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Scenario-based Multi-Energy Power Distribution System Planning Solution for Energy Loss Minimization

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***Abstract*—This paper presented a distributed system planning (DSP) solution for identifying an optimal fuel mix in the electric power distribution networks with the minimized power line losses. The optimal fuel mix consists of both renewable energy-based distributed renewable generators, i.e. wind turbines and photovoltaic as well as the conventional fuel-based DG units. In this work, the method based on the heuristic moment matching (HMM) is firstly adopted to generate WT-PV-LD operational scenarios that combine all system uncertainties of DG generation and power demand. Such a scenario matrix is then incorporated into the robust DSP problem formulation. The proposed solution is evaluated using a 53 bus test network. Finally, the HMM-based planning approach is validated through simulation experiments and the effectiveness is confirmed.**

Keywords-multi-energy; power distribution system planning; Heuristic moment matching;

Nomenclature

F	Objective function of DSP Problem
$i-j$	Line from node i to node j
$P_{ij,h}^{loss}, Q_{ij,h}^{loss}$	Active and reactive power line losses for line $i-j$
r_{ij}, x_{ij}	Resistance and reactance of line $i-j$
N_h, N_L	Number of scenarios and lines
$I_{ij,h}$	Current of branch $i-j$ of scenario h
S_{il}	Correlation coefficient of node i and branch l
$p_{ij,h}, q_{ij,h}$	Active and reactive power flow of branch $i-j$ of scenario h
$P_{i,h}^{S}, P_{i,h}^{WT}, P_{i,h}^{PV}$	Active power output of substation, wind turbine, solar photovoltaic at node i for scenario h
$Q_{i,h}^{S}$	Reactive power output of substation at node i for scenario h
P_i^{DE}, Q_i^{DE}	Active and reactive power rating of diesel engine at node i
$P_{i,h}^{LD}, Q_{i,h}^{LD}$	Active and reactive power demand at node i for scenario h
$v_{i,h}$	Voltage at node i for scenario h
P_i^{WT}, P_i^{PV}	Active power rating of wind turbine, photovoltaic and diesel engine at node i
$P_{\max}^{WT}, P_{\max}^{PV}, P_{\max}^{DE}$	Maximum allowable size of wind turbine, photovoltaic and diesel engine at node i
pf^{DE}	Power factor of diesel engine
Z^T	WT-PV-LD scenario matrix
Z_1^T, Z_2^T, Z_3^T	Column 1,2,3 of WT-PV-LD scenario matrix corresponding to scenarios of WT , PV generation and power demand, respectively.
α^{WT}, α^{DE}	Integer variables representing discrete sizes of wind turbine and diesel engine demand at node i for scenario h
$P_{rating}^{WT}, P_{rating}^{DE}$	Minimum rating of the commercially available wind turbine and diesel engine

I. INTRODUCTION

In recent decades, the issues concerning environmental pollution and energy security, the electricity generation from renewable energy sources (RES) has received much attention. Such energy generation sources are often in the form of small-scale generators connected directly to the medium and low voltage power distribution networks. Unlike conventional generation plants they are not concentrated at a single point, rather they are dispersed along with the network. It is considered fundamental to assess the impact of the renewable distributed generators (DGs), e.g, wind turbines (WTs), solar photovoltaic sources (PVs), on the distribution network, and plan accordingly to reinforce the network. These distributed generators in combination with distributed storage form a low voltage distribution network which is often known as a microgrid.

In the traditional distribution network, the power flow generally flows from the upper substation to the load node, and its operation mode and planning criteria are relatively simple. However, the large-scale access and application of distributed energy resources (DER) will significantly affect the original electrical characteristics such as power flow distribution, voltage level, short-circuit capacity and so on. However, the traditional distribution network does not consider the above factors in the design stage, so it is difficult to meet the requirements of high penetration renewable energy generation access and efficient utilization under the background of a low-carbon economy.

To fulfill the requirements of the future power demand-supply requirement and power grid infrastructure development, it is necessary to determine when, where and what type of line, substation or distributed generation (DG) equipment will be constructed. An active distribution

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network is a kind of public distribution network with flexible topology, which adopts the mode of active management of distributed generation, energy storage equipment and customer bidirectional load. The results of distribution network planning directly affect the investment and income of distribution network and the security, economy and stability of distribution network operators in the future. To reasonably plan DG, the appropriate coordination and optimal operation of DGs are important, and hence the active management and planning for distribution networks need to be investigated. The active distribution network (ADN) provides a new solution to solve the problem of voltage rise caused by DG access, increase the access capacity of DG, and significantly promote the asset utilization of the electric power distribution networks.

The distributed generation is a broad term used for small scale power generators which differ from large scale centralized generators of a generation because they are often located at places where a conventional power plant would not be installed. Therefore, DG contributes to increasing the geographic distribution of power generation in a given region. The distribution system planning (DSP) aims to plan the electric power distribution systems that can timely meet the power demand with the best tradeoff through cost-benefit analysis. In fact, this is often a complicated task due to the expansion of the power distribution system considering the economic factors as well as the power losses [1]. In recent years, the DSP problem becomes a non-trivial task due to the fact of high penetration of a massive number of distributed renewable generators (DGs), and encouraged by the national and regional policies worldwide (e.g., [2] [3]). Annual DG capacity installments of almost 142 GW have been reported for the year 2012 which accounted for about 39 percent of global power capacity additions and by 2020 annual DG capacity additions are projected to grow to 200 GW [4]. As a result, renewable energy sources continue to contribute to a rising share of the world's total electricity supply [5].

The conventional DSP problem aims to identify the most appropriate investment planning solution with the optimal sitting and sizing of the power substations and system topologies (e.g., radial or mesh connections) to meet the power supply requirement of forecasted demand. The common objective is to minimize the economic cost induced by the reinforcement of replacement or expansion of substations and/or feeders, subject to a collection of operational constraints (e.g., [6] [7]). In this work, the HMM method has been adopted to generate a WT-PV-LD scenario matrix that covers all possible uncertainties of the combination of DG generation and power demand. Afterwards, a robust DSP problem is proposed by incorporating the scenario matrix into the deterministic planning problem.

In this paper, the scenario-based multi-energy power distribution system planning is exploited and an algorithmic solution is presented for energy loss minimization. This work made the following contributions:

(1) Through the use of historical annual data of hourly WT and PV generation as well as the power demand profile, an HMM-based method is adopted for scenario generation of DG generation and demand profiles in the form of a WT-PV-LD scenario matrix. This matrix approximates the stochastic features and uncertainties WTs, PVs, and power demand;

(2) A DSP problem is addressed through adopting the WT-PV-LD scenario matrix to determine the optimal fuel mix of renewable DGs units, i.e. WTs, PVs and conventional fuel-based DGs, i.e. diesel engines (DEs), to minimize the active and reactive losses and meet the operational constraints of the power distribution systems.

The rest of this study is organized as follows: Section II overviews the developed multi-energy system planning solution; Section III shows and analyzes the experimental results; Section IV provides the conclusive remarks.

II. Proposed Scenario-Based Multi-Energy System Planning Method

This section presents the proposed multi-energy power distribution system planning considering the presence of different forms of uncertain renewable generation sources.

A. Heuristic Moment Matching Method

This section considers three different types of uncertainties introduced by the WTs, PVs and demands are considered by the representative scenarios by the use of the HMM method. As illustrated in Fig. 1, these three uncertainty factors constitute the WT-PV-LD scenario matrix that consists of H scenarios that lie between the upper and lower DG generation and demand bounds. Afterward, these scenarios are incorporated into the deterministic DSP problem and all representative scenarios are considered as a robust solution that can cope with the system uncertainties due to renewable generation and demand.

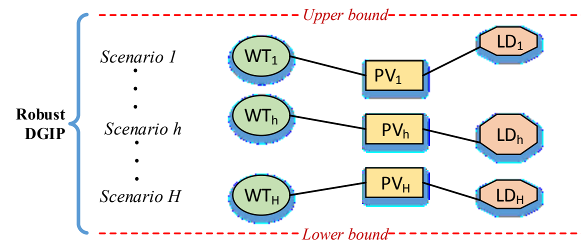


Fig. 1 Diagram of DSP considering the WT-PV-LD scenario matrix.

B. Multi-energy power distribution system planning

Robust optimization has been widely used in addressing the challenge of power systems planning in the presence of system uncertainties. Here, the uncertainties introduced by the power generation of intermittent DGs and the demand need to be fully considered in the process of system planning. Therefore a more realistic solution can be obtained if these uncertainties are considered during the optimization process since several scenarios representing the uncertain features of generation and demand are analyzed. In this section, the robust DSP problem is modeled using the representative scenario matrix. Robust DSP aims to plan an optimal distribution network that satisfies the uncertainties introduced by the WTs, PVs as well as power loads with the minimized power losses. The distribution system power losses are one of the main considerations in the system planning process as the appropriate DG allocation can result in minimized power losses.

In the problem formulation, the following assumptions are made as follows: (1) multiple types of DGs are allowed to be connected to the same network bus; (2) DG units operate at the unity power factor except for the DEs which have a lagging power factor of 0.9; (3) WT and DE base DG units can only have discrete output ratings. Here, the PV rating is considered with no limit as the PV array can be arranged as required. The planning formulation aims to minimize the active and reactive power line losses for all representative scenarios of the scenario matrix whilst meeting all the system operational constraints. The objective function is formulated in (1)-(3):

$$Minimize\ \ F = F_1 + F_2 \tag{1}$$

$$F_1 = \sum_{h=1}^{N_h}\sum_{i-j=1}^{N_L} P^{loss}_{ij,h} = \sum_{h=1}^{N_h}\sum_{i-j=1}^{N_L} r_{ij} I_{ij,h} \qquad h = 1,2,...,N_h \tag{2}$$

$$F_2 = \sum_{h=1}^{N_h}\sum_{i-j=1}^{N_L} Q^{loss}_{ij,h} = \sum_{h=1}^{N_h}\sum_{i-j=1}^{N_L} x_{ij} I_{ij,h} \qquad h = 1,2,...,N_h \tag{3}$$

The DSP problem needs to meet the following constraints as given in (4)-(13):

$$\sum_{l=1}^{N_L}(S_{il}\times p_{ij,h}) + P^{S}_{i,h} + P^{WT}_{i,h} + P^{PV}_{i,h} + P^{DE}_{i} = r_{ij} I_{ij,h} + P^{LD}_{i,h} \tag{4}$$

$$\sum_{l=1}^{N_L}(S_{il}\times q_{ij,h}) + Q^{S}_{i,h} + Q^{DE}_{i} = x_{ij} I_{ij,h} + Q^{LD}_{i,h} \tag{5}$$

$$v_{j,h} = v_{i,h} - 2(r_{ij}p_{ij,h} + x_{ij}q_{ij,h}) + (r_{ij}^2 + x_{ij}^2) I_{ij,h} \tag{6}$$

$$I_{ij,h} = \frac{p_{ij,h}^2 + q_{ij,h}^2}{v_{i,h}} \tag{7}$$

$$0.95\,pu \le V_{i,h} \le 1.05\,pu \tag{8}$$

$$\left|I_{ij,h}\right| \le 1.0\,pu \tag{9}$$

$$\begin{aligned} 0 &\le P_i^{WT} \le P_{\max}^{WT} \\ 0 &\le P_i^{PV} \le P_{\max}^{PV} \\ 0 &\le P_i^{DE} \le P_{\max}^{DE} \end{aligned} \tag{10}$$

$$Q_i^{DE} = (\tan(\cos^{-1} pf^{DE})).P_i^{DE} \tag{11}$$

$$\begin{aligned} P^{WT}_{i,h} &= P^{WT}_i \times Z_1^T \\ P^{PV}_{i,h} &= P^{PV}_i \times Z_2^T \\ P^{LD}_{i,h} &= P^{LD}_i \times Z_3^T \end{aligned} \tag{12}$$

$$\begin{aligned} P^{WT}_{i,h} &= \alpha^{WT}_{i,h} \cdot P^{WT}_{rating} \\ P^{DE}_{i,h} &= \alpha^{DE}_{i,h} \cdot P^{DE}_{rating} \end{aligned} \tag{13}$$

Here, (4) denotes that the active power supplies are required to balance the demands at each node; where, the supplies include branch power, power generation of the substation, WT, PV and DE, whereas the demands equal to the load plus the line losses.

The following constraints are considered:

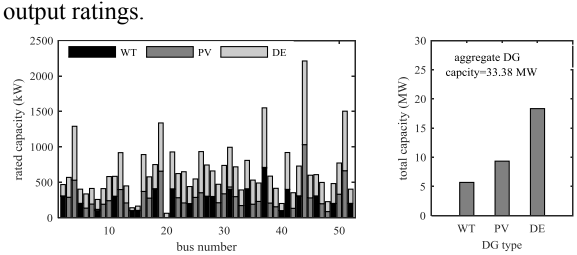
- (5) denotes the nodal power balance for supplies and demands of reactive power.
- (6) and (7) are used to calculate the bus voltage and branch current, respectively;
- (8) and (9) represent the lower/upper bounds of bus voltage and branch current, respectively.
- (10) provides the upper and lower generation limits of the power substation, WT, PV and DE.
- The DE reactive power output as a function of its power factor and active power output, as given in (11).
- In (12), the WT-PV-LD representative scenarios scenario matrix are used in the power flow calculation.
- (13) is used to ensure the discrete size of the DGs.

III. Experimental Analysis And Numerical Results

The developed HMM-based DSP solution is evaluated through a test distribution system with 53 nodes and 61 branches. The test network consists of 1 substation, 52 load nodes. The system nominal voltage is 13.8 kV and the nominal substation capacity is 50 MVA. In the normal condition, the active and reactive power demands are 45.67 MW and 22.12 MVAR, respectively.

Here, the following test case is considered: The initial distribution system loss without no DG integration is calculated in Matpower [8], considering the variability of load profile through a different number of load scenarios only, i.e. $N_h = 10, 20, ..., 100$, to analyze the impact of the number of scenarios.

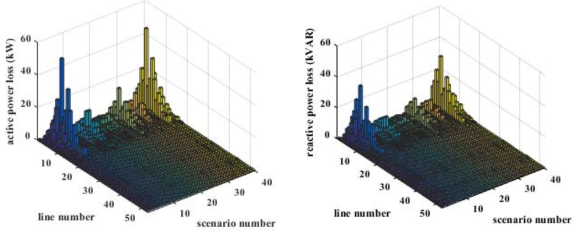
In Fig. 2 (a), it is shown that the optimal sizes of WTs, PVs and DEs at each bus (except the substation bus) of the 53 bus distribution system. These results can be used as a guideline to optimally integrate different forms of DGs into the power distribution system instead of the fit and forget policy of connecting arbitrary types of DG units at random locations, which usually result in enhanced system losses. In Fig. 6 (b), the total share of WT, PV, and DE based DG units in the optimal fuel mix is about 5.7 MW (15.7%), 9.34 MW (28.4%) and 18.34 MW (55.8%), respectively and the aggregated generation capacity of fuel mix is 33.38 MW. The higher penetration of DEs in the fuel mix is due to two reasons: firstly, DEs are considered as dispatchable and firm generation units whereas WTs and PVs are considered to be non-dispatchable and intermittent DG units; secondly, DEs provide local reactive power in addition to active power, so they play a crucial role in decreasing reactive power losses as compared to WTs and PVs, which deliver only active power. Moreover, the higher penetration of PVs in comparison with WTs can be explained because PV arrays can be arranged in any size to provide for any amount of required demand while WTs can only have discrete power output ratings.



(a) (b)

Fig. 2 Robust DSP Planning for the test system based on 40 scenarios. (a) Optimal WT, PV, DE size at each system bus; (b) Share of WT, PV, DE in the optimal fuel mix.

Fig. 3 presents the performance of system active and reactive power losses for each line of the distribution system for each scenario. It can be observed that there is a decreasing trend in power losses (both active and reactive) as we move downstream from the substation. This can be explained because the lines near the substation are subject to higher power flows arriving form the substation and hence higher losses occur in these lines. However, as we keep on moving downstream from the substation, some power is gradually consumed at each intervening bus and hence the power flows decrease gradually which results in the decrease of losses.



(a) *(b)*

Fig. 3 Line losses in the test distribution system for each scenario: (a) active line losses; (b) reactive line losses.

IV. CONCLUSION AND REMARKS

The power distribution system uncertainties introduced by the power generated of intermittent DGs and demand need to be fully considered in the power distribution system planning. In this work, the DSP problem is addressed through the adoption of representative WT-PV-LD scenarios. The proposed solution aims to obtain the optimal distribution network planning with the minimized active and reactive power losses.

The optimal fuel mix consists of both different forms of renewable energy-based distributed generators as well as conventional fuel-based DG units i.e. diesel engines. Based on historical annual statistics of hourly WT generation, PV generation and load profile, the HMM method are firstly adopted for the generation of a WT-PV-LD scenario matrix that combines all possible operational uncertainties of WTs, PVs and power demands. The proposed planning solution is implemented and evaluated through a case study of a 53 bus test distribution system. The numerical results demonstrated the effectiveness of the proposed planning method.

There are a few key issues that need to be further investigated in the future studies for optimal power distribution systems investment planning considering the massive penetration of different forms of small-scale DGs. The issues require further research effort are as follows:

1) The cost-benefit analysis of different energy storage devices needs to be carried out during the distribution network planning process.

2) It is eminent that the power system planning must meet the power quality standards of utility. Therefore, it needs to be highlighted that the power quality enhancement needs to be investigated in the future and the performance needs to be further assessed under different operational scenarios.

3) It can be anticipated that dc microgrid will be an important part of power system planning soon. It is because the dc microgrid eliminates the reactive power issue and reduces the investment on lines compared with a three-phase ac micro-grid.

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