For its use in this paper, renewable energy sources and BESSs have been incorporated, with the aim of giving it an ADS character. Therefore, information is also given on the models used for each component of the network. These models and their limitations will define the constraints of the cost function expressed in (2).

A. CASE STUDY

The test network used in this work was the IEEE 34-Node Test Feeder, which according to [67] can cause convergence issues in power flow studies due to its length and load unbalance. The IEEE 34-Node Test Feeder represents an actual feeder in Arizona, and displays a wide variety of components and topological features [68], which are representative of a typical rural distribution network with single and three-phase laterals and long feeders which could incorporate distributed generation. This distribution network is operated at 24.9 kV and has two voltage regulators, two capacitor banks and one low voltage lateral at 4.16 kV. The substation is rated at 2500 kVA, with a 69 kV/24.9 kV transformer.

- Modeling Considerations
  The network model has been implemented in DIgSILENT® (PowerFactory), taking into account the data of each component provided in [67]. The lines are modelled considering their geometric configuration, which is defined by the type of towers and the type of conductor. In this case, there are five-line configurations that are a combination of two types of towers (500 and 510) and three types of ACSR cables (1/0, #2 6/1, #4 6/1). In the system there are two types of loads, spot and distributed. The first ones are located in the corresponding node and the second ones are modelled as a point load located in the centre of the line.
  The network presents significant imbalances, with the presence of balanced and unbalanced three-phase loads, which can be connected in star or delta, as well as single-phase loads, some connected from line to line and others from line to ground. The representation of the loads in the software, in addition to taking into account their characteristics, includes the models of impedance, current or constant power, as appropriate. The two voltage regulators are modelled as single-phase transformer bank.
- IEEE 34-Node Test Feeder Model Validation
  DIgSILENT® PowerFactory's unbalanced mode load flow tool is used to check the status of the network at the point of operation under study. All voltages are checked to be within the range of 0.95 pu and 1.05 pu. The results obtained were compared with those provided by the IEEE 34-Node Test Feeder [67]. The percentage difference in the magnitude of voltage and angles of each phase does not exceed 1.5% and 0.7% respectively. The results are shown in Figure 4 and the model is considered validated.
- Distributed Energy Resources
  This network does not contain distributed generation sources. In order to achieve the objectives proposed in this work, it is proposed to incorporate RESs and BESSs. As a criterion for defining the installation priority of DERs, the ratio between the value of the local power demand in the different branches ($P_{Load,i}$) that make up the network, with respect to the total network power demand (P_{Dem}), has been taken. The units are placed from the side with the highest power to the side with the lowest power. Table 1 shows the results of applying the load priority criterion. Three possible locations are considered and the bars where the DERs are connected (WT, PVs and BESSs) are also reported. This decision represents a low DG dispersion scenario, since the installation of DG in four nodes of the system represents



(a)

(b)

FIGURE 4. **Voltage and angles comparation between IEEE 34-Node Test Feeder and DIgSILENT model. (a) Voltage, (b) Angle.**

11.8% of the total nodes. Figure 5 shows IEEE 34-Node Test Feeder with distributed generation incorporated.

B. WIND TURBINE

There exist a high number of publications dealing with the modeling and simulation of wind turbines [69], [70]. For our study, we will consider the sequel simplified model of the generator:

$$P_t^{WT} = \begin{cases} 0 & \text{for } v < v_{ci}, \\ P_r \frac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3} & \text{for } v_{ci} < v < v_r, \\ P_r & \text{for } v_r < v < v_{co}, \\ 0 & \text{for } v > v_{co}, \end{cases} \quad \forall t, \tag{5}$$

where P_r and v_r represent the rated power (kW) and wind speed (m/s), respectively, and v_{ci}, v_{co} and v are the cut-in, cut-out and actual wind speed, respectively. For a more detailed information about the model, reader is referred to [71].

C. PHOTOVOLTAIC GENERATOR

In this work, the simplified model presented in [72] is considered, i.e.,

$$P_t^{PV} = P_{STC} \frac{n \cdot E_{M,t}}{E_{STC}} [1 + k(T_{M,t} - T_{STC})], \quad \forall t, \tag{6}$$

where P_t^{PV} is the output power of the PV plant at time t, $E_{M,t}$ is the solar irradiance at t and P_{STC}, E_{STC} and T_{STC} are the maximum power, the irradiance and the temperature under Standard Test Conditions (STC), respectively. Those values correspond to a cell temperature of 25^oC and an irradiance of $1000\,W/m^2$ with an air mass 1.5. Finally, n denotes the number of PV panels, k the power temperature coefficient ($\%/^oC$) and $T_{M,t}$ is the temperature of the module at time t, which can be calculated as $T_{M,t} = T_{amb} + \varepsilon_{PV} \frac{E_{M,T}}{E_{STC}}$, where T_{amb} is the ambient temperature (^oC) and ε_{PV} is a constant module provided by the manufacturer.

D. POWER BALANCE

The power balance must be zero, that is, the power generated at each moment must be equal to the power consumed, being the power consumed the power demanded by the loads plus the power lost due to the operation of the network. This is expressed in equation (7).

As can be seen from equation (7), the 24 hours of the day have been discretised into 15-minute intervals, giving rise to 96 calculation points. The balance equation can be rewritten as a function of the generation units as observed in equation (7), separating in one term the decision variables of the optimisation algorithm, which decides the power generated or consumed by the batteries, as well as the external grid, and in a second term the rest of the variables. This second term of the equation is important, since depending on the sign of this term, the objective function of the problem changes.

$$P_t^{Ext} + P_t^{BESS_1} + P_t^{BESS_2} = P_t^{Dem} + P_t^{Loss} - P_t^{PV_1} - P_t^{PV_2} - P_t^{WT} \quad \forall t \in [1, 96] \tag{7}$$

E. GENERATION LIMITS

The power of the external grid can be positive, to cover the generation defect of the renewables, or negative if the second term of equation (7) is negative. Wind and photovoltaic generation excessively satisfy the demand of the network under study. In this situation, the batteries must absorb the excess of renewable generation and it would also be absorbed by the external network (negative power), if the batteries had reached some of their power or energy limits. Therefore, the external grid can take any positive and negative value, according to equation (8).

$$-\infty < P_t^{Ext} < \infty \quad , \forall t \in [1, 96] \tag{8}$$

The batteries can work as generators or loads, with positive and negative powers respectively, but without exceeding their limits of generation power and consumption, as shown in the equation (9), where the limits P_{max}^i and P_{min}^i are different

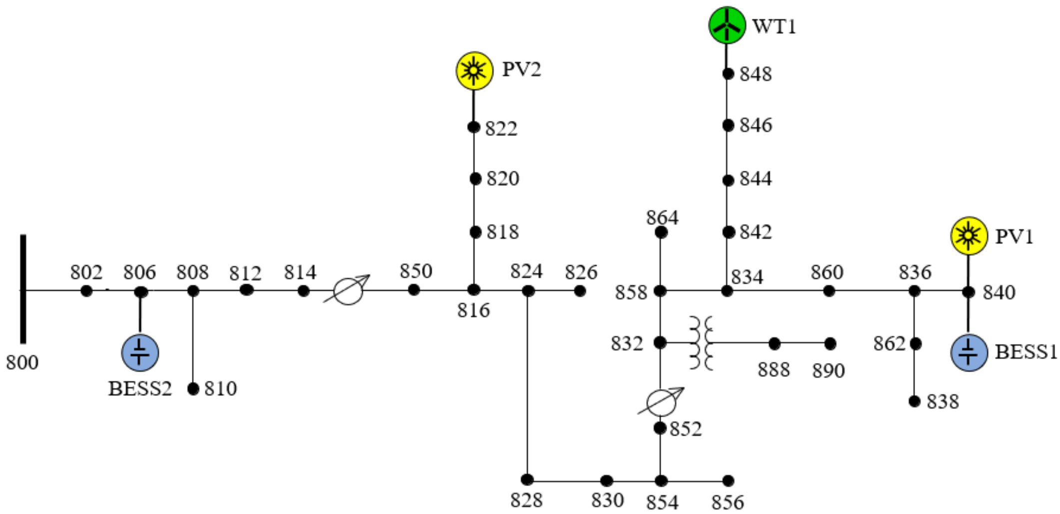


FIGURE 5. IEEE 34-Node Test Feeder with distributed energy resources.

according to the scenario.

$$P^i_{min} \leq P^i_t \leq P^i_{max} \quad \forall t \in [1, 96], \; \forall i \in [BESS_1, BESS_2] \tag{9}$$

photovoltaic generators have a minimum power of zero, in the absence of solar radiation, and a maximum power equal to the nominal power of the generator, so their limits are those expressed in equation (10).

$$0 \leq P^i_t \leq P^i_{max} \quad \forall t \in [1, 96], \; \forall i \in [PV1, PV2] \tag{10}$$

Finally, the wind generator has a maximum power and a positive minimum power that is different from zero. The generation limits are expressed in equation (11).

$$P^{WT}_{min} \leq P^{WT}_t \leq P^{WT}_{max} \quad \forall t \in [1, 96] \tag{11}$$

F. ENERGY STORAGE SYSTEM

The batteries have a maximum and minimum energy storage limit, which must not be exceeded to avoid damage. These restrictions are given in equation (12).

$$SOC^i_{min} \leq SOC^i_t \leq SOC^i_{max} \quad \forall t \in [1, 96], \; \forall i \in [BESS1, BESS2] \tag{12}$$

The batteries can work as a generator or as a consumer, so the stored energy levels are updated at each time sample by means of the power and the operating time through equations (13).

$$SOC^i_t = SOC^i_{t-1} - \begin{cases} \Delta t \cdot P^i_t \cdot \eta_c & \text{for } P^i_t < 0 \\ \frac{\Delta t \cdot P^i_t}{\eta_d} & \text{for } P^i_t > 0, \end{cases} \quad \forall t \in [1, 96], \; \forall i \in [BESS1, BESS2] \tag{13}$$

where η_c and η_d are respectively the charging and discharging efficiency and Δt is the time between samples.

G. GRID OPERATION LIMITS

For correct operation of the grid, the voltages at each node (k) must be within maximum and minimum values, which correspond to $\pm 5\%$ of the nominal voltage. Therefore, this type of constraint is expressed as equation (14):

$$V_{min} \leq V^k_t \leq V_{max} \;\; \forall k, \;\; \forall t \in [1, 96] \tag{14}$$

The network under study has two three-phase transformers with taps on each phase. As we have already seen, an OLTC control has been implemented that acts on the transformer taps to comply with the restrictions of the voltage levels.

Another of the network's operating restrictions is that the line from node (k) to node (j) do not exceed their ampacity value, thus avoiding overloads. These restrictions are expressed by equation (15):

$$0 \leq I^{kj}_t \leq I^{kj}_{max} \;\; \forall kj, \;\; \forall t \in [1, 96] \tag{15}$$

H. DEMAND AND THE RENEWABLE ENERGY FORECASTS

The power demand changes according to the curve shown in Figure 6. photovoltaic and wind generators provide the power as a function of the solar power curve, and the wind power curve (Figure 7).

IV. SIMULATION RESULTS

This section validates the ED optimisation model for ADSM in the IEEE 34-Node Test Feeder with built-in DERs. The ED tool is used to schedule the generation units, with a resolution of 15 minutes. To check the effectiveness of optimisation scheme, five scenarios with different levels of DERs penetration are proposed. The characteristics of these scenarios are shown in Table 2. Where the percentage of DERs penetration is the fraction of the total system load, provided by DERs (P_{DERs}). In this work the penetration level is considered as the ratio of total installed power of distributed generation resources (P_{DERs}) to peak demand power (P_{Load}) [73].

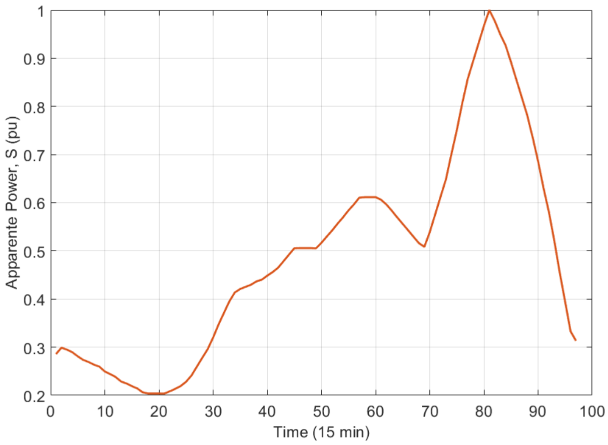


FIGURE 6. Power demand IEEE 34-Node Test Feeder.

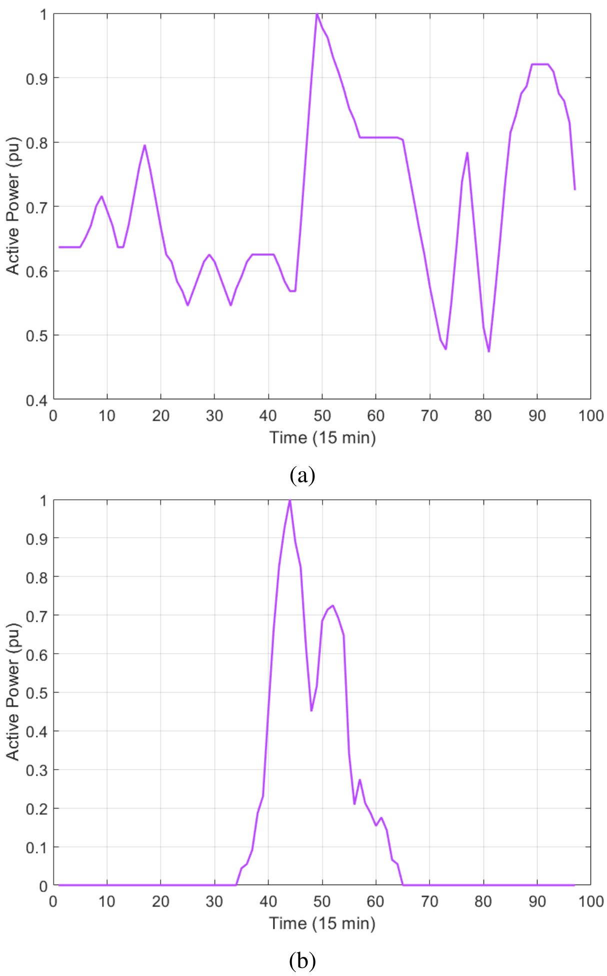


FIGURE 7. (a) Wind power curve, (b) Solar power curve.

A. SCENARIO 1

The base scenario shows 44.71% DERs penetration. Table 3 shows the technical characteristics of each RES (WT and PVs) and the BESSs installed in the IEEE 34-Node Test Feeder.

Figure 8 shows the values of power supplied by each generator, so that the economic dispatch meets the hourly demand.

TABLE 2. DERs penetration scenarios.

Case Number	DERs Penetration (%)	P_{DERs} (p.u)
1	44,71	0,77
2	89,42	1,58
3	100,74	1,78
4	112,05	1,98
5	112,05	1,98

TABLE 3. DERs configuration. Scenario 1.

Source	Type	Node	P_{min} (kW)	P_{max} (kW)	SOC_{min} (kWh)	SOC_{max} (kWh)
WT	3ϕ	B848	50	300	-	-
PV1	3ϕ	B840	0	300	-	-
PV2	1ϕ	B822	0	10	-	-
BESS1	3ϕ	B840	-80	80	70	280
BESS2	3ϕ	B806	-100	100	70	280

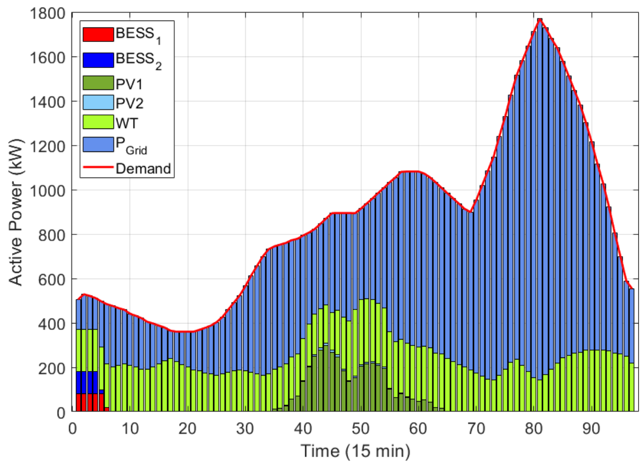


FIGURE 8. ED solution. Scenario 1.

The external grid is generating power during 24 hours, as is wind power generation (WT), with a lower value. The photovoltaic generation, PV1 and PV2, generate from 8.45 to 16.00. The batteries, BESS1 and BESS2, only deliver power to the grid during the first 6 intervals of time since they have energy stored initially. The batteries do not deliver power again because they are not charged at any time of the day since the installed renewable generation power is approximately 46% of the peak demand power. No excess power is produced to be recharged.

The batteries only work as generators (positive power), delivering their maximum power in several time intervals until they reach their minimum energy level (Figure 9). There is no recharging and therefore the energy always remains at the minimum level.

Figure 10(a) shows the voltages in per unit of all the network nodes at the instant of time corresponding to the maximum demand level, instant 81. It can be seen how all the voltages are within the ±5% levels.

B. SCENARIO 2

In scenario 2 the network under study is exactly the same but the power of the generators has been increased to double the

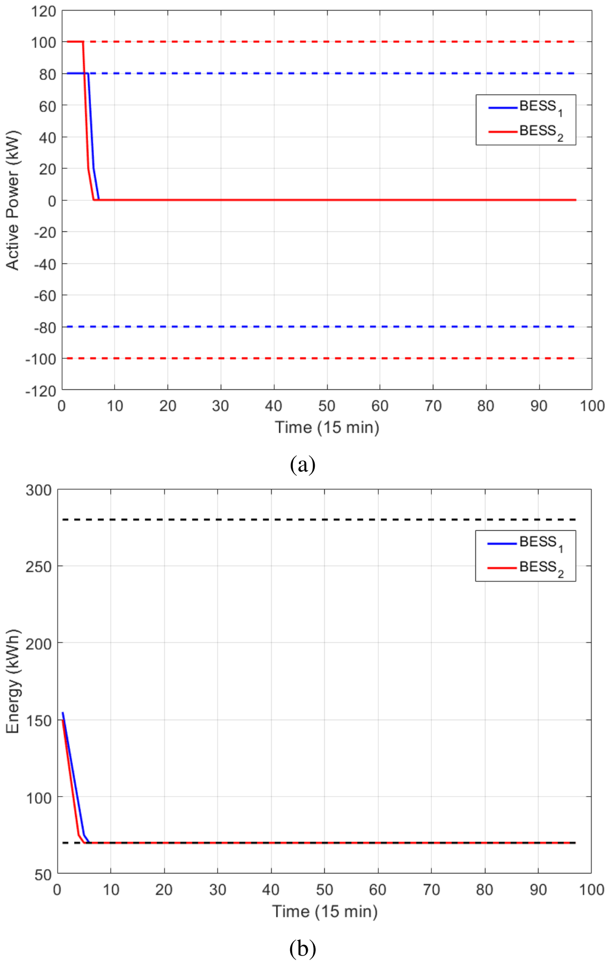


FIGURE 9. (a) Batteries active power, (b) State of charge of batteries. Scenario 1.

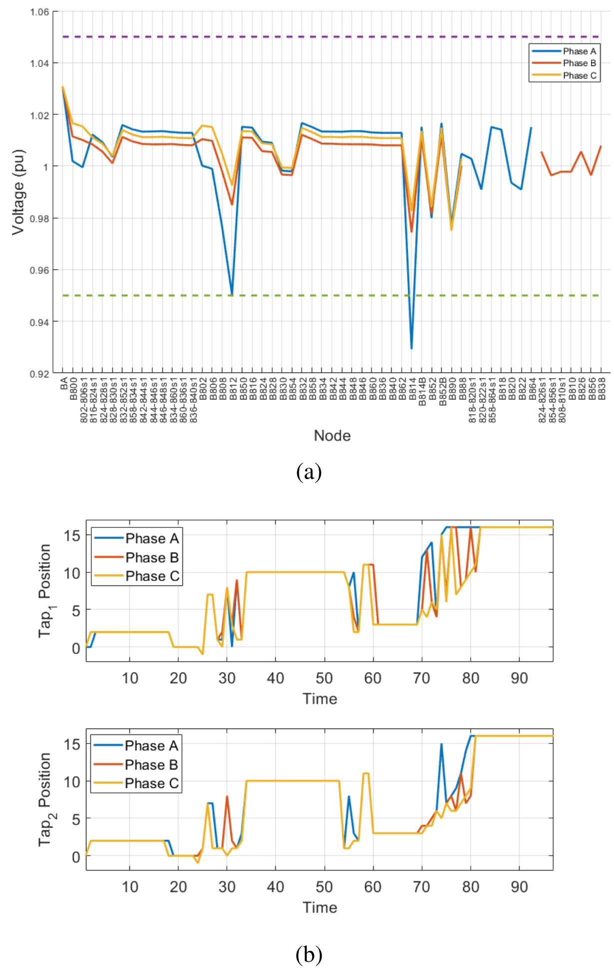


FIGURE 10. (a) Voltage levels, (b) Tap positions. Scenario base.

TABLE 4. DERs configuration. Scenario 2.

Source	Type	Node	P_{min} (kW)	P_{max} (kW)	SOC_{min} (kWh)	SOC_{max} (kWh)
WT	3ϕ	B848	50	600	-	-
PV1	3ϕ	B840	0	600	-	-
PV2	1ϕ	B822	0	20	-	-
BESS1	3ϕ	B840	-160	160	70	280
BESS2	3ϕ	B806	-200	200	70	280

base case. The configuration is summarised in Table 4. The battery energy levels have not changed.

Figure 11 shows how the power of the external grid is reduced with respect to the base case by making a small contribution from 2:00 to 3:15. From 3:15 there is excess renewable generation over demand that allows the batteries to be charged by absorbing the excess power. At 5:45 the demand is covered in part by the contribution of the batteries that are discharged until 7 o'clock when support from the external grid is needed.

As in Scenario 1, there is a surplus of renewable generation at 10:30 and 12:15 that allows the batteries to be charged and discharged. This new process of charging the batteries is due to the contribution of the photovoltaics.

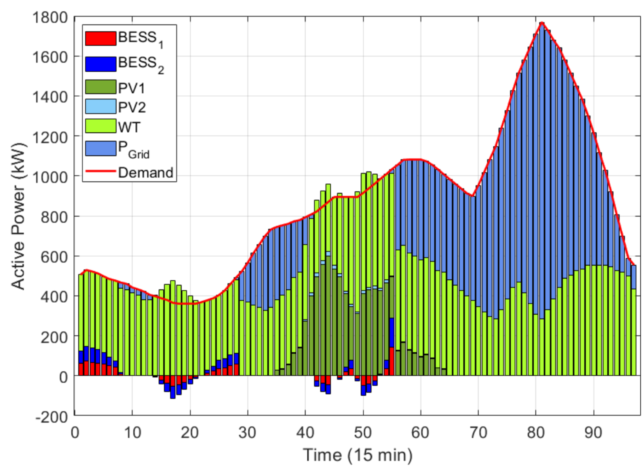


FIGURE 11. ED solution. Scenario 2.

As can be seen in Figure 12(b), throughout the scenario the batteries do not reach the maximum levels of energy storage. Neither do they reach the limits of charge and discharge power (Figure 12(a)).

Figure 13 shows the voltages in per unit of all the network nodes at the instant of time corresponding to the maximum demand level, instant 81.

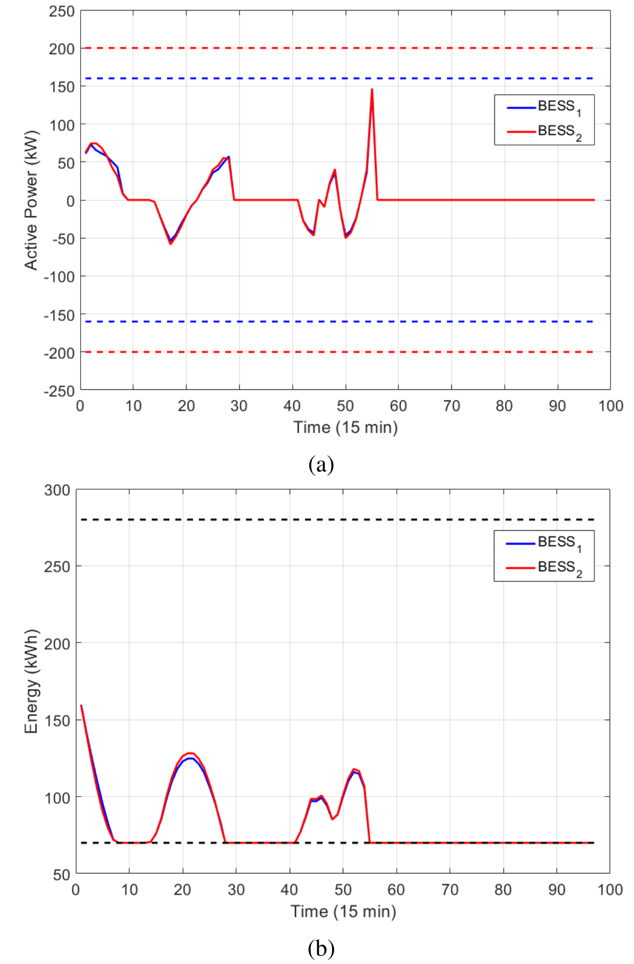


FIGURE 12. (a) Batteries active power, (b) State of charge of batteries. Scenario 2.

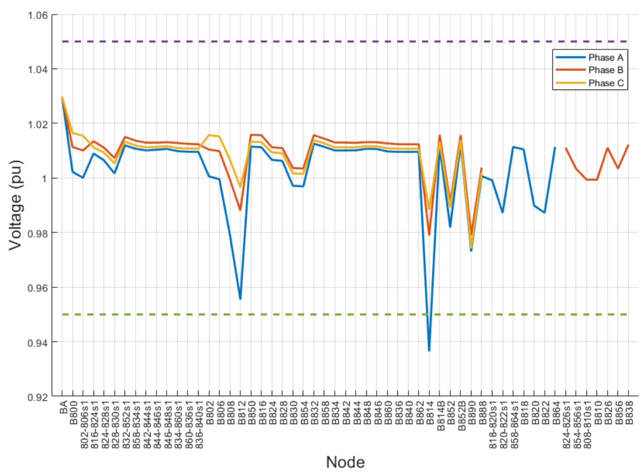


FIGURE 13. Voltage levels. Scenario 2.

C. SCENARIO 3

In scenario 3, the wind generator has increased from 0.6 MW to 0.8 MW with respect to scenario 2. The rest of the parameters remain the same as in scenario 2 (Table 5). Figure 14 shows the power distribution of the generation units in scenario 3. The power of the wind generator has increased and, therefore, there is more renewable power on the grid in the study. This implies that there are times of the day from 3:45 to 6:45 when demand is met by renewable generation, and there is even a surplus that is absorbed first by the batteries and then by the external grid. Therefore there are negative power values for BESS1, BESS2 and external grid.

TABLE 5. DERs configuration. Scenario 3.

Source	Type	Node	P_{min} (kW)	P_{max} (kW)	SOC_{min} (kWh)	SOC_{max} (kWh)
WT	3ϕ	B848	50	800	-	-
PV1	3ϕ	B840	0	600	-	-
PV2	1ϕ	B822	0	20	-	-
BESS1	3ϕ	B840	-160	160	70	280
BESS2	3ϕ	B806	-200	200	70	280

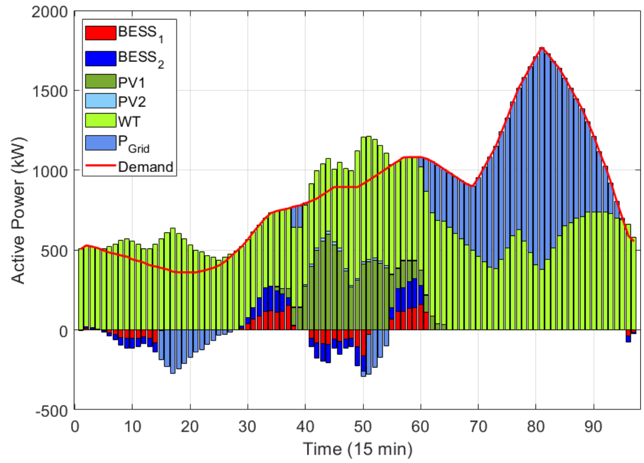


FIGURE 14. ED solution. Scenario 3.

The excess generation is first absorbed by the batteries during recharging, but when they reach their maximum storage limit (Figure 15(b)) it is the external grid that absorbs the rest of the excess. It can also be seen how the batteries are fully used because they are discharged to their minimum energy levels with one of them reaching its maximum charge and discharge power (Figure 15(a)).

Figure 16 shows the voltages in per unit of all the network nodes at the instant of time corresponding to the maximum demand level, instant 81.

D. SCENARIO 4

In scenario 4, wind power generation has again been increased from 0.8 MW to 1 MW. Figure 17 shows the power contribution of each generation unit. It can be seen that, by having more renewable power and not changing the parameters of the batteries, there is more excess generation that must be absorbed by the external grid for a longer period of time.

This means that the batteries begin their work by storing energy until they reach their maximum level (Figure 18(b)) and remain charged longer due to the increased availability of renewable power. This can also be seen in the time interval 30 to 40 (Figure 18(b)) where in this scenario the batteries

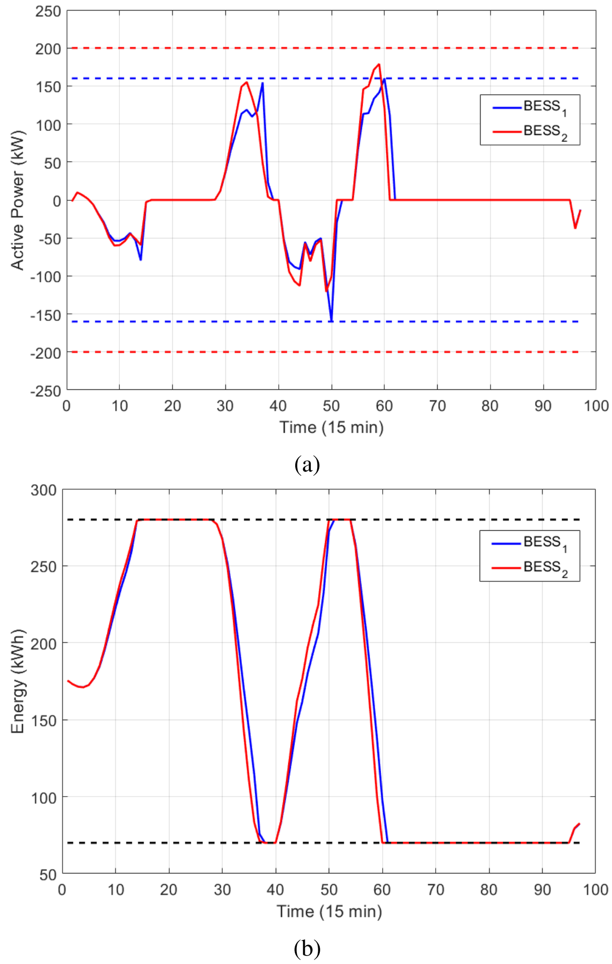


FIGURE 15. **(a) Batteries active power, (b) State of charge of batteries. Scenario 3.**

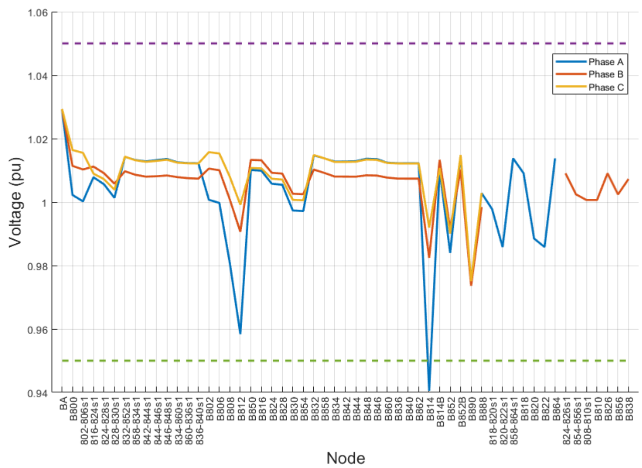


FIGURE 16. **Voltage levels. Scenario 3.**

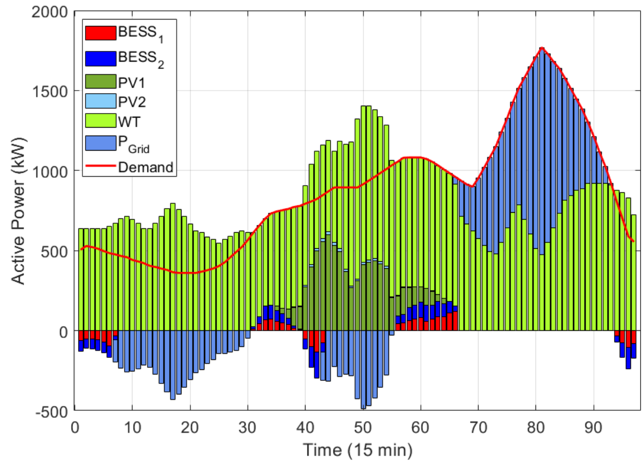


FIGURE 17. **ED solution. Scenario 4.**

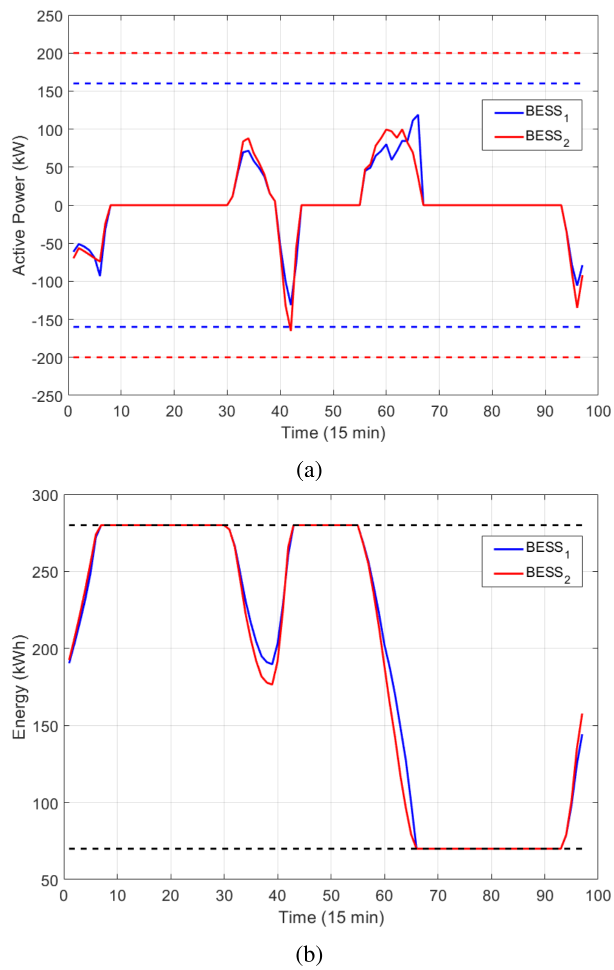


FIGURE 18. **(a) Batteries active power, (b) State of charge of batteries. Scenario 4.**

are not fully discharged. Nor does it imply the use of the maximum power of the batteries.

Figure 19 shows the voltages in per unit of all the network nodes at the instant of time corresponding to the maximum demand level, instant 81.

E. SCENARIO 5

In scenario 5, the elements remain the same by changing only the maximum battery energy levels, which have doubled. The configuration is summarised in Table 6. In scenario 4, the batteries remain at maximum charge for a long time because there is a lot of renewable power available, so in scenario 5 the

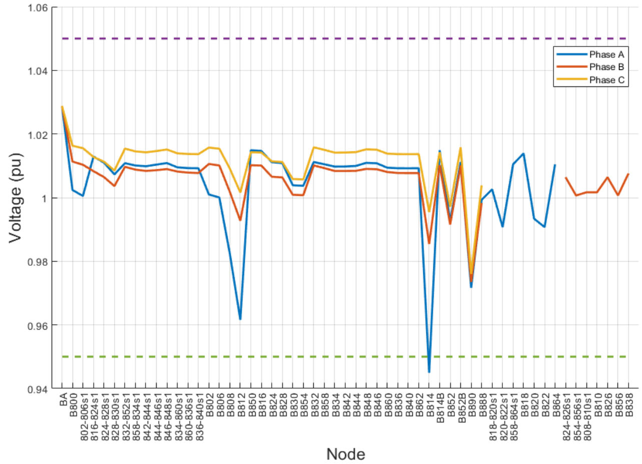


FIGURE 19. Voltage levels. Scenario 4.

TABLE 6. DERs configuration. Scenario 5.

Source	Type	Node	P_{min} (kW)	P_{max} (kW)	SOC_{min} (kWh)	SOC_{max} (kWh)
WT	3ϕ	B848	50	1000	-	-
PV1	3ϕ	B840	0	600	-	-
PV2	1ϕ	B822	0	20	-	-
BESS1	3ϕ	B840	-160	160	70	560
BESS2	3ϕ	B806	-200	200	70	560

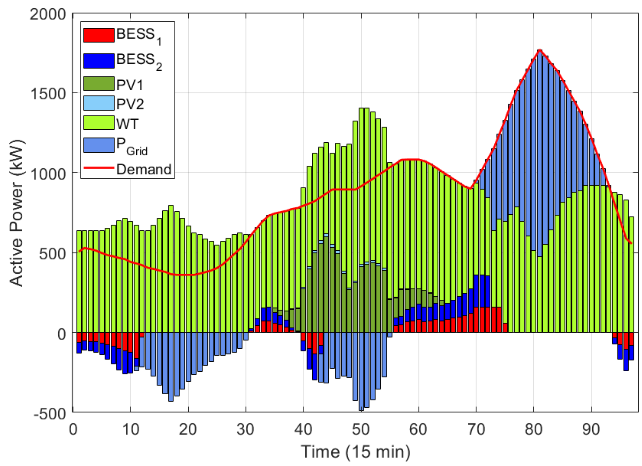


FIGURE 20. ED solution. Scenario 5.

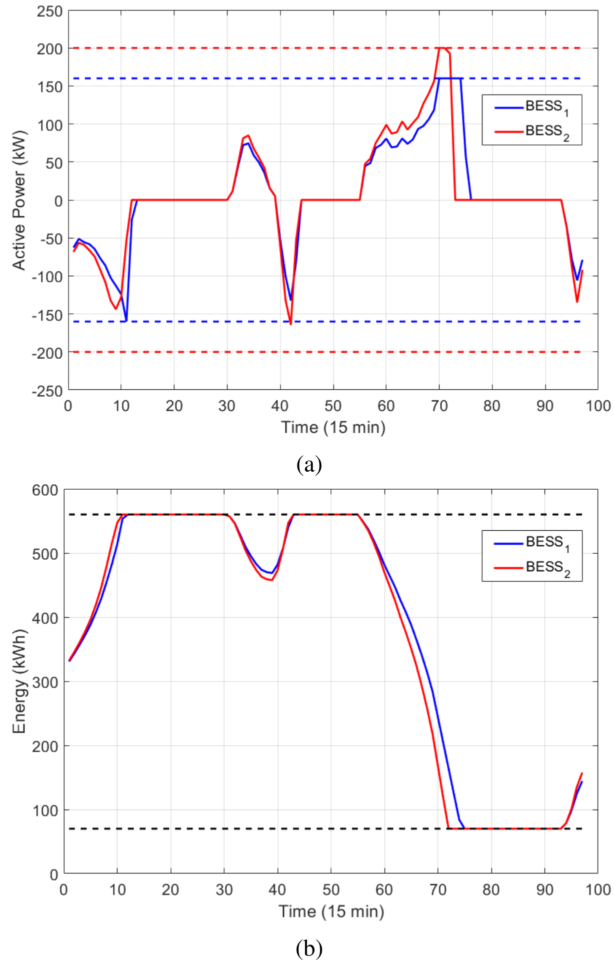


FIGURE 21. (a) Batteries active power, (b) State of charge of batteries. Scenario 5.

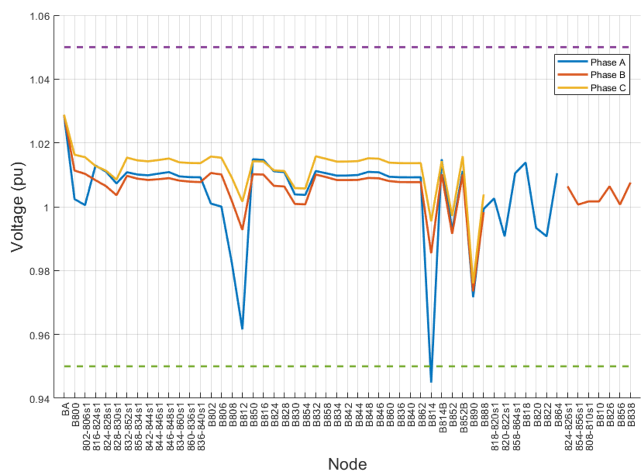


FIGURE 22. Voltage levels. Scenario 5.

storage capacity of the batteries has been increased to make better use of the renewable power. In Figure 20 it can be seen how the batteries' operating time has increased with respect to scenario 4 and at some points even delivering and absorbing more power.

In this scenario there are intervals where the batteries are running at their power limit as shown in Figure 21(a) in time intervals 12 and 70.

Figure 20 shows how in the interval 11 the batteries are charging by absorbing the excess power as well as the external network. However, in interval 12 the BESS1 battery is still charging a very similar power to the one absorbed by the network in interval 11. This is due to the fact that this battery has reached its maximum power in interval 11 although it had not reached its storage limit until interval 12. It can be seen in Figure 21(a).

Figure 22 shows the voltages in per unit of all the network nodes at the instant of time corresponding to the maximum demand level, instant 81.

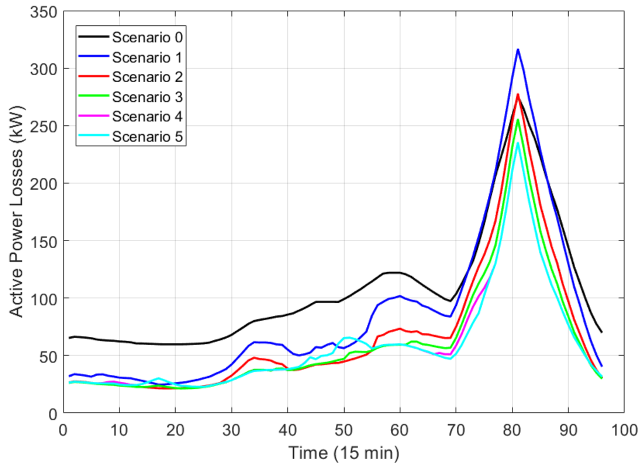


FIGURE 23. Active power losses. IEEE 34-Node Test Feeder.

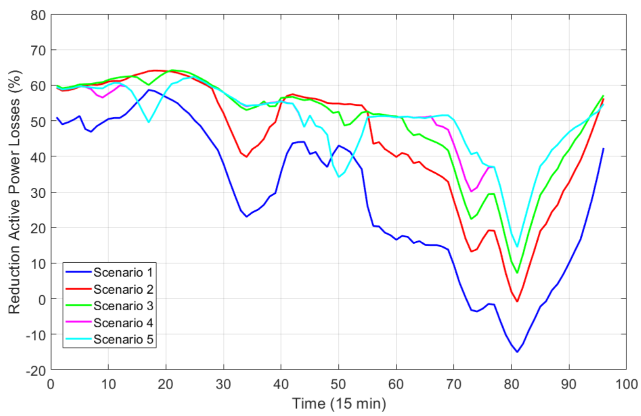


FIGURE 24. Reduction of active power losses (%). IEEE 34-Node Test Feeder.

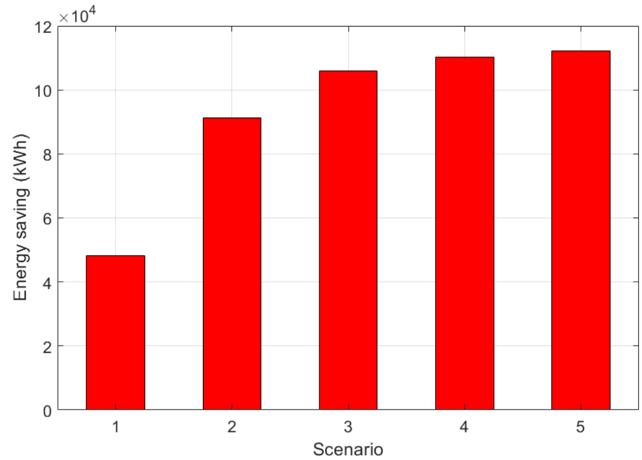


FIGURE 25. Energy saving for each scenario for the IEEE 34-Node Test Feeder.

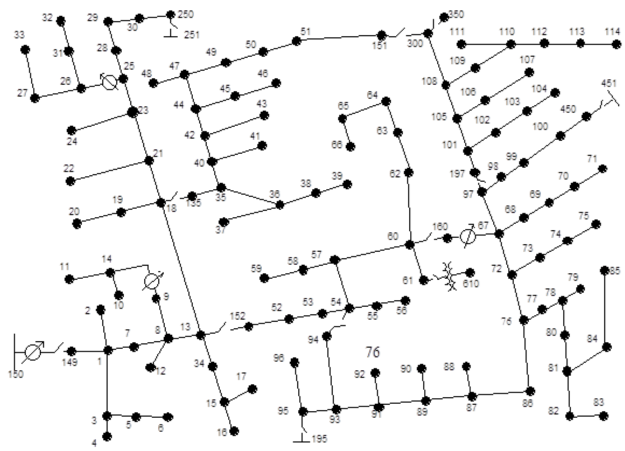


FIGURE 26. IEEE 123-Node Test Feeder.

F. IMPACT OF DISTRIBUTED ENERGY RESOURCES ON ACTIVE POWER LOSSES

This section analyses the impact of the incorporation of DERs on active power losses. To this end, the different scenarios are compared with the network without DERs (scenario 0). Figure 23 shows the active power losses in the scenarios analysed above. As can be seen, in all scenarios there is a reduction in active power losses during all time intervals, with the exception of scenario 1 at the moment of maximum demand, where losses increase. It should be noted that the incorporation of DERs, even if there is only a small amount of installed power (scenario 1), already produces a significant reduction in losses in the Distribution Network. Figure 24 shows the percentage losses reduction values of the different scenarios with respect to scenario 0 (network without DERs). It is observed that, as the penetration of DERs in the study network increases, the active power losses decrease. The reduction of losses is greater at those moments of the day that correspond to lower demand, showing the least reduction at the point of maximum demand. In scenario 5 there are moments (moments 16 and 50) where there is a decrease in active power losses due to a net export of power to the external grid.

The different scenarios present reductions in the active power losses with fluctuations in time. Adding the reductions of all the active power losses in the day, the energy savings of each scenario can be known (Figure 25). It is observed that for scenario 4 and 5 the greatest energy savings are obtained. With these results, the distribution company will receive income from loss-reduction incentives, which will result in a profit.

G. EXTENSION TO A LARGER ADS

The performance of the two-level control strategy is validated also in a larger distribution system. The unbalanced IEEE 123-Node Test Feeder (Figure 26) is selected for this purpose [74]. RESs and BESSs are incorporated following the same criteria as in section III-A. The study network is modelled and validated in DIgSILENT PowerFactory.

TABLE 7. DERs configuration. IEEE 123-Node Test Feeder.

Sources	Location	P_{min} (MW)		P_{max} (MW)		SOC_{min} (MWh)		SOC_{max} (MWh)	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
WT	B251	0.05	0.05	1	2	-	-	-	-
PV1	B350	0	0	0.25	0.5	-	-	-	-
PV	B195	0	0	0.25	0.5	-	-	-	-
BESS1	B350	-0.25	-0.5	0.25	0.5	0.07	0.07	0.5	0.5
BESS2	B195	-0.25	-0.5	0.25	0.5	0.07	0.07	0.5	0.5

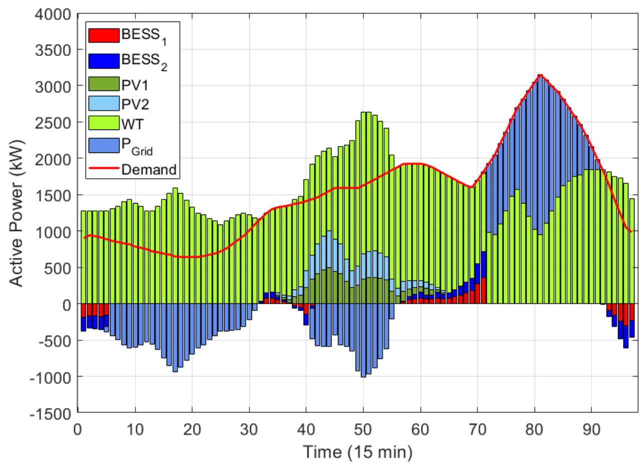


FIGURE 27. ED solution for IEEE 123-Node Test Feeder, Scenario 2.

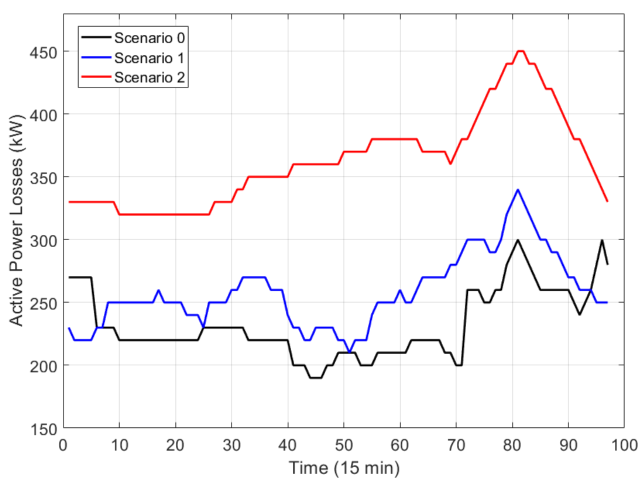


FIGURE 28. Active power losses. IEEE 123-Node Test Feeder.

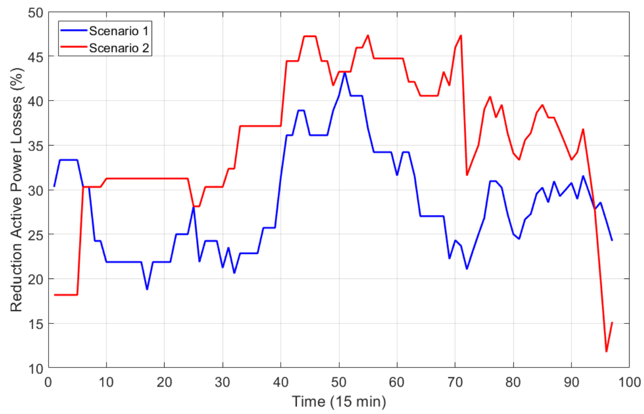


FIGURE 29. Reduction of active power losses (%). IEEE 123-Node Test Feeder.

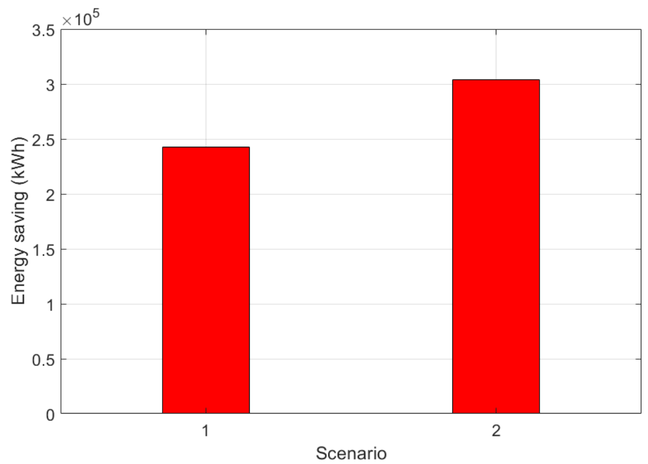


FIGURE 30. Energy saving for each scenario for the IEEE 123-Node Test Feeder.

Two scenarios are designed with 57.31% and 114.61% DERs penetration respectively. Table 7 shows the location and technical characteristics of the RESs and BESSs.

Figure 27 shows the result of the ED in scenario 2. It can be seen that the external network only provides power for 5 hours, being significant the power delivery of the DERs. The excess power from the RESs is used to charge the BESSs (3.5 hours) and the rest of the power is delivered to the external grid, complying with the power balance at all times. The BESSs contribute to cover the 3.75 hours demand.

Figure 28 shows the active power losses in the grid, scenario 0 without DERs and scenarios 1 and 2 with DERs. Figure 29 shows the percentage reduction in active power losses for scenarios 1 and 2 with respect to scenario 0. A reduction of between 18% and 47% is observed in scenario 2.

As in the IEEE 34-Node Test Feeder study, Figure 30 shows the economic benefit due to the reduction of losses, expressed in terms of energy savings, for the IEEE 123-Node Test Feeder.

Finally, Figure 31(a) shows the voltages in p.u. of many busbars in the network, at the time corresponding to the maximum energy demand (instant 81). It can be seen that

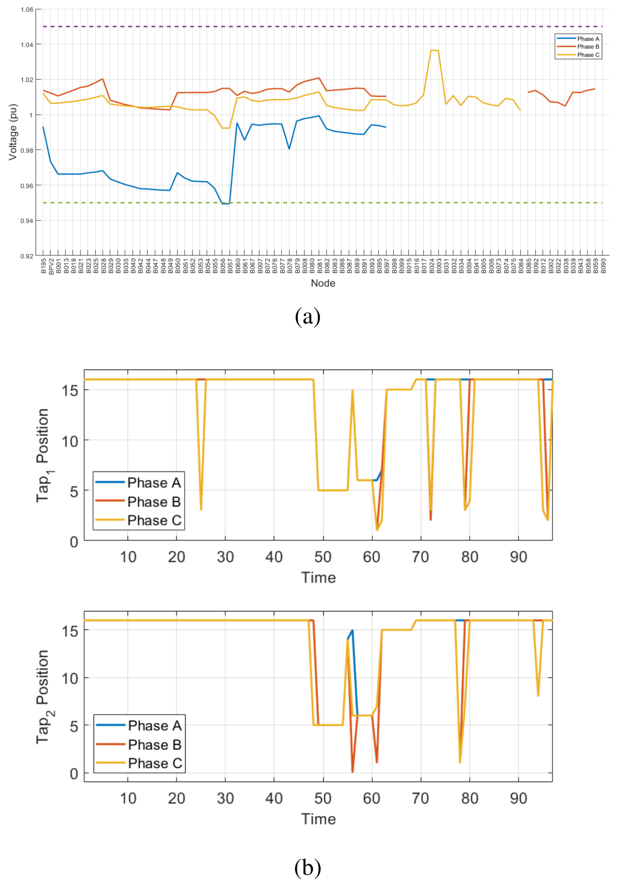


FIGURE 31. **(a) Voltage levels, (b) Tap positions. Scenario 2. IEEE 123-Node Test Feeder.**

all the busbars comply with the restrictions imposed by the DSO. This result shows the effectiveness of the control strategy.

V. CONCLUSION

This article provides a management tool to the DSO for the operation of the ADS. It proposes to use a new approach in the economic dispatch optimisation model for ADSM based on a two-level control strategy. The main objective is to minimise active power losses in unbalanced ADS by making use of available control resources, including storage devices, while increasing the penetration of distributed renewable energy systems and enforcing operational limits. The ED is implemented in a Matlab®-DIgSILENT PowerFactory® joint simulation platform through peer to peer communication. The control strategy is validated in the IEEE 34-Node Test Feeder. Five scenarios are used with different levels of distributed generation penetration composed of renewable energy sources and battery energy storage systems. The results show that an increase in the power of the RESs (PVs and WT) installed in the network reduces the power and the number of hours that the external network delivers power, and therefore reduces the active power losses of the network under study. On the other hand, an increase in the power of the RESs must be accompanied by an increase in the energy storage capacity of the batteries to optimise their use. Finally, this result is possible thanks to the action of the tap control algorithm, which manages to control reactive power flows, keeping the voltages within the limits imposed by the DSO. The scalability of the proposed approach has been demonstrated by validating the effectiveness of the control algorithm in the IEEE 123-Node Test Feeder, with satisfactory results.

In view of the benefits of the proposed approach, several improvements are proposed as future work. First, the application of advanced control techniques, considering the uncertainties due to prediction errors, when extending the time horizon. Besides, it is also proposed to incorporate reactive power constraints to the problem of minimising active power losses. Finally, it is also proposed to analyse the influence of factors such as the energy cost or storage efficiency and degradation on the optimal operation of the unbalanced active distribution network and the cost of depreciation of RESs converters and associated controllers.

REFERENCES

[1] S. Pye, P.-H. Li, I. Keppo, and B. O'Gallachoir, "Technology interdependency in the United Kingdom's low carbon energy transition," *Energy Strategy Rev.*, vol. 24, pp. 314–330, Apr. 2019.

[2] P. Nejat, F. Jomehzadeh, M. M. Taheri, M. Gohari, and M. Z. A. Majid, "A global review of energy consumption, co2 emissions and policy in the residential sector (with an overview of the top ten co2 emitting countries)," *Renew. Sustain. energy Rev.*, vol. 43, pp. 843–862, 2015.

[3] C. Gerbaulet, C. von Hirschhausen, C. Kemfert, C. Lorenz, and P.-Y. Oei, "European electricity sector decarbonization under different levels of foresight," *Renew. Energy*, vol. 141, pp. 973–987, Oct. 2019.

[4] F. H. Malik and M. Lehtonen, "A review: Agents in smart grids," *Electr. Power Syst. Res.*, vol. 131, pp. 71–79, Feb. 2016.

[5] S. Kakran and S. Chanana, "Smart operations of smart grids integrated with distributed generation: A review," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 524–535, Jan. 2018.

[6] P. M. Connor, P. E. Baker, D. Xenias, N. Balta-Ozkan, C. J. Axon, and L. Cipcigan, "Policy and regulation for smart grids in the United Kingdom," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 269–286, Dec. 2014.

[7] Nuclear Energy Agency. (2019). *The Costs Decarbonisation*. [Online]. Available: https://www.oecd-ilibrary.org/content/publication/9789264312180-en

[8] G. Allan, I. Eromenko, M. Gilmartin, I. Kockar, and P. McGregor, "The economics of distributed energy generation: A literature review," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 543–556, Feb. 2015.

[9] F. P. Vahl, R. Rüther, and N. Casarotto Filho, "The influence of distributed generation penetration levels on energy markets," *Energy Policy*, vol. 62, pp. 226–235, Nov. 2013.

[10] L. Mehigan, J. P. Deane, B. P. Ó. Gallachóir, and V. Bertsch, "A review of the role of distributed generation (DG) in future electricity systems," *Energy*, vol. 163, pp. 822–836, Nov. 2018.

[11] Z. Abdmouleh, A. Gastli, L. Ben-Brahim, M. Haouari, and N. A. Al-Emadi, "Review of optimization techniques applied for the integration of distributed generation from renewable energy sources," *Renew. Energy*, vol. 113, pp. 266–280, Dec. 2017.

[12] P. Paliwal, N. P. Patidar, and R. K. Nema, "Planning of grid integrated distributed generators: A review of technology, objectives and techniques," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 557–570, Dec. 2014.

[13] T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: A definition," *Electr. Power Syst. Res.*, vol. 57, no. 3, pp. 195–204, Apr. 2001.

[14] European Commission. (2011). *Impact Assessment of Energy Roadmap 2050*. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pd

[15] European Commission. (2017). *Energy Storage—The Role of Electricity*. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf

[16] C. D'Adamo, P. Taylor, S. Jupe, B. Buchholz, F. Pilo, C. Abbey, and J. Marti, "Active distribution networks: General features, present status of implementation and operational practices," *Electra*, vol. 246, pp. 22–29, 2009.

[17] F. Pilo *et al.*, "Planning and optimization methods for active distribution systems," CIGRE, Paris, France, Tech. Rep. 591, 2014.

[18] C. D'Adamo, S. Jupe, and C. Abbey, "Global survey on planning and operation of active distribution networks–update of CIGRE C6.11 working group activities," in *Proc. 20th Int. Conf. Exhib. Electr. Distrib. (CIRED)*, 2009, pp. 1–4.

[19] R. Hidalgo, C. Abbey, and G. Joós, "A review of active distribution networks enabling technologies," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–9.

[20] A. M. Adil and Y. Ko, "Socio-technical evolution of decentralized energy systems: A critical review and implications for urban planning and policy," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 1025–1037, May 2016.

[21] C. A. G. Garcez, "What do we know about the study of distributed generation policies and regulations in the Americas? A systematic review of literature," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 1404–1416, Aug. 2017.

[22] A. S. N. Huda and R. Živanović, "Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 974–988, Sep. 2017.

[23] S. Jain, S. Kalambe, G. Agnihotri, and A. Mishra, "Distributed generation deployment: State-of-the-art of distribution system planning in sustainable era," *Renew. Sustain. Energy Rev.*, vol. 77, pp. 363–385, Sep. 2017.

[24] M. Pesaran H. A, P. D. Huy, and V. K. Ramachandaramurthy, "A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 293–312, Aug. 2017.

[25] R. Viral and D. K. Khatod, "An analytical approach for sizing and siting of DGs in balanced radial distribution networks for loss minimization," *Int. J. Electr. Power Energy Syst.*, vol. 67, pp. 191–201, May 2015.

[26] C. Corinaldesi, A. Fleischhacker, L. Lang, J. Radl, D. Schwabeneder, and G. Lettner, "European case studies for impact of market-driven flexibility management in distribution systems," in *Proc. IEEE Int. Conf. Commun., Control, Comput. Technol. Smart Grids (SmartGridComm)*, Oct. 2019, pp. 1–6.

[27] K. Oureilidis, K.-N. Malamaki, K. Gallos, A. Tsitsimelis, C. Dikaiakos, S. Gkavanoudis, M. Cvetkovic, J. M. Mauricio, J. M. M. Ortega, J. L. M. Ramos, G. Papaioannou, and C. Demoulias, "Ancillary services market design in distribution networks: Review and identification of barriers," *Energies*, vol. 13, no. 4, p. 917, Feb. 2020.

[28] A. Saint-Pierre and P. Mancarella, "Active distribution system management: A dual-horizon scheduling framework for DSO/TSO interface under uncertainty," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2186–2197, Sep. 2017.

[29] H. Gao, J. Liu, and L. Wang, "Robust coordinated optimization of active and reactive power in active distribution systems," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4436–4447, Sep. 2018.

[30] M. J. Ghadi, S. Ghavidel, A. Rajabi, A. Azizivahed, L. Li, and J. Zhang, "A review on economic and technical operation of active distribution systems," *Renew. Sustain. Energy Rev.*, vol. 104, pp. 38–53, Apr. 2019.

[31] S. Carr, A. J. Guwy, R. M. Dinsdale, J. Maddy, and G. C. Premier, "Energy storage for active network management on electricity distribution networks with wind power," *IET Renew. Power Gener.*, vol. 8, no. 3, pp. 249–259, Apr. 2014.

[32] S. Sekizaki, I. Nishizaki, and T. Hayashida, "Electricity retail market model with flexible price settings and elastic price-based demand responses by consumers in distribution network," *Int. J. Electr. Power Energy Syst.*, vol. 81, pp. 371–386, Oct. 2016.

[33] S. Gill, I. Kockar, and G. W. Ault, "Dynamic optimal power flow for active distribution networks," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 121–131, Jan. 2014.

[34] P. Siano, P. Chen, Z. Chen, and A. Piccolo, "Evaluating maximum wind energy exploitation in active distribution networks," *IET Gener., Transmiss. Distrib.*, vol. 4, no. 5, pp. 598–608, 2010.

[35] P. Hallberg *et al.*, "Active distribution system management a key tool for the smooth integration of distributed generation," *Eurelectric TF Act. Syst. Manage.*, vol. 2, no. 13, Feb. 2013. [Online]. Available: https://www.eurelectric.org/media/1781/asm_full_report_discussion_paper_final-2013-030-0117-01-e.pdf

[36] T. Green, R. Silversides, and T. Lüth, "Power electronics in distribution system management," HubNet Position Paper Ser., Supergen Energy Netw. Hub, Newcastle upon Tyne, U.K., Tech. Rep., 2015.

[37] T. Ding, S. Liu, W. Yuan, Z. Bie, and B. Zeng, "A two-stage robust reactive power optimization considering uncertain wind power integration in active distribution networks," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 301–311, Jan. 2016.

[38] S. Abapour, E. Babaei, and B. Y. Khanghah, "Application of active management on distribution network with considering technical issues," in *Proc. Iranian Conf. Smart Grids*, 2012, pp. 1–6.

[39] S. K. Injeti and V. K. Thunuguntla, "Optimal integration of DGs into radial distribution network in the presence of plug-in electric vehicles to minimize daily active power losses and to improve the voltage profile of the system using bio-inspired optimization algorithms," *Protection Control Mod. Power Syst.*, vol. 5, no. 1, pp. 1–15, Dec. 2020.

[40] S. Ruester, S. Schwenen, C. Batlle, and I. Pérez-Arriaga, "From distribution networks to smart distribution systems: Rethinking the regulation of European electricity DSOs," *Utilities Policy*, vol. 31, pp. 229–237, Dec. 2014.

[41] M. Fan, Z. Zhang, A. Su, and J. Su, "Enabling technologies for active distribution systems," *Proc. CSEE*, vol. 33, no. 22, pp. 12–18, 2013.

[42] X. Zhao, Q. Chen, Q. Xia, C. Kang, and H. Wang, "Multi-period coordinated active-reactive scheduling of active distribution system," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, 2013, pp. 1–5.

[43] A. A. Ibrahim, B. Kazemtabrizi, and C. Dent, "Operational planning and optimisation in active distribution networks using modern intelligent power flow controllers," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. (ISGT-Europe)*, Oct. 2016, pp. 1–6.

[44] V. Kekatos, G. Wang, A. J. Conejo, and G. B. Giannakis, "Stochastic reactive power management in microgrids with renewables," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3386–3395, Nov. 2015.

[45] M. Izadi and A. Safdarian, "A MIP model for risk constrained switch placement in distribution networks," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 4543–4553, Jul. 2019.

[46] M. Izadi and A. Safdarian, "Financial risk constrained remote controlled switch deployment in distribution networks," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 7, pp. 1547–1553, Apr. 2018.

[47] J. Duan, T. Mu, F. Yan, L. Chen, K. Wang, and Y. Lei, "Optimization schedule of active distribution system based on improved harmony search algorithm," in *Proc. 5th Int. Conf. Electr. Utility Deregulation Restruct. Power Technol. (DRPT)*, Nov. 2015, pp. 2678–2683.

[48] A. Borghetti, M. Bosetti, S. Grillo, S. Massucco, C. A. Nucci, M. Paolone, and F. Silvestro, "Short-term scheduling and control of active distribution systems with high penetration of renewable resources," *IEEE Syst. J.*, vol. 4, no. 3, pp. 313–322, Sep. 2010.

[49] H. H. Abdeltawab and Y. A.-R.-I. Mohamed, "Mobile energy storage scheduling and operation in active distribution systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 6828–6840, Sep. 2017.

[50] A. Zakariazadeh, S. Jadid, and P. Siano, "Multi-objective scheduling of electric vehicles in smart distribution system," *Energy Convers. Manage.*, vol. 79, pp. 43–53, Mar. 2014.

[51] Y. Xiang, J. Liu, and Y. Liu, "Optimal active distribution system management considering aggregated plug-in electric vehicles," *Electr. Power Syst. Res.*, vol. 131, pp. 105–115, Feb. 2016.

[52] R. Li, W. Wang, Z. Chen, J. Jiang, and W. Zhang, "A review of optimal planning active distribution system: Models, methods, and future researches," *Energies*, vol. 10, no. 11, p. 1715, Oct. 2017.

[53] A. Garces, "A quadratic approximation for the optimal power flow in power distribution systems," *Electr. Power Syst. Res.*, vol. 130, pp. 222–229, Jan. 2016.

[54] D. Sun, B. Ashley, B. Brewer, A. Hughes, and W. Tinney, "Optimal power flow by Newton approach," *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 10, pp. 2864–2880, Oct. 1984.

[55] M. Liu, S. K. Tso, and Y. Cheng, "An extended nonlinear primal-dual interior-point algorithm for reactive-power optimization of large-scale power systems with discrete control variables," *IEEE Trans. Power Syst.*, vol. 17, no. 4, pp. 982–991, Nov. 2002.

[56] M. Bazrafshan, N. Gatsis, and H. Zhu, "Optimal power flow with step-voltage regulators in multi-phase distribution networks," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 4228–4239, Nov. 2019.

[57] K. Christakou, D.-C. Tomozei, J.-Y. Le Boudec, and M. Paolone, "AC OPF in radial distribution networks—Part I: On the limits of the branch flow convexification and the alternating direction method of multipliers," *Electr. Power Syst. Res.*, vol. 143, pp. 438–450, Feb. 2017.

[58] C. Lee, C. Liu, S. Mehrotra, and Z. Bie, "Robust distribution network reconfiguration," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 836–842, Mar. 2015.

[59] M. Sedghi, A. Ahmadian, and M. Aliakbar-Golkar, "Optimal storage planning in active distribution network considering uncertainty of wind power distributed generation," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 304–316, Jan. 2016.

[60] R. H. A. Zubo and G. Mokryani, "Active distribution network operation: A market-based approach," *IEEE Syst. J.*, vol. 14, no. 1, pp. 1405–1416, Mar. 2020.

[61] H. L. Willis, *Power Distribution Planning Reference Book*. Boca Raton, FL, USA: CRC Press, 2004.

[62] T. A. Short, *Electric Power Distribution Handbook*. Boca Raton, FL, USA: CRC Press, 2014.

[63] M. K. Gray and W. G. Morsi, "Power quality assessment in distribution systems embedded with plug-in hybrid and battery electric vehicles," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 663–671, Mar. 2015.

[64] S. S. Alkaabi, "Distributed generation planning and optimization: Deterministic versus heuristic approaches," in *Proc. IEEE PES Innov. Smart Grid Technol. Eur. (ISGT-Europe)*, Sep. 2019, pp. 1–5.

[65] K. Tian, W. Sun, D. Han, and C. Yang, "Coordinated planning with predetermined renewable energy generation targets using extended two-stage robust optimization," *IEEE Access*, vol. 8, pp. 2395–2407, 2020.

[66] Q. Yang, G. Wang, A. Sadeghi, G. B. Giannakis, and J. Sun, "Two-timescale voltage control in distribution grids using deep reinforcement learning," *IEEE Trans. Smart Grid*, vol. 11, no. 3, pp. 2313–2323, May 2020.

[67] IPADTFW Group. (1992). *34-Bus Feeder*. [Online]. Available: http://sites.ieee.org/pes-testfeeders/resources

[68] A. J. O. Owuor, J. L. Munda, and A. A. Jimoh, "The IEEE 34 node radial test feeder as a simulation testbench for distributed generation," in *Proc. IEEE Africon*, Sep. 2011, pp. 1–6.

[69] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Convers.*, vol. 18, no. 2, pp. 194–204, Jun. 2003.

[70] Y. Lei, A. Mullane, G. Lightbody, and R. Yacamini, "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies," *IEEE Trans. Energy Convers.*, vol. 21, no. 1, pp. 257–264, Mar. 2006.

[71] M. Deshmukh and S. Deshmukh, "Modeling of hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 12, no. 1, pp. 235–249, 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032106001134

[72] F. Lasnier and T. G. Ang, *Photovoltaic Engineering Handbook*. New York, NY, USA: Taylor & Francis, 1990, doi: 10.1201/9780203743393.

[73] F. González-Longatt, "Impact of distributed generation over power losses on distribution system," in *Proc. 9th Int. Conf. Elect. Power Qual. Utilization*, Barcelona, Spain, Oct. 2007, pp. 1–6. [Online]. Available: https://fglongatt.org/Papers/Papers2009/A2007-04.pdf

[74] IEEE. (1992). *Distribution Test Feeders-Distribution Test Feeder Working Group-IEEE PES Distribution System Analysis Subcommittee*. [Online]. Available: https://site.ieee.org/pes-testfeeders/resources/

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