Power grid dispatching operation domain division considering voltage stability constraints

Liaoyi Ning1, Guanxiong Zhao2*, Liang Du1, Shunjiang Wang1 and Yuda Chen1

1State Grid Liaoning Electric Power Co., Ltd., Shenyang, Liaoning, 110006, China
2Northeast Electric Power University, Jilin, Jilin, 132012, China
*Corresponding author’s e-mail: 422958162@qq.com

Abstract. The operational instability and scheduling complexity is brought by the high proportion of renewable energy access to the grid. In order to cope with this problem, this paper proposes a method based on the mean voltage stability L-index analysis of stochastic voltage stability and the grid operating domain. This method can quickly find the weakest node in the whole network and help the dispatchers monitor and control the weak nodes. Based on the observation of the voltage stability of the whole network, the grid operation domain division index is proposed, and the grid is divided into different operation domains based on the voltage stability constraint. The validity and correctness of the proposed scheme and indicators are verified by the typical example of IEEE-30 node.

1. Introduction
In order to cope with resource shortages, environmental pollution and other issues, humans use renewable energy to replace fossil energy to achieve sustainable energy development [1-2]. The advantages of renewable energy make it occupy a higher proportion in the operation of the power grid. Due to the intermittent and random nature of renewable energy, it has a great impact on the stability of the system voltage. A series of challenges [3-4] have greatly increased the complexity of scheduling. Therefore, ensuring the stable and safe operation of the power grid and realizing the reasonable division of the regional power grid operation scheduling domain has become one of the hot issues to be solved urgently by current scholars.

Many scholars have conducted in-depth research on the impact of uncertainties on grid voltage. Wang, et al. improved a static voltage stability probability model of transmission system based on stochastic power flow and static voltage stability domain is proposed, and the probability of voltage stability unsafe is calculated [5]. Xiong, et al. improved the continuous power flow algorithm with wind farm and accurately analyzed the system voltage stability [6]. Zhu, et al. evaluated the probability of static voltage stability margin of power systems with wind power for uncertainties [7]. Duan, et al. considered to improved continuous power flow algorithm, and the static power flow model based on load clustering is established to analyze the static voltage stability [8]. Zhu, et al. introduced random power into the wind power grid-connected system for static safety assessment [9].

In the future power system, the conventional unit, load and energy storage device will be used as the system scheduling resources at the same time. Therefore, the characteristics of various scheduling resources should be fully considered, and the power system optimization scheduling scheme should be given from the overall perspective to realize the “source-The Dutch-storage coordination and interaction maximizes the use of system resources [10]. Ju, et al. established a power system optimization scheduling
model based on “source-network-load-storage” coordination, but the model does not consider the high penetration rate of renewable energy and the phenomenon of abandoned wind and abandoned light [11]. There is still room for improvement.

In this paper, based on the uncertainty factors such as wind power, this paper proposes a method based on the mean voltage stability L index to analyze the random voltage stability, and proposes the concept of grid operation domain based on a series of effects brought by wind power grid connection, and proposes a grid based on the whole network voltage stability constraint. Divide indicators by different running domains.

2. L indicator based on random power flow calculation

The power system is a complex system with strong randomness, so the result of deterministic evaluation is relatively optimistic. This paper considers the uncertain factors to introduce random power flow, combined with the voltage stability L index [12], to evaluate the static voltage stability of wind-containing systems.

In a multi-node system, network nodes are divided into two categories, one is a load node, and the other is a generator node and a balance node.

![Simple system model](https://example.com/simple_system_model.png)

Define the voltage stability index L as:

\[
L = 1 + \frac{\tilde{V}_i}{V_i} = \frac{\tilde{S}_i}{Y_{ii} \cdot V_i^2}
\]  

(1)

After classifying the system nodes, the mixing matrix can be used to indicate the relationship between the node voltage and current.

\[
\begin{bmatrix}
V_L \\
I_L
\end{bmatrix} = H \cdot \begin{bmatrix}
I_G \\
V_G
\end{bmatrix} = \begin{bmatrix}
Z_{GL} & F_{LG} \\
K_{GL} & Y_{GG}
\end{bmatrix} \cdot \begin{bmatrix}
I_L \\
V_G
\end{bmatrix}
\]  

(2)

The expression of the L indicator is:

\[
L = \text{MAX}_{j=o,G} \left[ 1 - \frac{\sum_{k \neq j} F_p \cdot \tilde{V}_j}{V_j} \right]
\]  

(3)

In the formula, L<1 indicates that the node voltage is stable, L=1 indicates that the node voltage is critically stable, and L>1 indicates that the node voltage is unstable.

The power equation of the node in polar coordinates can be written in matrix form as:

\[
W = F(X, Y)
\]  

(4)

Inductive parameter λ is derived:

\[
\frac{dW}{d\lambda} = \int dV \frac{dV}{d\lambda}
\]  

(5)

which is:

\[
\Delta V = S_0 \Delta W
\]  

(6)

According to the nature of the semi-invariant, the r-th order semi-invariant ΔW(r) of the injection power of each node of the system is obtained from the r-order semi-invariant of the node load and the power injection power.
The $r$-th order semi-invariant of the voltage stability $L$ index is calculated from the additivity of the semi-invariant.

$$\Delta V^{(r)} = S_0^{(r)} \Delta W^{(r)} \quad (7)$$

$$\Delta L^{(r)} = \left| 1 - \frac{\sum_{i=0}^{n} F_{ij} V_i'}{V_j'} \right| \quad (8)$$

3. Grid operating domain

3.1 Grid operating domain concept

Due to the increasingly prominent environmental protection problems in the world, energy consumption is becoming more and more serious, and the proportion of renewable energy in the power grid is getting higher and higher. A high proportion of new energy access to the grid will bring a series of problems. This paper integrates existing resources and explores economic and reliable grid regulation and economic dispatch plans under the high-permeability clean energy ratio and proposes the concept of grid operation domain. Under the different boundary of system load level and renewable energy, the system shows different operating states intuitively, and the adjustable devices are different under different operating states. If the thermal power, water and electricity are regulated under normal conditions, the energy storage is adjusted under abnormal conditions, and the wind, light and nuclear power are adjusted in an emergency state. The division of the grid operation domain can reduce the complexity of the scheduling, and rationally plan the scheduling resources for the dispatchers, and provide the theoretical basis for the auxiliary decision-making when scheduling the different operating states of the grid.

3.2 Grid operating domain definition

Based on the above concepts, we divide the grid operation into three different areas. The power grid is in the normal regulation stage, which is called the normal regulation domain; the power grid has no normal regulation capability, and is in the abnormal regulation phase, which is called the abnormal regulation domain; the power grid loses its control capability and is in the emergency control state, which is called the emergency control domain. The normal regulatory domain, the control object is hydropower and thermal power, abnormal control domain, the control object is energy storage, emergency control domain, and the control objects are nuclear power, wind power and photovoltaic.

4. Grid operating domain indicator

When the grid runs to the critical point of each operating domain, the whole network voltage is observed and the weakest node is found, and the collapse voltage is calculated using the continuous power flow, as shown in Figure 2.

![Figure 2 Weak node PV curve](image-url)
The voltage of a weak node changes with the change of active power. Observing the voltage of a weak node is a key point to define the index of the operating domain of the grid.

The indicator is defined as:

\[ K_p = \frac{V_i}{V_{im}} \tag{9} \]

In the formula, \( V_i \) and \( V_{im} \) are the weak point voltage and the breakdown voltage, respectively.

According to the indicator \( K_p \), the grid operating domain is divided into:

\[
\begin{align*}
K_{p_{\text{max}}} &< K_p < K_{p_{\text{min}}} & \text{Normal domain} \\
K_{p_{\text{min}}} &< K_p < K_{p_{s}} & \text{Exception domain} \\
1 &< K_p < K_{p_{\text{max}}} & \text{Exception domain} \\
K_{p_{s}} &< K_p & \text{Emergency domain}
\end{align*}
\tag{10} \]

In the formula, \( V_{im} \) is the weak node voltage when the output of the conventional unit is the smallest, \( V_{\text{max}} \) is the weak node voltage when the output of the conventional unit is the largest, and \( V_{i} \) is the weak node voltage when the capacity of the energy storage device is full.

5. Case analysis

In this paper, based on the IEEE-30 node typical system, the generators of nodes 11 and 13 are replaced by wind power with a capacity of 50 MW. The ratio of wind power access capacity to total installed capacity is 25%, and the storage capacity of node 15 is 100 MW·h.

The mean voltage stability L index results are shown in Table 1.

| Node number | \( \tau (\sigma = 0.1) \) | \( \tau (\sigma = 0.2) \) | \( \tau (\sigma = 0.3) \) |
|-------------|----------------------|----------------------|----------------------|
| 3           | 0.4107               | 0.4445               | 0.4804               |
| 4           | 0.6299               | 0.6654               | 0.6994               |
| 7           | 0.7082               | 0.7506               | 0.7857               |
| 10          | 0.4154               | 0.4539               | 0.5648               |
The limit voltage $V_m$ of the node 30 is 0.55. According to the defined $K_p$ index method and related data, the $K_{p_{min}}$ value is approximately 1.87, the $K_{p_{max}}$ value is approximately 1.78, and the $K_p$ value is approximately 1.91.

### Table 2. Index value of each time period and grid operation status

| Time slot | $K_p$ | Energy storage state | Running domain |
|-----------|-------|----------------------|----------------|
| 1-13      | 1.78 $K_p$ | - | Normal domain |
| 17-23     | $<1.87$ | - | Normal domain |
| 0-1       | 1.87 $K_p$ | - | Charging |
| 13-14     | 1.87 $K_p$ | - | Exceptional domain |
| 23-25     | $1<K_p<1.78$ | - | Emergency domain |
| 14-17     | 1.91 $K_p$ | - | Emergency domain |

### 6. Conclusion

This paper proposes a method for dividing the grid’s operating domain. By establishing the average static voltage stability $L$ index under stochastic power flow, a grid stability index based on voltage stability constraints is constructed. Under the premise of 25% penetration of wind power, the typical daily windy period is analyzed, and the grid operation domain is divided by observing the weak nodes of the entire network voltage and calculating the $K_p$ index. The simulation results show that the source-load storage based on the grid operation domain division proposed in this paper effectively simplifies the complexity of the dispatch. As the voltage stability constraints are taken into account, the safe and reliable operation of the power system is ensured, and it provides a certain decision-making role for grid dispatchers.

### References

[1] Yao, J.G., Yang, S.C., Wang, K., et al. (2012) Concept and research framework of smart grid “Source-Grid-Load” interactive operation and control. J. Automation of Electric Power Systems., 36(21):1-6.

[2] Pilo, F., Pisano, G., Soma, G.G. (2009) Advanced DMS to manage active distribution networks. PowerTech, IEEE Bucharest, Romania. pp. 1-8.

[3] Xu, C.X., Liu, L.Q., Xie, Y.M., et al. (2015) Real-time data based online evaluation of output performance for wind turbine units. J. Thermal Power Generation., 44(4): 88-91.
[4] Liu, L. (2015) Active power control in photovoltaic power plants. J. Thermal Power Generation., 4(11): 104-108.
[5] Wang D, Yu, Y. (2010) Probabilistic Static Voltage Stability Security Assessment for Power Transmission System. J. China Academic Journal Electronic Publishing House., 43(03): 10-14.
[6] Xiong, C.P., Zhang X.H., Meng Y.J., et al. (2012) Analysis on static voltage stability of system with large-scale wind power integration. J. Power System Protection and Control., 40(21): 132-137.
[7] Zhu, X.Y., Liu, W.X., Zhang, J.H. (2013) Probabilistic Load Flow Method Considering Large-scale Wind Power Integration. J. Proceedings of the CSEE., 33(07): 77-85+16.
[8] Duan, G.Z., Qin, W.P., Lu, R. P., et al. (2018) Static voltage stability analysis considering the wind power and uncertainty of load. J. Power System Protection and Control., 46(12): 108-114.
[9] Zhu, X.Y., Huang, Y.F., Zhang, J.H., et al. (2014) Static Security Assessment Based on Probabilistic Load Flow for Wind Power Integrated Power Systems J. Automation of Electric Power Systems., 38(20): 46-53+60.
[10] Xu, H.P., Li, Y.W., Miao, Y.Y., et al. (2017) Optimization dispatch strategy considering renewable energy consumptive benefits based on “source-load-energy storage” coordination in power system J. Power System Protection and Control., 45(17): 18-25.
[11] Ju, L.W., Yu, C., Tan Z.F. (2015) A Two-Stage Scheduling Optimization Model and Corresponding Solving Algorithm for Power Grid Containing Wind Farm and Energy Storage System Considering Demand Response. J. Power System Technology., 39(5): 1287-1293.
[12] KESSEL, P. (1986) Glavitsch H. Estimating the Voltage Stability of a Power System. IEEE Transactions on Power Delivery., 1(3): 346-354.