Comprehensive vulnerability assessment method for nodes considering anti-interference ability and influence

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Abstract. The vulnerability assessment of power grid is of great significance in the current research. Power system faces many kinds of uncertainty factors, and the disturbance caused by them has become one of the main factors which restrict the safe operation of power grid. To solve this problem, considering the anti-interference ability of the system when the system is disturbed and the effect of the system when the node is out of operation, a set of index to reflect the anti-interference ability and the influence of nodes are set up. On this basis, a new comprehensive vulnerability assessment method of nodes is put forward by using super efficiency data envelopment analysis to scientific integration. Finally, the simulative results of IEEE30-bus system indicated that the proposed model is rational and valid.

1. Introduction
There have been a series of large-scale power outages at home and abroad in recent years, which have brought serious challenges to the safe and stable operation of power systems [1,2]. Compared with the open line, the result of large power outage caused by bus trip is more serious. And not easy to take effective measures to control short-term emergency. Therefore, fast and accurate identification of the weak nodes of the system, can provide valuable theoretical reference for the power system safe and stable operation, and early warning, is of great significance.

Power grid vulnerability research, as the safety and reliability of the depth and extension of electricity has been a focus of attention of academic and engineering. Traditional vulnerability assessment methods of power grid are mainly Energy function method based on system operation state, risk theory, complex network theory, etc. However, any system and component is not isolated and there is a relationship, power grid vulnerability assessments should take into account the interaction between system and components.

This paper proposes the indexes to reflect the anti-interference ability and the influence of nodes by four steps, which can recognize the weak nodes of the system effectively.

1. Application energy margin, sensitivity and components Outage probability model build the anti-interference ability indexes.
2. According to the electrical between and load loss rate build node influence indexes.
3. And on this basis, the indexes can be generated scientifically by the super efficiency data envelopment analysis, thus, a new comprehensive vulnerability assessment method of nodes was introduced. Relatively, this method can select the weight of the index objectively, so that it can recognize the weak nodes of the system comprehensively and effectively.
4. The results of the IEEE30-bus system simulation can verify the rationality and feasibility of the method.

2. The anti-interference ability of nodes

2.1 The anti-interference ability of nodes under load fluctuation

Static energy function is an effective tool to assessment nodes vulnerability under load fluctuation [3]. The energy function of nodes is expressed as follow:

\[
E_i = \int_{(\delta_i, V_i)} \left[ f_i(\delta_i, V_i), g_i(\delta_i, V_i) \right] \cdot \frac{d\delta_i}{dV_i} \tag{1}
\]
where $V_i$ is the voltage amplitude of node $i$; $\delta_i$ is the phase angle of node $i$; $f_i$ is the active power of node $i$; $g_i$ is the reactive power of node $i$.

This paper take into account energy margin and sensitivity to assessment the anti-interference ability of nodes under load fluctuation. The energy margin of nodes is defined as follow:

$$\lambda(i) = \frac{|E_i - E_{icr}|}{|E_{i0} - E_{icr}|}$$  (2)

Where $E_{i0}$ is the initial static energy of nodes; $E_i$ is the static energy of nodes in the current running state; $E_{icr}$ is critical energy corresponding to the critical point of voltage stability. The sensitivity of nodes is expressed as follow:

$$\beta(i) = \frac{\partial E_i}{\partial V_i}$$  (3)

with the aggravation of the load, voltage amplitude will drop continuously, the energy changes of each node show different sensitivity.

Considering the energy margin and sensitivity under load fluctuation, the anti-interference ability index of nodes is defined as follow:

$$C_n(i) = \begin{cases} \beta(i) \times \lambda(i), & \beta(i) \geq 0 \\ \beta(i) \times \lambda(i)^{-1}, & \beta(i) < 0 \end{cases}$$  (4)

2.2 The anti-interference ability of nodes under fault condition

In this paper, the voltage offset of the node after the line is out of operation to measure the anti-interference ability of the node in the failure mode. Because of the difference of the power flow, the probability of failure of each line is different[4], this will have a certain effect on the node voltage offset, therefore, the fault probability of the line is introduced to the anti-interference ability index of nodes under fault condition. The curve of the line fault probability changes with the line power flow is shown in Figure1.
Figure 1. Failure probability model for transmission line

In Figure 1, $F_{\text{nor}}^{\text{max}}$ and $F_{\text{nor}}^{\text{min}}$ which respectively indicates the maximum and minimum values of the allowable flow during the normal operation of the line; $F_{\text{max}}$ is the limit value of line transmission capacity. When the power flow of line is in the rated transmission range, the protection movement is almost no effect by the tidal current. Take the statistical value $\bar{P}$. The failure probability caused by internal factors is defined as follow:

$$P_L = \begin{cases} \bar{P}, & F_{\text{nor}}^{\text{min}} < F \leq F_{\text{nor}}^{\text{max}} \\ \frac{F - F_{\text{nor}}^{\text{max}}}{F_{\text{max}} - F_{\text{nor}}^{\text{max}}} \times (1 - \bar{P}) + \bar{P}, & F_{\text{nor}}^{\text{max}} < F \leq F_{\text{max}} \\ 1, & F > F_{\text{max}} \end{cases}$$

The anti-interference ability of nodes under fault condition is defined as follow:

$$\Delta V_a = \sum_{b=1}^{N_i} \omega_b (V_a^i - V_{N_a}^i)$$

(6)

Where $\omega_b$ is probabilistic weight of line $b$, $\omega_b = p_b \sqrt{\sum_{i=1}^{N_i} \sum_{l=1}^{N_i} p_i}$; $p_b$ is failure probability of line $b$; $V_a^i$ is actual voltage of node $a$; $V_{N_a}^i$ is rated voltage of node $a$.

3. Influence of nodes

In order to study the influence of nodes in power system, it should be considered from two aspects: the importance of nodes in the topology and the impact on the system after the nodes out of running.

3.1 The electric betweenness model of nodes

The electric betweenness of nodes[5] is expressed as follow:

$$B(i) = \sum_{m \in G, n \in L} \sqrt{|W_m^i W_n^i|} |B_{mn}^i(i)|$$

(7)

$$B_{mn}^i(i) = \begin{cases} \frac{1}{2} \sum_j |I_{mn}^i (i, j)|, & i \neq m, n \\ 1, & i = m, n \end{cases}$$

(8)

where $G$ and $L$ which respectively indicates the set of generators and load nodes; $W_m$ is the weight factor of generator node $m$, take actual output or
rated capacity of the generator; $W_n$ is the weight factor of load node $n$, take actual or peak load; $I_{mn}(i,j)$ is the current generated on branch $i-j$ after the "generator-load" nodes is injected current element.

3.2 Load loss rate
Loss of load ratio is the ratio of the load loss after failure and the initial total load of power grid. This paper the influence of component is expressed as the effect of component failure on the terminal loads, we take the load loss rate to measure the degree of influence of the system after node failures. The load loss rate is expressed as follow:

$$S_i = \frac{P_i}{\sum_{j \in L} P_j} \times 100\%$$

(9)

where $P_i$ is the load loss after node $i$ failure; $P_j$, the load capacity of load node $j$ in normal operation; and $L$ is the load nodes set.

4. The model of SEDEA
DMUi ($i=1,2,...,n$) is expressed the decision making unit of $i$ [6], each decision making unit has $m$ input indexes which belong to cost index, the smaller the better; each decision making unit also has $s$ output indexes, it is belong to profit index, the bigger the better. Efficiency index is expressed as follow:

$$E_i = \frac{u^T y_i}{v^T x_i} = \frac{\sum_{r=1}^{s} u_r y_{ri}}{\sum_{k=1}^{m} v_k x_{ki}}$$

(10)

where $x_{ki}$ is the number $k$ input index of DMUi, $x_{ki} > 0$, $x_i = (x_{1i}, x_{2i},...,x_{mi})^T$ is input vector of DMUi; $v_k$ is the weight of number $k$ input index, $v = (v_1, v_2,...,v_m)^T$ is the weight vector of input index; $y_{ri}$ is the number $r$ output index of DMUi, $y_{ri} > 0$, $y_i = (y_{1i}, y_{2i},...,y_{ui})^T$ is output vector of DMUi; $\mu_r$ is the weight of number $r$ output index, $u = (u_1, u_2,...,u_s)^T$ is the weight vector of output index.

When evaluating the efficiency of decision making units DMUi, we take the weight vector of the input and output indexes as variables, with the
efficiency index $E_i$ as the goal, and all DMU efficiency index $E_a$ ($a = 1, 2, ..., n, a \neq i$) as constraint except $DMU_i$, then we get fractional programming model as follows:

$$\max E_i = \frac{u^T y_i}{v^T x_i}$$

s.t. $E_a = \frac{u^T y_a}{v^T x_a} \leq 1$

$$v \geq 0, u \geq 0$$

Based on the fractional programming model, solving each decision making unit respectively, we can get the corresponding maximum value of $E$, and then evaluate the efficiency of each decision making unit. The model of SEDEA is more objective to select the weight, thus making the result more practical.

5. The comprehensive vulnerability assessment method of nodes based on SEDEA

This paper proposes a method to evaluate the vulnerability of nodes, which is based on the SEDEA model, and carries out a comprehensive consideration from anti-interference ability and influence these two aspects. In this method, we can regard each node as a decision making unit (DMU), and make the anti-interference ability index into cost type as the input, where the index is smaller, the anti-interference ability of the node is weaker. Meanwhile, making the influence index into efficiency as the output, where the index is bigger, the influence of nodes is greater. The efficiency index, $E$, is defined as the comprehensive vulnerability index of nodes, where the higher the index, the weaker the anti-interference ability of nodes and the greater the influence in the system. The proposed method in this paper has a clear physical meaning and a certain practical significance.

6. Test scenario

This paper takes the IEEE 30-bus system as an example. Load fluctuation mode is selected as the load increased by 30% to calculate the anti-interference ability of nodes under load fluctuation. Branch outage probability statistics is set to $1.81 \times 10^{-4}$, limit value of branch power flow normal value is set to 0.95-1.05 times of the rated capacity to calculate the anti-interference ability of nodes under fault conditions.

Using the traditional DEA and super efficiency data envelopment analysis (SEDEA) model to calculate the comprehensive vulnerability index of nodes. The result is shown in Figure 2.
Figure 2. Node comprehensive vulnerability index with different models

As shown in Figure 2, the node comprehensive vulnerability index curve trend is very close with traditional DEA and SEDEA model, so the rationality of the method in this paper is demonstrated. But the traditional DEA model cannot identify the nodes which comprehensive vulnerability indicators are 1, and this paper can effectively distinguish the vulnerability of each node. Finally, the comprehensive vulnerability of all nodes is sorted.

Node 6 is the most vulnerability in this paper, further analysis showed that node 6 is the most important links in the system, it undertake the task of power injection from generators to end of load, this node needs to add transport capacity immediately to maintain the power flow balance when the load changes, so it is more susceptible to be disturbed than other nodes, and the anti-interference ability is more weak; furthermore, node 6 is the node of main transformer branch, it will lead 5 and 8 generator node power cannot transport to the central section of system if node 6 fault or outage, it is very easy to cause the whole power flow to move significantly, eventually lead to large-scale blackout, it has great influence to the power system. Node 5 is similar to node 6, node 5 is one of few generator nodes which affected by load fluctuations greatly, and the ability to maintain voltage stability is weak, in addition, it will cause large-scale blackout if node 5 quit running, so node 5 shows a strong vulnerability.

Through the simulation results and analysis above, the vulnerability nodes are mostly generator nodes or important links in the system. Results show that the presented method is feasible and reasonable.

7. Conclusion

In this paper, a comprehensive vulnerability index set of nodes is proposed, which is based on the ability of anti-interference and influence. Then, the SEDEA model is used to integrate multiple indexes, and a new method for
evaluating the vulnerability of nodes is obtained, which is more objective to select the index weight, and it can effectively identify the weak and influential nodes in the system. The comprehensive vulnerability index resulted in this paper is expected to be applied in engineering practice, and it can provide valuable theoretical reference for early-warning and stable operation of power system.

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