Research on Site Selection Method of Battery Energy Storage System Based on Critical CutSet Identification

Jingjie Zeng\textsuperscript{1,2}, Peiqiang Li\textsuperscript{2,\textdagger}, Zhongkai Zhang\textsuperscript{1,2}, Xinke Liu\textsuperscript{1,2}

\textsuperscript{1}Fujian University of Technology School of Electronic, Electrical Engineering and Physics, Fuzhou, China
\textsuperscript{2}Fujian Provincial University Engineering Research Center for Smart Grid Simulation Analysis and Integrated Control, Fuzhou, China

Corresponding author: lpqcs@fjut.edu.cn

Abstract. Under different operating conditions, the influence of energy storage battery on the power grid is different, and the location and capacity determination methods are also different. Therefore, how to scientifically and reasonably select the location is of great significance. This paper proposes a candidate set identification method for the most vulnerable branch and critical cut set of power system transient stability based on branch potential energy, and uses the improved comprehensive index to identify the critical cut set. This method does not need to wait for the end of time domain simulation to determine the most vulnerable lines and critical cut sets, thus providing the basis for the location of battery energy storage system (BESS). Through the power system comprehensive analysis program (PSASP) simulation, the accuracy of theoretical analysis and engineering practicability are verified.

1. Introduction

At present, the research on the site selection of the energy storage battery in the power system at home and abroad is mainly aimed at the analysis of a certain characteristic of the power grid and has not yet formed a complete site selection index system. In literature [1], a cutset with the smallest index is proposed as a critical cutset based on calculation. This method greatly simplifies the selection of candidate cutsets. The line near the fault point can be used as a candidate cutset, which can be selected according to the actual situation of the fault and the system. When the network structure parameters of the power system and the type and location of the fault change, this selection method may have a large error. Literature [2] based on the concept of branch potential energy and combined with trajectory prediction method, an online detection algorithm for power system out-of-step is proposed, which only needs voltage and current measurements. However, the algorithm cannot identify the critical cutset when the system is stable. Literature [3] used the transient program to analyze the unstable generator, took any unstable generator node to any generator node in the other part of the cluster, and generated the short tree defined in this paper through the unrepeated vertices and edges. Then, the association edge search was carried out along the tree from its root node, and the result was the critical cutset. Literature [4] describes in detail the modeling problem of battery energy storage electromechanical transient time scale, and verifies that this model can improve the transient stability of power grid in the power system comprehensive simulation program (PSASP), but does not analyze the mechanism of battery energy storage improving the transient stability of power grid.
In this paper, a candidate set identification method for the most vulnerable branch and critical cutset based on branch potential energy is used, and on this basis, the improved comprehensive index is used to determine the critical cutset. The selected critical cutset is used as the basis for the location of the BESS. The effectiveness of the BESS is verified by the energy storage model built in the PSASP and the New England 10 machines 39-bus system, and the superiority of the critical cutset identification in the location of the BESS is verified.

2. Determination of critical cutset for power grid

2.1. Identification of critical cutset of improved synthetic index

If $C_i$ is a cutset, the branch set on the cutset $C_i$ with the same positive direction as $C_i$ is $C_i^+; otherwise, it is $C_i^-$. If the branch angle of the network at stable equilibrium point (SEP) is $\sigma_0^0$, the positive branch angle $\sigma_k^+$ is:

$$
\sigma_k^+ = \begin{cases} 
\sigma_k^u & \text{ke}C_i^+ \\
\sigma_k^l & \text{ke}C_i^- \\
\sigma_k^0 & \text{ke}C_i
\end{cases}
$$

In the equation(1): $\sigma_k^u = \pi - \sigma_k^0, \sigma_k^l = -\pi - \sigma_k^0$.

Similarly, $\sigma^+$ and $\sigma^-$ could be defined as the unstable equilibrium point (UEP) $(\sigma^+,0)$ and $(\sigma^-,0)$ respectively.

The vulnerability index of network cutset is:

$$
\gamma_{C_i} = \begin{cases} 
\sum_{c_i} b_k u_k^u + \sum_{c_i} b_k u_k^l \\
\sum_{c_i} b_k u_k^u + \sum_{c_i} b_k u_k^l
\end{cases}
$$

(2)

In the equation(2):

$$
\mu_k^u = h \left( \sigma_k^u, \sigma_k^0 \right) = 2 \left[ \cos \sigma_k^0 + \left( \sigma_k^0 + \frac{\pi}{2} \right) \sin \sigma_k^0 \right] \\
\mu_k^l = h \left( \sigma_k^l, \sigma_k^0 \right) = 2 \left[ \cos \sigma_k^0 + \left( \sigma_k^0 - \frac{\pi}{2} \right) \sin \sigma_k^0 \right]
$$

The values of $\gamma_{C_i}^+$ and $\gamma_{C_i}^-$ can be explained as the algebraic sum of the deceleration region on the cutset. For each cutset $C_i$, there are two instability modes corresponding to the vulnerability indicators of cutset $\gamma_{C_i}^+$ and $\gamma_{C_i}^-$ respectively. Therefore, the vulnerability index of each cutset is defined as:

$$
\gamma_{C_i} = \min \{ \gamma_{C_i}^+, \gamma_{C_i}^- \}
$$

(3)

Obviously, the larger the kinetic energy of the generator is when the fault is cleared, the easier the generator is to lose its stability. Therefore, it is more reasonable to consider the sum of the kinetic energy of the generator set corresponding to the fault clearing and the cutset as a factor to judge whether the generator set is unstable or not, rather than the size of the initial acceleration as a factor. The vulnerability index of the network after the accident is the deceleration area corresponding to the instability of the cutset, which belongs to the category of potential energy. The lower the vulnerability index of the cutset (potential energy) is, the more prone to the instability of the cutset. Therefore, the ratio of the kinetic energy of the unstable generator (or generator cluster) at the time of the accident clearance to the vulnerability index on the corresponding unstable mode cutset can be used as the index to identify the critical cutset -- the improved comprehensive index, i.e:

$$
\beta_{C_i} = \frac{\sum_{j=1}^{n_{C_i}} \frac{1}{2} M_j \omega_j^2}{\gamma_{C_i}}
$$

(4)

In the equation(4), $n_{C_i}$ is the number of unstable generators that the system is divided into unstable parts and two parts by cutset $C_i$. 

2
The secant set corresponding to \( \beta = \max \{ \beta_{C_1} \} \) is the critical secant set for which the system really lists the unstable part and the rest of the system.

3. Transient model of BESS

The BESS is composed of battery packs, grid-connected converter PCS and a control and monitoring system, as shown in Figure 1. The establishment of the dynamic model of BESS mainly includes electromagnetic transient model and electromechanical transient model. The electromagnetic transient model needs to consider the power electronic components, circuit structure, and dynamic response of each component in the grid-connected system in detail. The model is complex and the simulation speed is slow. It can be used to study the components of the BESS or to design the control strategy, but not to simulate the transient process of the grid-connected system. The mechanical and electrical transient model mainly designs its control part, which is simple and fast in calculation and can achieve better practical engineering effects. Therefore, this paper establishes the electromechanical transient model of the BESS based on Figure 1.

3.1. Transient mathematical model of BESS

The electromechanical transient model structure diagram of the BESS in this paper is shown in Figure 2. The model mainly consists of four modules: power outer loop module, PCS inner loop control module, charge and discharge power limitation module, and grid-connected interface module. The energy storage battery model is simplified in the limit of charge and discharge power of the converter. The grid-connected converter adopts internal and external loop control strategy and adjusts system deviation through proportional-integral control. The grid interface model converts active and reactive power into the real and imaginary parts of ac grid injection current and then controls the grid parameters. In Figure 2, \( P_{\text{set}} \) and \( Q_{\text{set}} \) control the output direction of active and reactive power; \( Q \) and \( P \) are the expected output reactive and active power of the BESS; \( I_x \) and \( I_R \) are the imaginary and real parts of the grid current injected into the BESS.

Figure 1. Power grid connected structure diagram of BESS

Figure 2. Model structure of BESS

The port characteristics of the BESS connected to the power grid are closely related to the PCS control method. The control strategy of the converter can usually be divided into two parts: the outer loop control and the inner loop control. The outer loop control is reactive and active power control, which produces power adjustment according to the system deviation. The inner loop control is current
and voltage control, which generates pulse width modulation (PWM) signal to control the active and reactive power output of the BESS, as shown in Figure 3. In the figure, m and δ are PWM modulation signal and trigger Angle control signal respectively. ∆U and ∆ω are the frequency and voltage deviations respectively.

![Figure 3. BESS dual-loop control strategy](image)

Finally, this paper uses the user-defined modeling function in PSASP to build the electromechanical transient simulation model of BESS as shown in Figure 4.

![Figure 4. BESS model built in PSASP](image)

4. Case analysis

In verifying the validity and rationality of the identification method of the most vulnerable branches and critical cutset based on branch potential energy proposed in this paper, a standard example of New England 10 machines 39-bus system was selected on the PSASP simulation platform to determine the critical cutset of the system with the above method and check the calculation. The baseline capacity of the system is 100MV•A.

Using the critical cutset selection method mentioned above, it can be known that in the New England 10 machines 39-bus system, its critical cutset is \{1-2, 8-9\} for most faults, indicating that this cutset is the weak area of the system. By analyzing the network structure and parameters of the system, it can be found that, on the one hand, branches 1-2 and 8-9 are at the edge of the network, and the connection with the main network is fragile. On the other hand, the impedance parameters of branch 1-2 and branch 8-9 are larger, which makes the structure of cutset \{1-2,8-9\} more fragile.

After obtaining the critical cut sets of the New England 10 machines 39-bus system, by comparing the cut sets existing in the New England 10 machines 39-bus system, it can be seen that \{26-29\} is also relatively fragile cut sets. Therefore, the battery energy storage models are connected to BUS8 and BUS26 respectively, and then a point of BUS22 is taken arbitrarily. When the system fault is set to 0.2 s, the load connected to the BUS4 bus is removed by 30 %, and the active power output of the
energy storage is set to 1pu. Compared with the voltage waveform when the energy storage is not connected, the voltage fluctuation of the fault point is observed, as shown in Figure 5.

![Figure 5. Comparison of voltage stability of fault point under energy storage access different nodes and without energy storage access](image)

It can be seen from Figure 5 that in the case of energy storage connected to the system, the voltage fluctuation amplitude is significantly smaller than that without energy storage participating in the regulation. Under the same system disturbance, the disturbance suppression effect of the battery energy storage system with BUS8 in the critical cutset is much better than that with BUS22 and BUS26.

5. Conclusion
Based on the design principles of each part of the BESS, this paper builds the electromechanical transient model of the BESS that can reflect the energy storage characteristics in the user-defined modeling of PSASP. The power flow calculation function of PSASP is used to calculate the New England 10 machines 39-bus system, and the critical cutset in the system is determined, and the relevant nodes of the cutset are taken as the access position of the BESS.

In this paper, the load shedding of the system is simulated and analyzed. The results show that the BESS can improve the voltage stability of the system, and the energy storage model is connected to the cutset node to suppress the bus voltage fluctuation. The effect is better than that of other nodes, which verifies the superiority of the critical cutset recognition in the location of the BESS. In summary, the selection of BUS8 as the node of the BESS connecting to the power grid has a good effect on improving the operation fluctuation of the power grid.

References
[1] Chandrashekhar K.S., Hill D.J.. Cutset stability criterion for power systems using a structure-preserving model[J]. Elsevier, 1986, 8(3).
[2] Padiyar K R, Krishna S. Online detection of loss of synchronism using energy function criterion[J]. IEEE Transactions on Power Delivery, 2006, 21(1): 46-55.
[3] Hu Zhe, Mu Gang. All algorithm of the power grid critical cutset and its application[J]. Journal of Northeast China Institute of Electric Power Engineering, 1996, 16(1): 13-18.
[4] Li Jianlin, Niu Meng, Zhang Boyue, et al. Electromechanical transient simulation model of battery energy storage system[J]. Transactions of China Electrotechnical Society, 2018, 33(8): 1911-1918.

[5] Li Jianlin, Ma Huimeng, Yuan Xiaodong, et al. Review on key application technologies of large-scale distributed energy storage[J]. Power System Technology, 2017, 41(10): 3365-3375.

[6] Mu Gang. The Analysis Method Based on Trajectory of Transient Energy and Its Application for Analysis of Power System Transient Stability[D]. Beijing: Department of Automation, Tsinghua University, 1991.

[7] Feng Fei. The Study of Power System Dynamic Security Region[D]. Tianjin: School of Electrical Engineering and Automation, Tianjin University, 1991.

[8] Yu Yixin, Chen Liyi. The Stability and Security of Power System[M]. Beijing: Science Press, 1988.

[9] Yin Jianhong, Wu Kaiya. Graph Theory and Its Algorithm[M]. Hefei: China Science and Technology University Press, 2003.

[10] Wu Zhongxi, Zhou Xiaoxin. Power System Analysis Software Package (PSASP)-an integrated power system analysis tool[C]. 1998.