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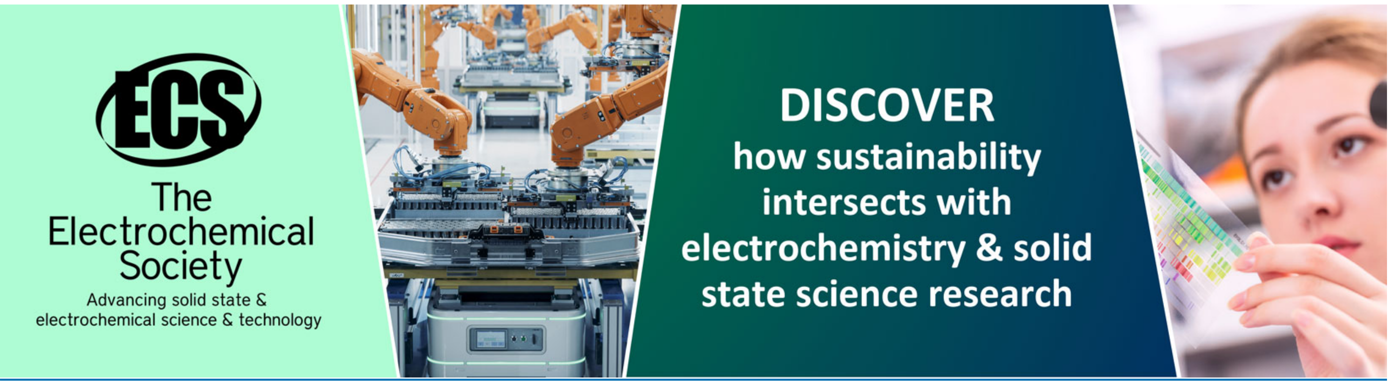

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Probabilistic Energy Flow Analysis for Integrated Energy Systems Considering Correlated Uncertainties

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Abstract. The integrated energy systems (IES) contain various energy sub-systems, thus uncertainties of one sub-system will not only threaten its own safety operation but also be likely to have a significant impact on the operation of other sub-systems. Therefore, it is of great significance to study the variation of state variables when random fluctuations emerge in the IES. This paper proposes a unified steady state probabilistic energy flow (PEF) analysis for the IES considering the correlated uncertainties. Firstly, a Latin hypercube sampling with inverse Nataf transformation is developed to deal with correlated uncertainties of the IES. Furthermore, in order to solve the PEF problem, a unified method, Newton-Raphson embedded with Newton Downhill technique, is proposed to accelerate the iteration and improve the computation efficiency. The effectiveness of the proposed PEF analysis method is verified by a set of test results conducted on an IES composed of the IEEE 118-bus system coupled with 15-natural gas system and 32-district heating system.

1. Introduction

With the increasing penetration of renewable energy sources and other sub-system, like natural gas system (NGS) and district heating system (DHS), jointing up into the electrical power system (EPS), the interconnections of different sub-systems will bring a huge impact on the operation of EPS, but also the other sub-systems [1]. IES operates with many uncertainties such as load demands, outages of devices, the fluctuation of wind-solar power, the change in weather temperature and natural gas pipeline parameters [2]. Thus, it is necessary to study the variation of state variables when random fluctuations emerge in the IES.

The probabilistic power flow (PPF) evaluation, first proposed by Borkowska in the early 1970s [3], is a powerful approach to investigate the steady-state power system operation characteristics under various uncertainties for IES. The methods to solve PPF problems can be classified into three categories, namely simulation methods, approximation methods and analytical methods [4] [5]. Monte Carlo simulation(MCS) is one of the simulation methods that is generally treated as reference results for comparisons, because it has the virtue that can obtain accurate results after a large number of simulations. In order to improve the calculation efficiency of MCS, LHS method is adopted, [6] and [7] applied MCS approach with LHS to solve PEF problems.

In the IES, the input variables may be dependent to each other, when the input random variables depend on each other, variation of one variable affects the other variables too. However, there is a

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defect that the input random variables have no any correlation by using the MCS and LHS with known probability density functions (PDF). To this end, a correlation transformation technique is proposed to tackle the correlation problem. The Copula model [8]–[10] and its modified method, Nataf transformation [4], [11]–[13], Rosenblatt transformation [14] and polynomial normal transformatiom [15] are constantly used to tackle the correlation problem in energy systems. However, there are few researchers who consider the extensive uncertainties of the EPS coupled with NGS and DHS and the uncertainties correlation of wind-solar power [2], [4], [11], [12], [16]. In [11], [17], the two papers established a unified energy flow model of EPS coupled with NGS, but they only considered the PEF of the EPS coupled with NGS without considering the potential effect the wind-solar correlation and the DHS. In this paper, we will focus on the uncertainties each sub-system how to affect the operation of IES.

The main contributions of this paper are summarized as follows:

1) Based on the traditional energy flow model, the modeling techniques and methods of EPS are effectively extended to the modeling of IES and a standardized unified steady-state energy flow model of IES is established.

2) A Newton-Raphson embedded with Newton Downhill (NR-ND) technique is presented to solve unified steady-state energy flow problem, which can overcome the shortcoming of Newton-Raphson (NR) method that is sensitive to the initial point.

3) A Latin hypercube sampling (LHS) with inverse Nataf transformation (INT) is developed to tackle the high-dimensional correlated uncertainties of IES.

This paper is organized as follows: the problem formulation of IES is first described in Section 2. Section 3 then presents the unified steady-state power energy technique, LHS and INT for PEF analysis of IES. The performances of the proposed method are studied in Section 4, and finally, Section 5 concludes this paper.

2. The Problem Formulation of IES

2.1. Uncertainties

For IES, there are various uncertainties such as load demands, outages of devices, the fluctuation of wind-solar power, the change in weather temperature and natural gas pipeline parameters, and etc. Thus, it is of great significance to consider the fluctuations between the EPS couple with other sub-systems.

For EPS, the AC power flow formulation is utilized for the EPS. Hence, active and reactive power injection at i bus can be written as [16]:

$$P_i^{\mathrm{W}} + P_i^{\mathrm{PV}} + P_i^{\mathrm{GEN}} + P_i^{\mathrm{CHP}} + P_i^{\mathrm{GF}} - P_i^{\mathrm{LD}} = V_i \sum_{j \in i} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \tag{1}$$

$$Q_i^{\mathrm{W}} + Q_i^{\mathrm{PV}} + Q_i^{\mathrm{GEN}} - Q_i^{\mathrm{CHP}} + Q_i^{\mathrm{GF}} - Q_i^{\mathrm{LD}} = V_i \sum_{j = i} V_j \left(G_{ij} \cos\theta_{ij} - B_{ij} \sin\theta_{ij} \right) \tag{2}$$

where V_i and V_j are voltage magnitudes of bus i and j, while $\theta_{ij} = \theta_i - \theta_j$ and θ_i and θ_j are voltage angles of those buses. G_{ij} and B_{ij} are the conductance and susceptance of this transmission line, respectively. P_i^{W} and Q_i^{W} are the output power of wind-driven generator; P_i^{PV} and Q_i^{PV} are the output power of photovoltaic generator; P_i^{CHP} and Q_i^{CHP} are the active and reactive power of a combined heating and power (CHP) unit, that is major infrastructure to coupled EPS, NGS and DHS togethor; P_i^{GF} and Q_i^{GF} denote the output power of a gas-fired generator (GF) which is used to couple

EPS and NGS; P_i^{GEN} and Q_i^{GEN} represent the traditional generators of the active and reactive power; P_i^{LD} and Q_i^{LD} are electrical loads.

For NGS, a nodal gas flow balance must be satisfied at each node of the gas infrastructure to assure that the sum of the gas entering and injected is equal to the sum of the gas leaving the node and the total gas withdrawal, which is given by

$$f_m^{\mathrm{GS}} - f_m^{\mathrm{LD}} - f_m^{\mathrm{CHP}} - f_m^{\mathrm{GF}} - \sum_{m=1}^{N_C} f_m^{\mathrm{com}} = \sum_{n=1}^{N_N} f_{mn}^{\mathrm{P}} - \sum_{n=1}^{N_C} f_{mn}^{\mathrm{C}} \tag{3}$$

where f_m^{GS} denotes the amount of gas flow of the gas source connected to node m, f_m^{LD} denote the amount of gas flow consumed by the load. f_m^{CHP} and f_m^{GF} denote as the amount of gas flow consumed by CHP units and GF units, respectively; f_m^{com} is the consumed gas from gas pipeline by a gas-driven compressor. f_{mn}^{P} denotes as the gas flow through a pipeline between nodes m and n, while f_{mn}^{C} denotes the gas flow through the a compressor between nodes m and n. N_N and N_C are the number of the gas nodes and compressors, respectively.

For DHS, it usually consists of supply and return pipelines that deliver heat, in the form of hot water or steam, from the point of generation of the heat to the consumers. A generic framework for steady-state of DHS can be divided into two parts: hydraulic model and thermal model.

The hydraulic model is based on the Kirchhoff's laws: the continuity of flow and the head loss of the network is zero, which is expressed as

$$\begin{cases} \dot{\boldsymbol{m}}_{\mathrm{q}} = \boldsymbol{A}\dot{\boldsymbol{m}} \\ \boldsymbol{BK}\dot{\boldsymbol{m}} \,|\, \dot{\boldsymbol{m}} \,| = 0 \end{cases} \tag{4}$$

where incidence matrix $\boldsymbol{A}$ is without the slack node, $\dot{\boldsymbol{m}}$ is the mass flow within each pipeline, $\dot{\boldsymbol{m}}_{\mathrm{q}}$ is the mass flow through each node injected from a source or discharged to a load. $\boldsymbol{B}$ is the loop incidence matrix that relates the loops to the pipelines. $\boldsymbol{K}$ denotes the resistance coefficients of each pipeline.

The thermal model is used to determine the temperatures at each node.

For heat load nodes, the heat power is calculated by using as following equation

$$\Phi_i^{\mathrm{LD}} = C_{\mathrm{p}} \dot{m}_{\mathrm{LD},i} \left(T_{s,i} - T_{\mathrm{r},i} \right) \tag{5}$$

For heat source nodes (CHP uints), the heat power is calculated as follows:

$$\Phi_i^{\mathrm{CHP}} = C_{\mathrm{p}} \dot{m}_{\mathrm{CHP},i} \left(T_{s,i} - T_{r,i} \right) \tag{6}$$

where C_{p} is the specific heat capacity of water. $T_{s,i}$ and $T_{r,i}$ are the supply temperature and return temperature, respectively.

For heating network, the transferred heat power by a pipeline is calculated using the temperature drop equation [18]:

$$T_{\mathrm{end}} = \left(T_{\mathrm{start}} - T_a \right) e^{-\frac{\xi L}{C_{\mathrm{p}} \dot{m}}} + T_a \tag{7}$$

where T_{start} and T_{end} are the temperatures at the inlet node and the outlet node of a pipeline; T_a is the ambient temperature; ξ is the overall heat transfer coefficient the of each pipeline; L is the length of each pipeline.

As mentioned above, (1) - (7) of the energy injections and bus or pipeline energy of IES can be expressed as:

$$\boldsymbol{W} = f(\boldsymbol{X}) \tag{8}$$

$$\boldsymbol{Z} = g(\boldsymbol{X}) \tag{9}$$

where $\boldsymbol{W} = \left[\boldsymbol{W}_{\mathrm{e}}, \boldsymbol{W}_{\mathrm{g}}, \boldsymbol{W}_{\mathrm{h}}\right]$ is the energy injection vector with a certain correlation of the nodes or buses, the index of e, g and h represent EPS, NGS and DHS. While $\boldsymbol{X} = \left[\boldsymbol{X}_{\mathrm{e}}, \boldsymbol{X}_{\mathrm{g}}, \boldsymbol{X}_{\mathrm{h}}\right]$ for the node or bus state variables, including the bus voltage amplitude and phase angle of EPS, the node pressure of NGS and the node temperature of DHS; $\boldsymbol{Z} = \left[\boldsymbol{Z}_{\mathrm{e}}, \boldsymbol{Z}_{\mathrm{g}}, \boldsymbol{Z}_{\mathrm{h}}\right]$ is the branch or pipeline of the energy flow vector of IES.

In the probabilistic energy flow model, the node or bus energy injection and the state variables are random variables, i.e.

$$\boldsymbol{W}_0 + \Delta\boldsymbol{W} = f(\boldsymbol{X}_0 + \Delta\boldsymbol{X}) \tag{10}$$

where, $\boldsymbol{W}_0$ and $\boldsymbol{X}_0$ are the mean values of the injected energy of the node $\boldsymbol{W}$ and the state variable $\boldsymbol{X}$, respectively. $\Delta\boldsymbol{W}$ and $\Delta\boldsymbol{X}$ are stochastic perturbations, which can be regarded as random variables subject to a certain distribution.

Expanding (10) around the operating point by Taylor series and omitting the items which are higher than twice order, then which is obtained as follows

$$\boldsymbol{W}_0 + \Delta\boldsymbol{W} = f\left(\boldsymbol{X}_0 + \Delta\boldsymbol{X}\right) = f\left(\boldsymbol{X}_0\right) + \boldsymbol{J}_0\Delta\boldsymbol{X} + \cdots \tag{11}$$

$$\Delta\boldsymbol{X} = \boldsymbol{J}_0^{-1}\Delta\boldsymbol{W} \tag{12}$$

where $\boldsymbol{J}_0$ is Jacobian matrix which used for the last iteration of the NR-ND technique. From (12), we can know the $\Delta\boldsymbol{X}$ is the random response of stochastic perturbation $\Delta\boldsymbol{W}$.

From the above-mentioned, when the energy injection of the IES is disturbed, it will affect the state variables of every sub-system.

2.2. Correlation

In the IES, the input random variable $\boldsymbol{W}$ contain the eletricity/gas/heat loads, the output power of wind-driven generator and photovoltaic generator, and etc. In simulation, many approaches were proposed with assuming no correlations among those random variables. However, in the actual scene, such as wind/photovoltaic/weather temperature and various kinds of loads, there is a certain correlation between them. Therefore, it is necessary to introduce a certain transformaiton method to transform the non-correlated random variables into the correlated ones, which is described mathematically as follows.

$$\boldsymbol{W} = T(\boldsymbol{S}) \tag{13}$$

where T is the a certain transformaiton, $\boldsymbol{S}$ is the non-correlated random variables, where $\boldsymbol{S} = [\boldsymbol{S}^{\mathrm{W}}, \boldsymbol{S}^{\mathrm{PV}}]$ in this paper, $\boldsymbol{S}^{\mathrm{W}}$ and $\boldsymbol{S}^{\mathrm{PV}}$ denote the wind speed and solar radiation, respectively.

3. PEF analysis of IES

3.1. Latin hypercube sampling

The LHS is adopted, in order to obtain the input samples of N random variables with a size of K for the probabilistic energy flow efficiently. The purpose of LHS in this paper is to generate representative samples reflecting the distribution of each input random variable. The basic principles of LHS can be found [7] and the main idea is described below.

Let the sample matrix $\boldsymbol{S}$ of size $n \times k$ is shown below

$$\boldsymbol{S} = \begin{bmatrix} s_{11} & x_{12} & \cdots & s_{1k} \\ s_{21} & s_{22} & \cdots & s_{2k} \\ \vdots & \vdots & \cdots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nk} \end{bmatrix} \tag{14}$$

where the sample s_{ij} is generated as follows.

$$s_{ij} = \Phi^{-1}\left(\frac{\theta_{ij} - \mu_{ij}}{n}\right) \quad i = 1, \cdots, n; j = 1, \cdots, k \tag{15}$$

where $\Phi^{-1}(\bullet)$ is the inverse cumulative distribution function (CDF), θ_{ij} is a random permutation, and μ_{ij} is a uniformed random variable.

3.2. Inverse Nataf transformation

Nataf transformation is to map a given set of correlated random variables $\boldsymbol{W}$ with a correlation coefficient matrix $\mathbf{R}_{\mathrm{W}}$ to the set of uncorrelated variables $\boldsymbol{S}$. Inversely, the INT is to map a set of uncorrelated variables to the set of correlated random variables. The detail introduction of Nataf transformatiom and the INT can be found [14] and the main idea of INT is show as below.

The INT $T_1 : \boldsymbol{S} \to \boldsymbol{U}$ is the composition of two functions $T = T_2 \circ T_1$

$$T_1 : \boldsymbol{S} \to \boldsymbol{U} = \boldsymbol{LS} \tag{16}$$

$$T_2 : U_i \to W_i = F_{W_i}^{-1}\left(\Phi\left(U_i\right)\right) \quad i = 1, \ldots, n \tag{17}$$

$\boldsymbol{U}$ is correlated standard Gaussian variables with a correlation coefficient matrix $\mathbf{C}_{\mathrm{U}}$, where $\boldsymbol{L}$ satisfies the equation $\mathbf{C}_{\mathrm{U}} = \boldsymbol{LL}^T$, in which $\boldsymbol{L}$ is a lower triangular matrix and can be obtained by means of Cholesky decomposition on $\mathbf{C}_{\mathrm{U}}$. The $\Phi(\bullet)$ is the CDF of the ith Gaussian random variable U_i and $F_{W_i}^{-1}(\bullet)$ is the inverse function of the corresponding CDF of the random variable W_i.

3.3. NR-ND technique

The unified energy flow of a IES consisting of electricity, natural gas, and heat sub-system can be obtained by combining the stated flow formulations of each energy flow while considering the interdependencies. Therefore, a set of non-linear equations is achieved which should be solved for the state variables of IES. These nonlinear set of (1) - (7) can be summarized in a vector of total mismatches $\Delta \boldsymbol{F}$ that as follows:

$$\Delta \boldsymbol{F} = \begin{bmatrix} \Delta \boldsymbol{P} & \Delta \boldsymbol{Q} & \Delta \boldsymbol{f} & \Delta(\phi, \boldsymbol{p}) & \Delta \boldsymbol{T}_s & \Delta \boldsymbol{T}_r \end{bmatrix} \tag{18}$$

where $\Delta \boldsymbol{P}$ and $\Delta \boldsymbol{Q}$ denote as the set of mismatches of active and reactive power of EPS. $\Delta \boldsymbol{f}$ is the mismatches of the sum of the gas leaving the node minus the total gas withdrawal in NGS. $\Delta(\phi, \boldsymbol{p})$ is the heat power mismatches and loop pressure mismatches of DHS. $\Delta \boldsymbol{T}_s$ and $\Delta \boldsymbol{T}_r$ represent the supply temperature mismatches and return temperature mismatches of DHS. The details of NGS and the DHS can be referred to and [18] and [19].

(18) should be solved for a set of unknown variables given by:

$$\boldsymbol{X}_{\mathrm{IES}} = \begin{bmatrix} \boldsymbol{\theta} & |\boldsymbol{V}| & \boldsymbol{\pi} & \boldsymbol{H} & \dot{\boldsymbol{m}} & \boldsymbol{T}_s & \boldsymbol{T}_r \end{bmatrix} \tag{19}$$

where $\boldsymbol{\theta}$ and $|\boldsymbol{V}|$ indicate the voltage angle and magnitude, respectively. $\boldsymbol{\pi}$ is the node pressure and $\boldsymbol{H}$ represents the horsepower the compressor needed. $\dot{\boldsymbol{m}}$ is the mass flow within each pipeline, $\boldsymbol{T}_s$ denotes the supply temperature and $\boldsymbol{T}_r$ represents the return temperature of DHS.

For the sake of simplicity, let $\Delta\boldsymbol{F}_{\mathrm{e}} = \left[\Delta\boldsymbol{P}, \Delta\boldsymbol{Q}\right]$, $\Delta\boldsymbol{F}_{\mathrm{g}} = \Delta\boldsymbol{f}$, $\Delta\boldsymbol{F}_{\mathrm{e}} = \left[\Delta(\boldsymbol{\phi}, \boldsymbol{p}),\ \Delta\boldsymbol{T}_s,\ \Delta\boldsymbol{T}_r\right]$, $\boldsymbol{X}_{\mathrm{e}} = \left[\boldsymbol{\theta},\ |\boldsymbol{V}|\right]$, $\boldsymbol{X}_{\mathrm{g}} = \left[\boldsymbol{\pi}, \boldsymbol{H}\right]$, $\boldsymbol{X}_{\mathrm{h}} = \left[\dot{\boldsymbol{m}},\ \boldsymbol{T}_s, \boldsymbol{T}_r\right]$.

The Newton-Raphson technique can be generalized to multiple dimensions. In this manner, the iterative scheme is

$$\Delta\boldsymbol{X}_{\mathrm{IES}}^{(k)} = -\left[\boldsymbol{J}^{(k)}\right]^{-1} \Delta\boldsymbol{F}^{(k)} \tag{20}$$

$$\boldsymbol{X}_{\mathrm{IES}}^{(k+1)} = \boldsymbol{X}_{\mathrm{IES}}^{(k)} + \Delta\boldsymbol{X}_{\mathrm{IES}}^{(k)} \tag{21}$$

where k is the current iteration and $\boldsymbol{J}$ is the Jacobian matrix. The integrated Jacobian matrix $\boldsymbol{J}$ is derived from the mismatches $\Delta\boldsymbol{F}$. It consists of nine submatrices: electricity submatrix $\boldsymbol{J}_{\mathrm{ee}}$, gas to electricity submatrix $\boldsymbol{J}_{\mathrm{eg}}$, heat to electricity submatrix $\boldsymbol{J}_{\mathrm{eh}}$, electricity to gas submatrix $\boldsymbol{J}_{\mathrm{ge}}$, gas submatrix $\boldsymbol{J}_{\mathrm{gg}}$, heat to gas submatrix $\boldsymbol{J}_{\mathrm{gh}}$, electricity to heat submatrix $\boldsymbol{J}_{\mathrm{he}}$, gas to heat submatrix $\boldsymbol{J}_{\mathrm{hg}}$ and heat submatrix $\boldsymbol{J}_{\mathrm{hh}}$, which is calculated as below.

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{J}_{\mathrm{ee}} & \boldsymbol{J}_{\mathrm{eg}} & \boldsymbol{J}_{\mathrm{eh}} \\ \boldsymbol{J}_{\mathrm{ge}} & \boldsymbol{J}_{\mathrm{gg}} & \boldsymbol{J}_{\mathrm{gh}} \\ \boldsymbol{J}_{\mathrm{he}} & \boldsymbol{J}_{\mathrm{hg}} & \boldsymbol{J}_{\mathrm{hh}} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{e}}}{\partial\boldsymbol{X}_{\mathrm{e}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{e}}}{\partial\boldsymbol{X}_{\mathrm{g}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{e}}}{\partial\boldsymbol{X}_{\mathrm{h}}} \\ \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{g}}}{\partial\boldsymbol{X}_{\mathrm{e}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{g}}}{\partial\boldsymbol{X}_{\mathrm{g}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{g}}}{\partial\boldsymbol{X}_{\mathrm{h}}} \\ \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{h}}}{\partial\boldsymbol{X}_{\mathrm{e}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{h}}}{\partial\boldsymbol{X}_{\mathrm{g}}} & \dfrac{\partial\Delta\boldsymbol{F}_{\mathrm{h}}}{\partial\boldsymbol{X}_{\mathrm{h}}} \end{bmatrix} \tag{22}$$

Each energy sub-system interacts with each other through the coupling devices, then affecting the distribution of energy flow of the whole system. While (22) of the off-diagonal blocks represent the coupling devices with other energy sub-systems.

Due to the NR of (20) - (21) has a defect that it is sensitive to the initial point. Moreover, the main disadvantage of the nodal method of NGS is the poor convergence characteristics for gas flow problems. The nodal equations contain square-root or close to square-root type terms in NGS gas flow [20]. Therefore, a step-factor λ is introduced to solve the combined energy flow problem, i.e. Newton-Raphson technique embedded with Newton Downhill (NR-ND), which is show as (23).

$$\mathbf{X}_{\mathrm{IES}}^{(k+1)} = \mathbf{X}_{\mathrm{IES}}^{(k)} + \lambda\Delta\mathbf{X}_{\mathrm{IES}}^{(k)} \tag{23}$$

where the processing technique of the step-factor λ is shown in Table 1 and the framework of the proposed method for IES as shown in Fig. 1.

3.4. Detail steps of LHS with INT for PEF of IES

According to the description in the previous section, the flowchart of the proposed method for unified energy flow probability analysis of IES considering correlated uncertainty is expressed in Fig. 2.

Table 1. The processing technique of the step-factor.

set: $\lambda^{(k)} = 1$, $f_1 = \left\| f\left(\boldsymbol{X}_{\mathrm{g}}^{(k)}\right)\right\|_2$

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$\boldsymbol{Y} = \boldsymbol{X}_{\mathrm{g}}^{(k)} + \lambda^{(k)} \Delta \boldsymbol{X}_{\mathrm{g}}^{(k)}$, $\mathrm{eps} = \| f(\boldsymbol{Y}) \|_2 - f_1$

While $\mathrm{eps} > 0$;

$\lambda^{(k)} = \lambda^{(k)} / 2$

$\boldsymbol{Y} = \boldsymbol{X}_{\mathrm{g}}^{(k)} + \lambda^{(k)} \Delta \boldsymbol{X}_{\mathrm{g}}^{(k)}$

$\mathrm{eps} = \| f(\boldsymbol{Y}) \|_2 - f_1$

End

Output $\lambda^{(k)}$

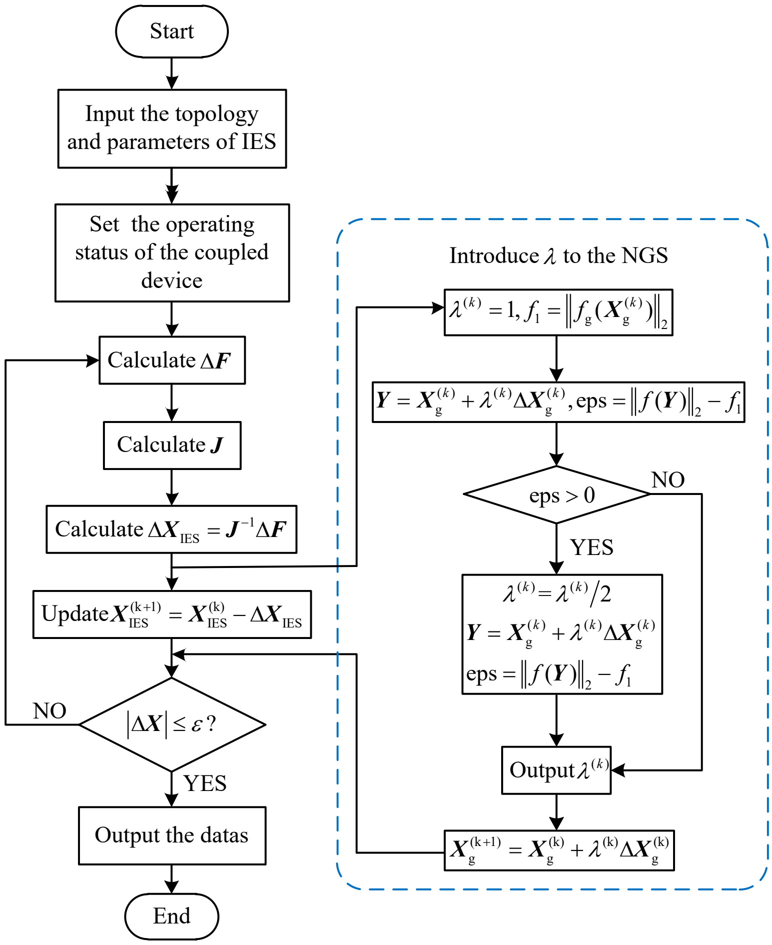

Figure 1. The framework for the proposed NR-ND method.

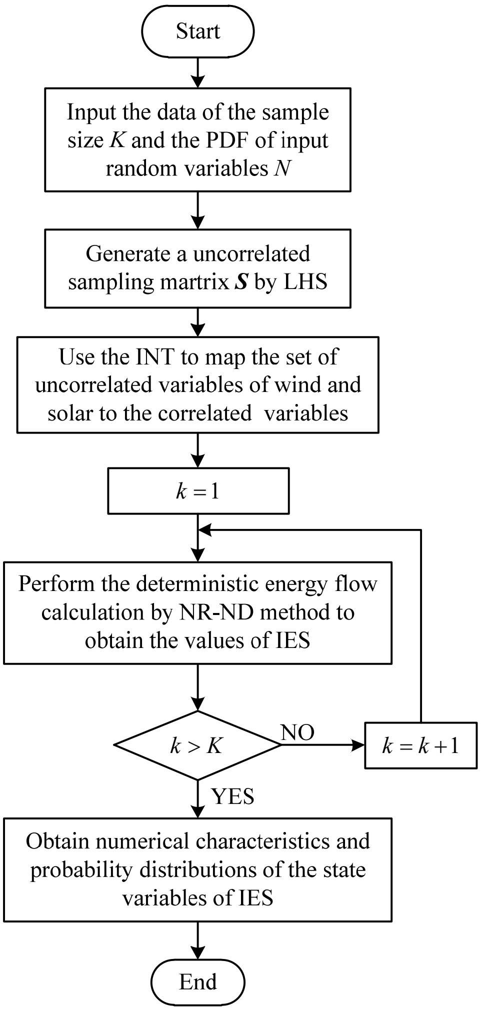

Figure 2. The framework of LHS with INT for probabilistic power flow method by NR-ND.

4. Case study

4.1. Test System Description

The test IES applied in the IEEE 118-bus system (EPS) coupled with 15-natural gas system (NGS) and 32-district heating system (DHS). The network topology of NGS and DHS is shown in Fig. 3. This EPS includes 99 loads in total, all of which are treated as the random variables. The 99 loads are divided equally into 2 groups according to their bus numbers. The first half loads follow normal distribution and the second half are modeled as T distribution. The generators located in bus 10, 69, 80 and 89 are regarded as traditional generators. Eight wind farms installed at bus 12, 25, 26, 31, 46, 49, 54, and 59 of EPS, and four photovoltaic power plants which modeled as beta distribution are connected at bus 61, 65, 66, and 87. The random variables of the first four wind generators are modeled as Weibull distributions and the last four wind generators follow Lognormal distributions, and heat load and gas load both follow normal distribution [4] [18] [21].

The following several scenarios are designed in this subsection to investigate the effects of uncertainties of each sub-system on the whole IES.

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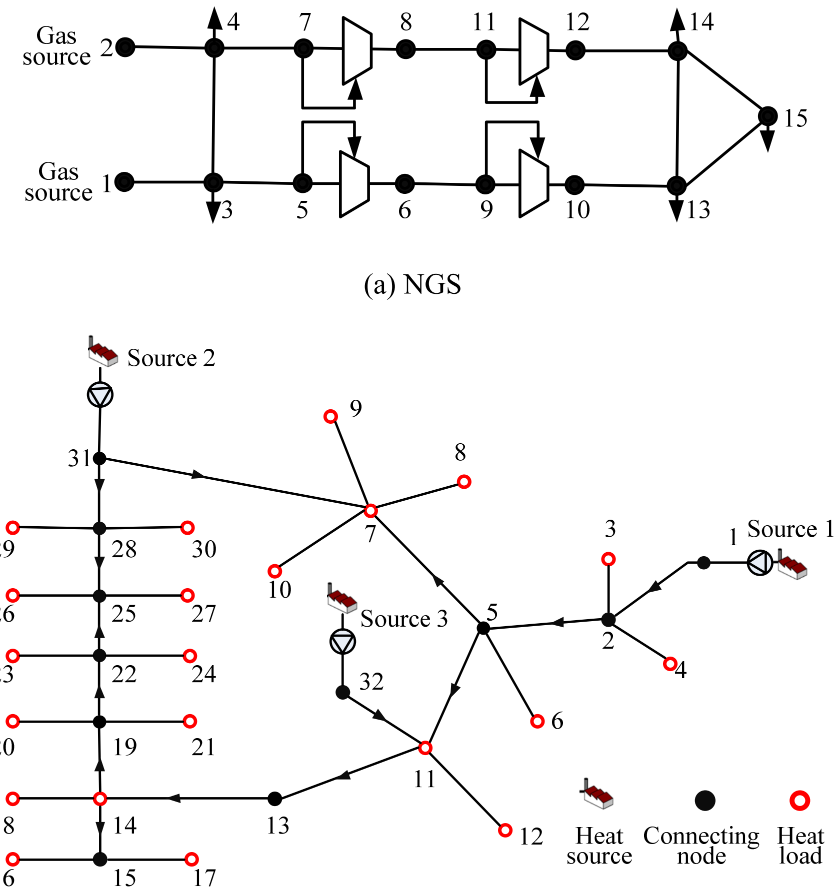


(a) NGS

(b) DHS

Figure 3. The topology of NGS and DHS.

- Scenario 1: IES operates decoupled without considering the wind-solar correlation.
- Scenario 2: IES operates decoupled with considering the wind-solar correlation.
- Scenario 3: EPS coupled with NGS with considering the wind-solar correlation. The two sus-systems are connected via three gas-fired units. Gas-fired (GF) units are located at node 13, 14 and 15 of NGS and bus 100, 103 and 111 of EPS. The operating mode of the GF units is modelled as following the gas load (FGL).
- Scenario 4: EPS coupled with DHS with considering the wind-solar correlation, which connected via three combined heat and power (CHP) units. CHP units are located at node 1, 31 and 32 of DHS and bus 100, 103 and 111 of EPS. The operating mode of the CHP units is set as following the heat load (FTL).
- Scenario 5: EPS coupled with NGS and DHS with considering the wind-solar correlation, the three sus-systems are connected via three CHP units and two GF units. EPS coupled with DHS via three CHPs is the same as Case4, and CHP units are located at the node 13, 14, and 15 of NGS. Two GF units are located at node 3, 4 of NGS and bus 112 and 116 of EPS.

4.2. Analysis of NR-ND method

In this subsection, we use the case of EPS coupled with NGS and DHS to verify the proposed method, and all input variables are deterministic. As shown in Fig. 4, it can be seen that oscillatory convergence occurs in the iteration process when NR is used to solve the power flow problem of IES, and the number of convergence is 20 times. When a factor λ is introduced, i.e. NR-ND, the convergence speed is accelerated, which is much better than NR, moreover, it only need 7 times to reach convergence.

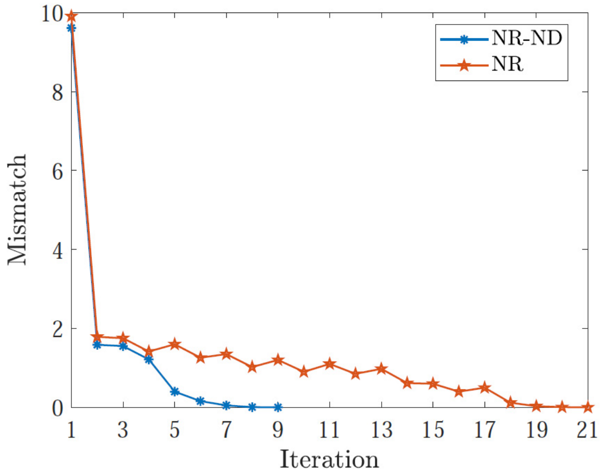


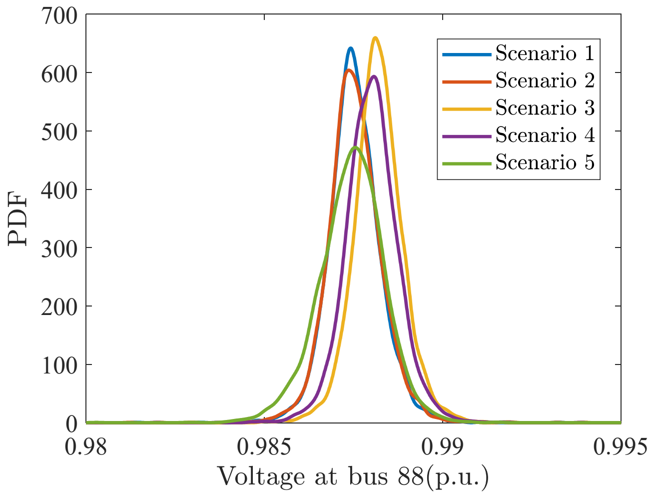
Figure 4. The process iteration of NR and NR-ND.

4.3. Probabilistic analysis of IES

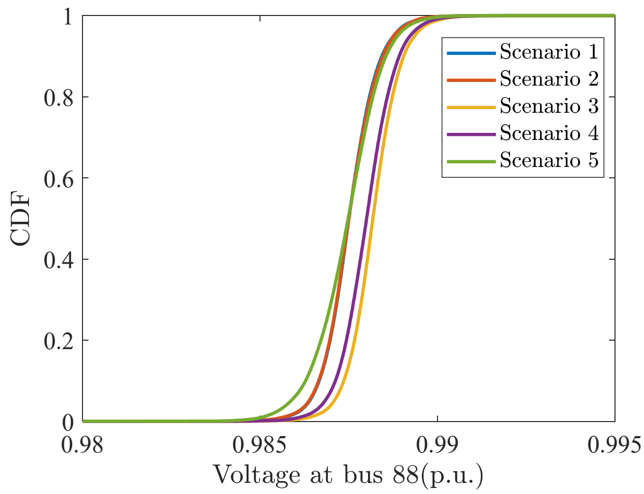
4.3.1. For EPS: In all scenarios, the sub-system EPS of the bus voltage in the IES are both studied by probabilistic energy to verify the effect of random factors and the other two sub-systems are introduced on the state variables. For the sake of simplicity, we only select some typical buses and nodes in the IES. Comparing the curve fitting at bus 88 in different scenarios. As Fig. 5 shows, it is clear that the bus voltage is no longer a constant when there appears a fluctuation of bus injection, intuitively. In scenario 5, the voltage fluctuation is the largest, while in scenario 1 is the smallest. From the scenario 1 to scenario 5, it can be seen that considering the wind-solar correlation and the volatility of the NGS and DHS, it has an important impact on the safe and stable operation of the EPS. In order to show the voltage fluctuation, intuitively. Two indexes are introduced to show the voltage fluctuation, which are L-index (Voltage stability) and Var-index (Voltage fluctuation) [22]. The Var-index is defined as the average variance of all nodes fluctuating at different input sample variables, and it is formulated as follows.

$$\psi = \frac{\sum_{i=1}^{N} \mathrm{var}(\mathrm{V}(i,:))}{N} \tag{24}$$

where var means the variance function. N indicates the number of the system buses. $\mathrm{V}(i,:)$ refers to the row matrix of voltage fluctuations of bus i at different input sample variables. The corresponding different type of voltage index are summarized in Table 2. As can be seen from the table, from the point of voltage stability and voltage fluctuation, when considering the wind-solar correlation, DHS and NGS coupled with EPS, which the fluctuation and uncertainty will seriously affect the safe and stable operation of the EPS.



(a) PDF



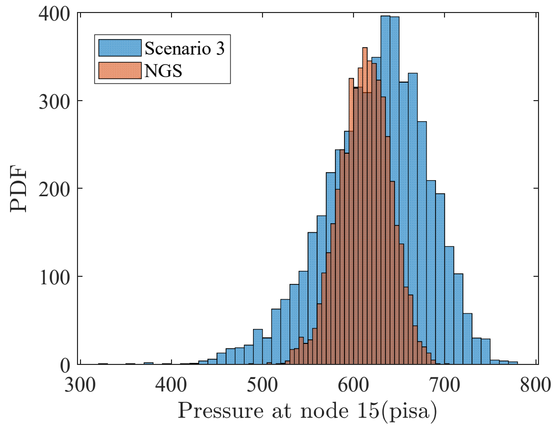
(b) CDF

Figure 5. The EPS of the voltage of the PDF and CDF in different scenarios at bus 88.

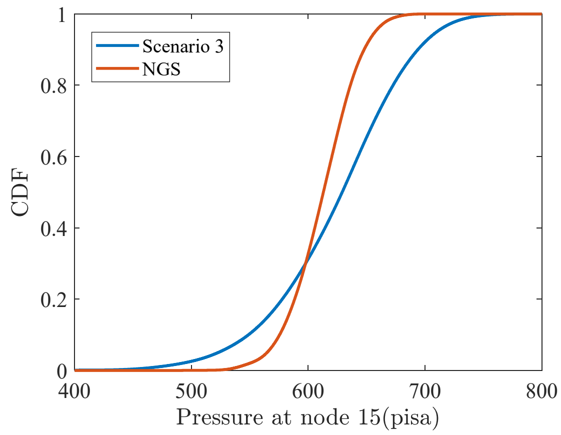
Table 2. Voltage fluctuation of different type and operation states.

Index / Scenario	L-index	Var-index($\times 10^4$)
Scenario 1	1.0577	1.3748
Scenario 2	1.0579	2.4176
Scenario 3	1.0592	2.4938
Scenario 4	1.0609	2.5361
Scenario 5	**1.0693**	**2.6067**

4.3.2. For NGS: As show in Fig. 6 NGS in the Fig. 6 denotes the node pressure in the natural gas system when only the the input variables of gas load are considered. It is clear that the node pressure of scenario 3 fluctuates more than that of NGS, and the node pressure is no longer a constant when there appears a fluctuation of node injection in the above scenario.



(a) PDF



(b) CDF

Figure 6. The NGS of the pressure of the PDF and CDF in different scenarios at node 15.

5. Conclusion

This paper has established a unified steady-state power energy model of IES, and then a probabilistic energy flow analysis for IES considering the correlated uncertainties of wind-solar power, electricity/gas/heat loads is proposed. The NR-ND embedded with LHS and INT developed to solve the PEF problem of IES. According to the simulation results above, the conclusions can be summarized as that: 1) The NR-ND technique can accelerate the iteration and improve the computation efficiency compared with the NR technique 2) The uncertainties and correlations of different energy carriers will pose non-negligible impacts on IES, especially for EPS and NGS. The potential risks to the operation of IES may be underestimated if they are neglected.

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References

[1] G. Wang, H. Xin, D. Wu, P. Ju, and X. Jiang, "Data-driven arbitrary polynomial chaos-based probabilistic load flow considering correlated uncertainties," IEEE Transactions on Power Systems, vol. 34, no. 4, pp.3274–3276, 2019.

[2] X. Deng, P. Zhang, K. Jin, J. He, X. Wang, and Y. Wang, "Probabilistic load flow method considering large-scale wind power integration," Journal of Modern Power Systems and Clean Energy, vol. 7, no. 4,pp. 813–825, 2019.

[3] B. R. Prusty and D. Jena, "A critical review on probabilistic load flow studies in uncertainty constrained power systems with photovoltaic generation and a new approach," Renewable and Sustainable Energy Reviews, vol. 69, pp. 1286 – 1302, 2017.

[4] X. Lin, Y. Jiang, S. Peng, H. Chen, J. Tang, and W. Li, "An efficient nataf transformation based probabilistic power flow for high-dimensional correlated uncertainty sources in operation," International Journal of Electrical Power & Energy Systems, vol. 116, p. 105543, 2020",.

[5] C. Chen, W. Wu, B. Zhang, and H. Sun, "Correlated probabilistic load flow using a point estimate method with nataf transformation," International Journal of Electrical Power & Energy Systems, vol. 65, pp. 325 – 333, 2015.

[6] Y. Chen, J. Wen, and S. Cheng, "Probabilistic load flow method based on nataf transformation and latin hypercube sampling," IEEE Transactions on Sustainable Energy, vol. 4, no. 2, pp. 294–301, 2013.

[7] H. Yu, C. Y. Chung, K. P. Wong, H. W. Lee, and J. H. Zhang,"Probabilistic load flow evaluation with hybrid latin hypercube sampling and cholesky decomposition," IEEE Transactions on Power Systems, vol. 24, no. 2, pp. 661–667, 2009.

[8] G. Papaefthymiou and D. Kurowicka, "Using copulas for modelling stochastic dependence in power system uncertainty analysis," IEEE Transactions on Power Systems, vol. 24, no. 1, pp. 40–49, 2009.

[9] I. Konstantelos, M. Sun, S. H. Tindemans, S. Issad, P. Panciatici, and G. Strbac, "Using vine copulas to generate representative system states for machine learning," IEEE Transactions on Power Systems, vol. 34, no. 1, pp. 225–235, 2019.

[10] L. Bin, M. Shahzad, Q. Bing, M. U. Shoukat, M. Shakeel, and E. K. Mohammedsaeed, "Probabilistic computational model for correlated wind farms using copula theory," IEEE Access, vol. 6, pp. 14179–14187, 2018.

[11] Y. Hu, H. Lian, Z. Bie, and B. Zhou, "Unified probabilistic gas and power flow," Journal of Modern Power Systems and Clean Energy, vol. 5, no. 3, pp. 400–411, 2017.

[12] L. Yang, X. Zhao, X. Hu, G. Sun, and W. Yan, "Probabilistic power and gas flow analysis for electricity-gas coupled networks considering uncertainties in pipeline parameters," in 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), 2017, pp. 1–6.

[13] P. Liu and A. Der Kiureghian, "Multivariate distribution models with prescribed marginals and covariances," Probabilistic Engineering Mechanics, vol. 1, no. 2, pp. 105–112, 1986.

[14] M. Rosenblatt, "Remarks on a multivariate transformation," Annals of Mathematical Statistics, vol. 23, no. 3, pp. 470–472, 1952.

[15] X. Chen and Y. Tung, "Investigation of polynomial normal transform," Structural Safety, vol. 25, no. 4, pp. 423–445, 2003.

[16] A. Shabanpour-Haghighi and A. R. Seifi, "An integrated steady-state operation assessment of electrical, natural gas, and district heating networks," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3636–3647, 2016.

[17] X. Deng, P. Zhang, H. Liu, J. He, L. Wu, X. Wang, and Y. Wang, "An improved cumulant-based probabilistic energy flow computation method for integrated electricity and natural gas systems," in 8th Renewable Power Generation Conference (RPG 2019), 2019, pp. 1–7.

[18] X. Liu, J. Wu, N. Jenkins, and A. Bagdanavicius, “Combined analysis of electricity and heat networks,” Applied Energy, vol. 162, pp. 1238 –1250, 2016.
[19] S. An, Q. Li, and T. W. Gedra, “Natural gas and electricity optimal power flow,” in Transmission and Distribution Conference and Exposition, 2003 IEEE PES, 2004, pp. 138–143 Vol.1.
[20] Q. Li and T. Gedra, “Solving natural gas loadflow problems using electric loadflow techniques,” 2003.
[21] P.-L. Liu and A. Der Kiureghian, “Multivariate distribution models with prescribed marginals and covariances,” Probabilistic Engineering Mechanics, vol. 1, no. 2, pp. 105 – 112, 1986.
[22] J. H. Zheng, J. J. Chen, Q. H. Wu, and Z. X. Jing, “Multi-objective optimization and decision making for power dispatch of a large-scale integrated energy system with distributed DHCs embedded,” Applied Energy, vol. 154, pp. 369 – 379, 2015.