Sensitivity Analysis of Island Micro-Grid Based on Probabilistic Load Flow Model

Yu Ye*
Ningxia Information and Communication Corporation of State Grid
Yinchuan, 750001
E-mail: afeier81@163.com

Guo Jingwei
Ningxia Information and Communication Corporation of State Grid
Yinchuan, 750001

Zhang Lizhong
Ningxia Information and Communication Corporation of State Grid
Yinchuan, 750001

Liu Siyao
Ningxia Information and Communication Corporation of State Grid
Yinchuan, 750001

***Abstract*—In the global energy crisis and environmental pollution problems, vigorous development of clean energy is a common initiative of all countries in the world. As an important means of new energy consumption and reliability improvement of power supply, micro-grid has a very broad development prospect. In order to overcome the problem of low efficiency of traditional MCS calculation, an micro-grid GSA method based on sparse polynomial chaotic expansion in the paper is proposed, which is used to accurately and quickly identify key input random variables that affect the operating state of the system. Furthermore, the accuracy and efficiency of the proposed method are verified by the example analysis of the island micro-grid.**

Keywords-Load Flow Model; Island Micro-Grid; Sensitivity Analysis

I. INTRODUCTION

In order to cope with the global energy crisis and environmental pollution, vigorous development of clean energy is a common initiative of all countries in the world. The micro-grid is used as an integrated distributed power source, energy storage system, and load distribution system. and can effectively eliminate clean energy and has broad development prospects. However, as the penetration rate of renewable energy sources continues to increase, the uncertainties caused by intermittent energy sources such as wind power and solar energy increase, and the stable operation of the micro-grid is challenged. Therefore, it is of great value to study the influence of uncertain factors on the stable operation of micro-grids. In order to improve the computational efficiency of FSI and TSI, an micro-grid power flow proxy model based on SPCE in the paper is presented. The output of the system is represented by a sparse chaotic polynomial with random variables, and the polynomial coefficients are determined by a small number of input and output samples. The chaotic polynomial is used as the proxy model to achieve fast calculation of GSA indicators[1-2].

II. ISLAND MICRO-GRID PROBABILISTIC LOAD FLOW MODEL

A. *droop control DG device model*

In the island-connected micro-grid load flow model under integrated control, the DG device is usually processed into three types of nodes: PQ node, PV node and droop control node. Generally, the application of inductive components such as transformers and filters and the virtual impedance method are considered. The equivalent impedance of the line is inductive. The droop control node often adopts the control strategy of Pf/QU, So the power equation of the droop control node i in the island micro-grid is

$$\begin{cases} P_{Di} = \dfrac{1}{m_{pi}}(\omega_o - \omega) \\ Q_{Di} = \dfrac{1}{n_{qi}}(\mu_{oi} - \mu_i) \end{cases} \quad (1)$$

In equation (1), PDI and QDI are the active and reactive power of the droop control node *i* flowing into the system, respectively; M_{pi} and n_{qi} are the droop gains of the active and reactive power of the droop control node i, respectively[3]; ω_o and μ_{0i} are the system no-load angular frequency and the no-load output voltage amplitude of node i, respectively; ω and μ_i are the angular frequency of the actual run time system and the output voltage amplitude of node i, respectively.

B. Probabilistic load flow equation of island micro-grid

In the island alternating current (AC) micro-grid operation, the system frequency is generally unstable at the industrial frequency. Therefore, the impact of node voltage and frequency on the static model of the load needs to be considered. The PQ node, PV node, droop control node and load model in the integrated island AC micro-grid need to establish the load flow equation of the island AC micro-grid, as follows.

$$\begin{cases} g_{1,i}^{P}(\omega,\mu,\lambda) = P_{gi} - P_{li} - P_i = 0 \quad i \in \Omega_{pQ} \\ g_{1,i}^{Q}(\omega,\mu,\lambda) = Q_{gi} - Q_{li} - Q_i = 0 \quad i \in \Omega_{pQ} \\ \vdots \\ g_{3,i}^{Q}(\omega,\mu,\lambda) = \dfrac{\mu_{gi} - \mu_i}{n_{qi}} - Q_{li} - Q_i = 0 \quad i \in \Omega_D \end{cases} \quad (2)$$

In equation (2), μ and λ are the node voltage amplitude and phase angle vector to be obtained, respectively; Q_{Gi} is the reactive power output by the RDG at node i; P_{Li} and Q_{Li} are the active and reactive loads at node i respectively. When the node is an EVs fast charging station, the active and reactive loads correspond to P_{Ei} and Q_{Ei} respectively; P_i and Q_i respectively input active and reactive power for node i; ΩPQ, ΩPV, and ΩD are the set of PQ, PV, and droop control nodes in the island micro-grid, respectively[4-5]. It should be noted that when the output power of the PV node or the droop control node exceeds the limit value, the node type will be converted into a PQ node, and the power flowing into the micro grid will remain at a limit value. At the same time, because the frequency variation has little influence on the line parameter model, the line parameters in the paper is set to remain unchanged during the power flow calculation process of the island AC micro-grid. When considering the uncertainty factor, the active and reactive power of the RDG and the active and reactive power of the load node in the island micro-grid are the input random variables of the system, which can be further expressed as:

$$G(x,\zeta) = 0 \quad (3)$$

In equation (3), $x = [\omega, \mu^T, \lambda^T]^T$ ξ is a vector of input random variables. Equation (3) is the probabilistic load flow equation of the island AC micro-grid. The required quantity x is the output random variable of the system, which include the system frequency, the node voltage and the phase angle. After obtaining the samples of the input random variable ξ, which consists of RDG output and load, the probability distribution characteristics of the output random variable x are often obtained by MCS for multiple deterministic load flow calculations, and the deterministic island micro-grid load flow calculation can be solved by the applied method[6-7].

III. GSA METHOD

Based on the theory of variance analysis, mathematician Sobol proposed a GSA method and defined various levels of global sensitivity indicators to evaluate the effect of a single input variable or multiple input variables on the system output. Among them, the first-order sensitivity index and the total sensitivity index are commonly used GSA indicators. Generally, FSI and TSI expressions can be obtained from the conditional variance equation.

The function Y=g(ξ) is defined on the space Rk, where the random variable ξ=[ξ1,ξ2,...,ξk] is input. According to the conditional variance, the equation is

$$D(Y) = D_{\xi i}\left[E_{\xi i}\left(Y|\zeta_i\right)\right] + E_{\xi i}\left[D_{\xi i}\left(Y|\zeta_i\right)\right] \quad (4)$$

In addition to ξi, input random variables are vectors; Eξ(~i)(Y|ξi) is a conditional expectation based on ξi; Dξ(~i)(Y|ξi) is the conditional variance based on ξi; Dξi is the variance of the internal function of ξi; Eξi is the expectation of the internal function of ξi. By transforming equation (4), we can get

$$1 = \frac{D_{\xi i}\left[E_{\xi i}\left(Y|\zeta_i\right)\right]}{D(Y)} + \frac{E_{\xi i}\left[D_{\xi i}\left(Y|\zeta_i\right)\right]}{D(Y)} \quad (5)$$

Then the two items on the right side of equation (5) are FSI of ξi.

$$S_i = \frac{D_{\xi i}\left[E\zeta i\left(Y|\zeta_i\right)\right]}{D(Y)} \quad (6)$$

For the same reason, we can get the TSI of ξi:

$$S_{ti} = \frac{E_{\xi i}\left[D_{\xi i}\left(Y|\zeta_i\right)\right]}{D(Y)} \quad (7)$$

The FSI reflects the influence of the input random variable ξi on the system output. The larger the Si, the greater the influence of the uncertainty of ξi on the system output. The TSI reflects the combined effect of the input random variable ξi and the interaction of ξi with all other input random variables on the system output, which can be used to reflect the non-overlapping nature of the input's influence on the output. It is worth noting that the volatility of the system output variables is not caused by the simple superposition of each input random variable alone, and there is an interaction between the input random variables.

IV. SPCE-BASED ISLAND MICRO-GRID GSA PROCESS

The sensitivity model of the island micro-grid load flow is established based on the SPCE method with a small number of input random variables and output response samples. The specific steps are shown in Figure 1.

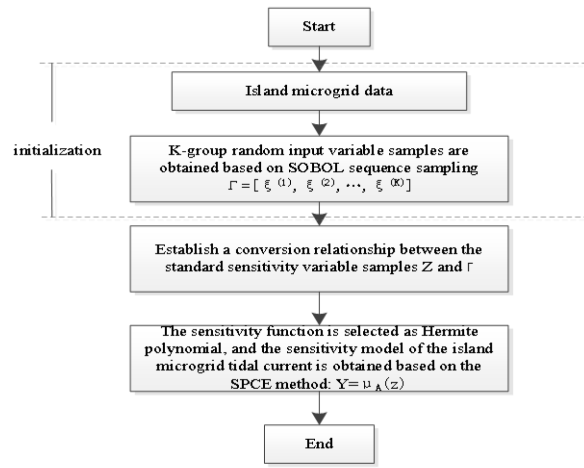

Figure 1. The process of Island micro-grid GSA

Step 1: The source-load uncertainty factor is selected to form the m-dimensional input random variable ξ, which is used for the GSA of the island micro-grid, and the sampling scale K is set to establish the sensitivity model of the island micro-grid.

Step 2: The sample Γ=[ξ(1),ξ(2),…,ξ(K)] of K-group input random variables acquired by LHS or based on Sobol sequence sampling can be obtained. Sobol sequence sampling in the paper is applied when establishing the island micro-grid sensitivity model.

Step 3: The conversion relationship between the input random variable sample Γ and the standard normal distribution variable sample Z is established by the cumulative distribution function transformation, and the obtained sample Z is used to establish a sensitivity model of the SPCE-based island micro-grid load flow.

Step 4: The LM algorithm is used to calculate the tidal current output result Y(i) corresponding to each group of samples ξ(i), so as to form a correspondence relationship between the standard normal distribution variable sample Z and the output random variable sample Y.

Step 5: The basis function as Hermite polynomial is selected, and the sensitivity model representation

$Y = \mu_A(z)$ of the island micro-grid can be obtained based on the SPCE method.

V. CASE ANALYSIS

In the paper, UQLab is used to construct the SPCE proxy model of the island micro-grid power flow and work out the coefficients to be solved. The FSI and TSI are further calculated and compared with the traditional MCS based on Sobol sequence sampling and MCS based on LHS sampling. The highest order of the SPCE proxy model is t=5, and the sample size required for model establishment is K=1000. First, only the uncertainty of the five RDG outputs of the ESS on the power supply side is considered, and the load is set to its expected value, and the correlation of the input random variables is not considered. Taking the system frequency as the output variable, the sampling scale calculated by the global sensitivity index is N0=30000. Three methods calculate the convergence of FSI and TSI of the put WT1(PWT1), as shown in Figure 2.

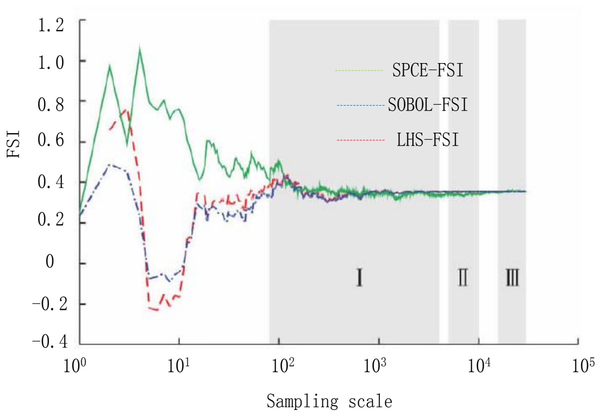

Figure 2. Convergence of global sensitivity index calculation

The SPCE method consumes extra time in the process of establishing the proxy model, but the FSI and TSI based on the proxy model can greatly improve the computational efficiency. The total computation time is reduced from 8000s to 33.5s in the Sobol-MCS method or the LHS-MCS method. The GSA index based on the SPCE method has a fast convergence rate and accurate calculation results, which is more efficient than the Sobol-MCS method and the LHS-MCS method.

VI. CONCLUSIONS

In the paper, the analysis of the operational sensitivity of the island micro-grid is considered, thereby the probabilistic load flow model of the island micro-grid is established. The SPCE-based GSA method is proposed to identify the key input random variables in the island micro-grid.

The main conclusions are as follows.

1) The FSI and TSI calculation process based on SPCE method has a fast convergence rate, and the obtained calculation result is accurate. Compared with Sobol-MCS method and LHS-MCS method, it has higher computational efficiency.

2) The GSA method can identify the key factors affecting the operation status of the island micro-grid, such as system frequency, node voltage and line load flow, obtain the importance ranking results of the input random variables, and provide the basis for the priority configuration of the ESS and monitoring devices in the island micro-grid.

3) The GSA method is also applicable for studying the common influence of multiple input random variables on the system output variables.

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