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Heuristic Moment Matching based Scenario Generation for Regional Energy Network Planning considering the Stochastic Generation and Demands

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Abstract—**In this paper, the Heuristic Moment Matching (HMM) is adopted and evaluated in the investigation of regional energy network planning considering the uncertainties introduced by the stochastic generation and demands. The adoption of the scenario generation solution can effectively include the uncertainties in the system planning process in the multi-energy networks, including wind turbines (WTs) and solar photovoltaic (PVs). The scenario generation approach is implemented and the effectiveness is validated through numerical experiments. Finally, the scenario generation approach is adopted through a 53 bus test network and the effectiveness is confirmed through comparison against the conventional planning solution.**

Keywords-distribution system planning; Renewable generation; Heuristic moment matching;

I. INTRODUCTION

The widespread utilization of renewable distributed generations (DGs) challenges the conventional planning philosophy for distribution systems because the power output of renewable-based DGs has a high degree of uncertainty introduced by the renewable generators i.e. solar and wind energy. Thus, it cannot be accurately formulated using a tractable mathematical equation [1].

After the distributed generation is connected to the distribution system, the impact on the relay protection of the distribution system is mainly manifested in the following aspects:

(1) The sensitivity of the original relay protection device may decrease or refuse to operate. The fault current generated by distributed generation may reduce the current flowing through the feeder relay, so that the quick break protection cannot be started, thus the fault cannot be removed in time.

(2) It may cause misoperation of relay protection in distribution system. The fault of adjacent feeders may lead to the misoperation of the line protection where the DG is located.

(3) The fault level of the distribution network has changed. The different number and types of distributed generation will improve or reduce the fault level of distribution network. Distributed generation with large capacity will lead to great change of fault current.

(4) The range of power failure will be enlarged under asynchronous closing. If the distributed generation does not stop running or cut off from the power grid after the fault trip, the asynchronous reclosing will lead to the misoperation of the relay protection device and expand the scope of the accident power failure.

The power distribution system planning (DSP) problem needs further research effort and the DG uncertainties need to be included to the consideration. The development of a reasonable DSP model based on these uncertainties is of primary importance. The solution of DSP model is expected to provide the flexibility to be easily implemented that covering the intermittent DG generation scenarios. In recent years, the planning flexibility has been investigated in many domains, e.g., electric generation portfolios [2], expansion planning of transmission or distribution networks (e.g., [3], [4]). Robust Optimization (RO) has been implemented to address the uncertainties from the renewable DGs [5], [6]. However; the uncertainty set needs to be carefully designed [7] as a small uncertain set that cannot cover the all the possible system uncertain situations.

On the other hand, the authors in [8] developed a robust planning solution based on the Taguchi's orthogonal array (OA) testing. This effectively avoids the choice of an uncertainty set. However, the generated scenarios are extreme and the probability of their occurrence is very little. Moreover, Monte Carlo simulations have also been implemented to generate scenarios [9]-[11]. However, this generally requires a massive number of scenarios to approximate the diversity of the uncertain features, and hence the computational complexity can be prohibitive. Although many solutions have been developed to address the issue through scenario reduction (e.g. [12]-[14]), the efficiency and accuracy still need to be further promoted. To overcome the disadvantages of the aforementioned methods, a heuristic moment matching (HMM) method [15] was adopted for scenario generation of renewable generations.

In this work, the HMM method has been adopted to generate a scenario matrix of WT-PV-LD that covers all possible uncertainties of the combination of WT and PV generation as well as the power demand. A robust DSP problem is formulated through incorporating the scenario matrix into the deterministic planning problem. The proposed solution can provide the optimal fuel mix to minimize the active and reactive power losses.

This work is organized as the following sections: Section II describes the HMM based operational scenario generation method; Section III shows and analyzes the experimental results; Section IV provides the conclusive remarks.

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II. Heuristic Moment Matching Based Scenario Generation

A. HMM Method

At present, due to the uncertainty of power market and policy, the distribution network system itself is a multi-dimensional, nonlinear and complex system. With the access of distributed generation (especially the renewable distributed generation with randomness and uncertainty), the complexity of distribution network system also increases, which puts forward higher technical requirements for the safe and stable operation of distribution network. Therefore, in this chapter, a method based on heuristic moment matching (HMM) can be used to analyze and solve the uncertainty of DG output.

In general, the traditional moment matching method aims to generate scenarios meeting the target moments and correlation, it should be noted that, the calculations involved are associated with intractable high-dimensional discrete variables. The Heuristic Moment Matching (HMM) method avoids complex calculations and can be applied to tackle the stochastic variations associated with renewable-based DGs and load profiles. The adopted HMM approach consisting of two transformations that are described as follows:

- Matrix transformation

The matrix transformation is formulated as in (1):

$$Y = L \times X = \sum_{j=1}^{i} L_{ij} \times X_i \tag{1}$$

where $X_1, X_2, ...X_n$ are independent and L is the lower triangular matrix of R [16], i.e. $R = LL^T$.

- Cubic transformation:

The cubic transformation can be formulated as in (2):

$$Z_i = a_i + b_i Y_i + c_i Y_i^2 + d_i Y_i^3 \tag{2}$$

where $Y_i \varepsilon Y, Z_i \varepsilon Z$, a_i, b_i, c_i and d_i are the transforming coefficients. The k moments of target scenarios $M_{i,k}(Z_i)$ are equal to the k target moments $M_{i,k}{}^T$, as given in (3):

$$M_{i,k}(Z_i) = M_{i,k}{}^T \quad i = 1,2,3 \; k = 1,2,3,4 \tag{3}$$

Here, $i = 1,2,3$ refers to WT generation, PV generation and load profile, respectively.

B. HMM based WT-PV-LD scenario generation

The HMM method is adopted for scenario generation whilst meeting the target moments (i.e. expectation, standard deviation, skewness, kurtosis and correlation) and correlation of historical data of WT/PV generation and power demand. The steps involved are illustrated in Fig. 1.

- Calculate $M^T_{i,k}$ and correlation matrix R using the hourly statistics.
- Normalize the target moments $M_{i,k}{}^{NT}$ and the normalization is based on (4):

$$M_{i,1}{}^{NT} = 0, M_{i,2}{}^{NT} = 1$$

$$M_{i,3}{}^{NT} = \frac{M^T_{i,3}}{\left(\sqrt{M^T_{i,2}}\right)^3}, M_{i,3}{}^{NT} = \frac{M^T_{i,3}}{\left(\sqrt{M^T_{i,2}}\right)^4} \tag{4}$$

- Randomly generate N_h scenarios of WT-PV-LD scenario matrix denoted as $X_{N\_h} = [X_1, X_2, X_3]$, which satisfy the normal distribution $N(0,1)$, where X_1, X_2, X_3 are the scenarios of WT generation, PV generation and load profile, respectively.
- Transform X_{N_h} through matrix transformation to satisfy the target R, where the output is denoted as Y_{N_h}.
- Calculate the transforming a_i, b_i, c_i, d_i and transform Y_{N_h} through cubic transformation, to satisfy the normalized moments $M_{i,k}{}^{NT}$; the output of this step is denoted as Z_{N_h}.
- Obtain the error ε_m between M^G_{ik} and $M_{i,k}{}^{NT}$ by using (5) and the correlation error ε_R can be obtained by (6).

$$\varepsilon_m = \sum_{i=1}^{N_h} \left(\left| M^G_{i1} - M^{NT}_{i1} \right| + \sum_{k=2}^{4} \left| M^G_{ik} - M^{NT}_{ik} \right| \Big/ M^{NT}_{ik} \right) \tag{5}$$

$$\varepsilon_R = \sum_{i=1}^{N_h} \sqrt{ \frac{2}{N_w (N_w - 1)} \sum_{i=1}^{N_w} \sum_{i=1}^{N_w} \left(R_{il}{}^G - R_{il}{}^{NT} \right)^2 } \tag{6}$$

- The normalized scenarios Z_{N_h} can be inverted to satisfy the target moments based on (7).

$$Z_i^T = \sqrt{M_{i,2}{}^N} \times Z_i + M_{i,1}{}^N \tag{7}$$

where $Z_i \varepsilon Z$ and $Z_i^T = [Z_1^T, Z_2^T, Z_3^T]$. Z_i^T is the WT-PV-LD scenario matrix and Z_1^T, Z_2^T, Z_3^T are the generated scenarios of power generation of WT and PV, and the demand.

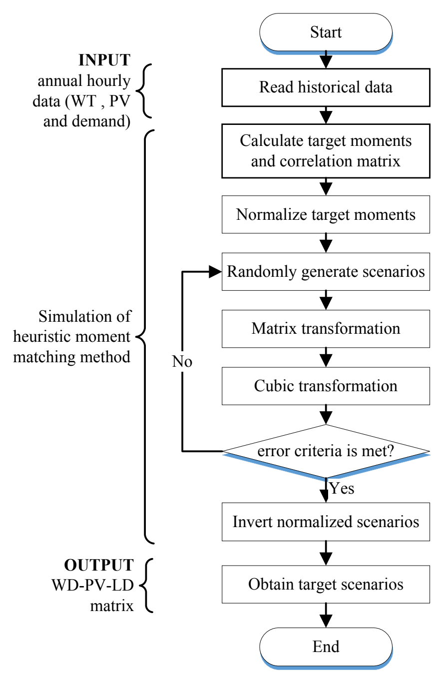


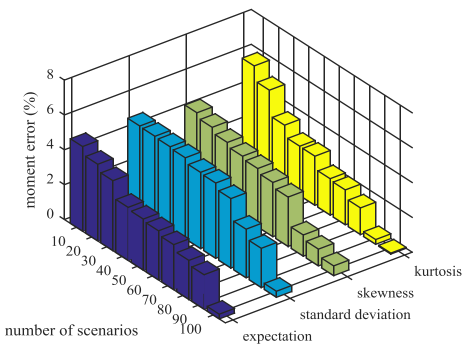
Figure 1. Steps involved in the HMM method.

III. Experimental Analysis And Numerical Results

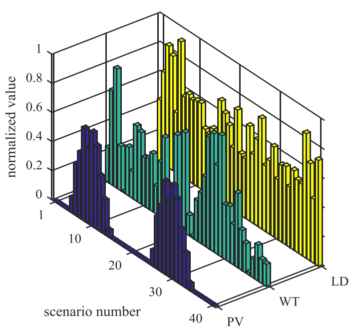
A. Numerical analysis of scenario generation approach

This section adopts the HMM based scenario generation to obtain the scenario matrix through using the available data measurements. Afterwards, these generated scenarios are incorporated into the DSP problem and evaluated through a test distribution system.

The annual historical data of DG generation and power demand (on hourly basis) for the year 2015 are obtained from Electric Reliability Council of Texas [17]. In total 8760 historical data measurements are adopted as the original scenarios. In this work, the threshold correlation and moment errors are set to 5%. The errors of generation scenarios are shown in Fig. 2(a). It can be observed that there is a general decreasing trend in the error of all four moments as the number of scenarios increase and the errors are less than 5%. Therefore, it can be concluded that the HMM method performs well in approximating the uncertainties of the original scenarios. The normalized values of 40 scenarios of the matrix are shown in Fig. 2 (b).



(a)



(b)

Figure 2. HMM based scenario generation: (a) errors between the original and generated scenarios; (b) 40 WT-PV-LD scenarios

B. Comparison with the conventional planning solution

This section conducts the experimental simulations and evaluates the HMM-based planning solution against the conventional planning approach. The performance of the regional energy network planning based on HMM method is evaluated using a test power network with 53 nodes and 61 branches; which consists of 1 substation, 52 load nodes.

The review of literature on the planning of renewable DGs shows that majority of the work considers the power output of the WTs and PVs to be dispatchable. This assumption may not result in determining the optimal fuel mix based on renewable DGs as they are intermittent and their output is non-dispatchable and uncertain. In this section, we have compared the conventional DG planning approach with an HMM-based robust planning approach to establish the significance of considering DG uncertainties in the DSP problem with the help of representative scenarios. The two methods to be compared are as follows:

(1) HMM-based planning approach using 40 WT-PV-LD representative scenarios considering the stochastic generation of WTs and PVs, in addition to and uncertainties of load profile.

(2) Conventional planning approach considering 40 representative scenarios of load profile only and assuming the WT and PV generation controllable.

For each scenario, the total system demand, the total output of optimal fuel mix, power imported from the substation and the lines losses are presented in Fig. 3. It is shown that for each scenario, there is a higher mismatch between the active power DG output and active power demand in the case of the conventional approach as compared to the HMM-based approach, as shown in Fig. 3(a). In the same way, it can be observed that for each scenario, there is a higher mismatch between the reactive power DG output and reactive power demand in the case of the conventional approach as compared to the HMM-based approach, as shown in Fig. 3(b). Therefore, such higher mismatch results in substantially higher reactive power flow between the substation and the distribution nodes and hence higher line losses for each scenario. As a result, the conventional approach results in a higher mean line loss of 58.6 kW and annual active energy losses of 513.34 MWh as compared to that of 39.23 kW and 343.65 MWh in case of HMM-based planning. This corresponds to significant savings of annual active energy of about 33.4 %, i.e. 170 MWh. In this study, only the diesel engine is considered to generate reactive power among the optimal fuel mix.

IV. Conclusions

This paper addresses this challenge by examining the HMM-based scenario generation to fully include the consideration of stochastic power generation and power demands into the distribution network planning process. The scenario generation approach is assessed through numerical experiments in a case study of 53 bus distribution system. The simulation results clearly demonstrated the effectiveness of using scenario generation in addressing the uncertainties in network planning. In future, under the condition that the location and capacity of DG in active distribution network change, a kind of distribution network planning problem based on the self-healing ability of distribution network can be considered, including the location and capacity determination of distributed generation and the line expansion problem of distribution network.

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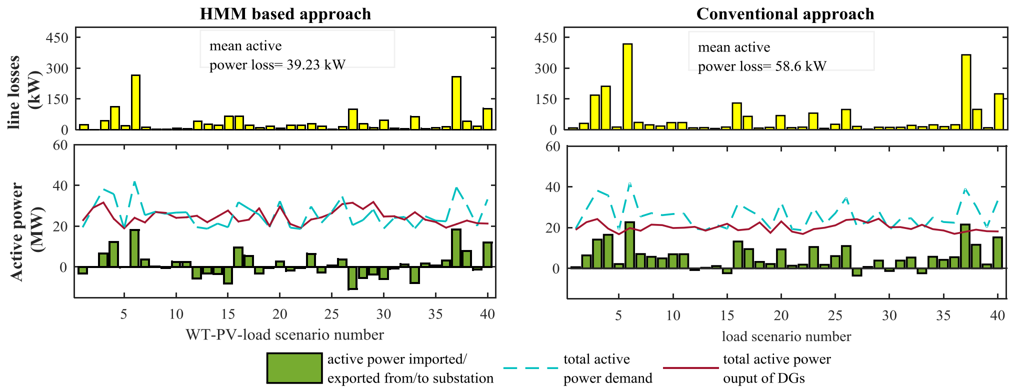
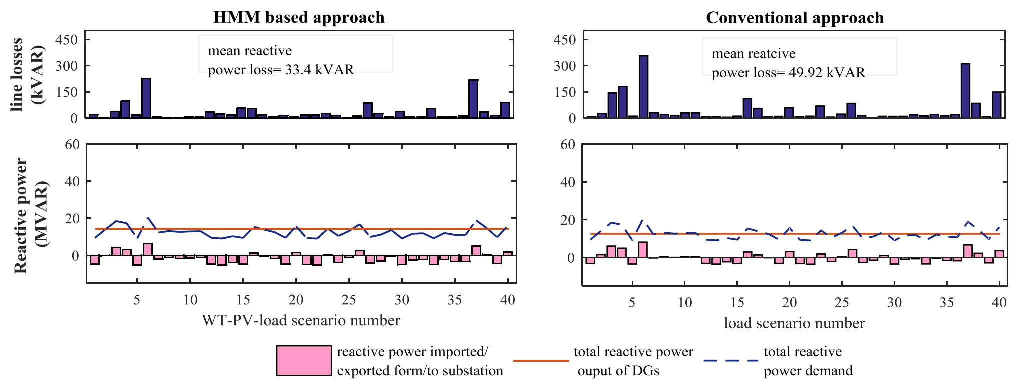


(a)



(b)

Figure 3. DG , demand, substation power and lines losses for HMM-based and conventional approach (a) Active power; (b) Reactive power.

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