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Short-circuit ratio index of new energy grid-connected system with DC feed

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***Abstract*—With DC increase of large-scale proportion and new energy in power system and rapid development of new energy power generation technology and DC transmission, the characteristics and power grid stability have changed, and it is urgent to put forward a scientific and perfect short-circuit ratio index for systems stability of DC and new energy grid-connected. Based on the superposition theorem, the definitions of SCR_{edi} and $SCR_{edi\text{-}U}$ of new energy grid-connected points are proposed, taking the interaction between new energy stations and DC lines influence into account. Secondly, according to the definition, the theoretical derivation of the critical short-circuit ratio is carried out, and specific value is given. Finally, the model is built on the PSASP platform, and the rationality, effectiveness and feasibility of the proposed indexes SCR_{edi} and $SCR_{edi\text{-}U}$ are verified by simulation examples.**

Keywords-short-circuit ratio; new energy grid-connected system; Dc feed system; critical short-circuit ratio; voltage stability

I. INTRODUCTION

As China's energy demand continues to rise and the energy crisis is increasingly tense, China proposed "Carbon Peak, Carbon Neutral" strategic target, and developing renewable energy sources such as wind power and photovoltaics has become a trend[1-3]. The wind power and photovoltaics development, and direct current transmission in China has shown a significant growth trend, large-scale new energy power generation equipment is centralized access to the grid, while a number of DC lines are fed into the AC grid, the form of the grid is becoming more complex and diversified.in order to ensure the safe operation of the grid, it is more necessary for the grid to provide sufficient support strength. Short circuit ratio is an important index to assess system security and stability, the higher the short-circuit ratio indicates that the system has stronger stability, and the smaller the system voltage fluctuation after failure. For a system which is new energy grid-connected containing DC feed at the same time, it is urgent to put forward a scientific and reasonable short-circuit ratio index of the new interconnection network. Can directly and energy effectively indicate the stability and system strength of the DC feed-in and new energy grid-connected system.

As an intuitive and concise static analysis method, short-circuit ratio plays a significant role in evaluating power system stability and the planning of power grid.[4]. New energy units are usually through power electronic equipment connected to the grid with strong randomness and volatility, and the power system stability is seriously affected, and the large-scale grid connected system voltage support strength for new energy is gradually weakening[5-10].Therefore, the effective evaluation of the new energy grid-connected system stability is particularly important. In literature [11-12], when calculating new energy grid-connected system short-circuit ratio index, the traditional single-feed ratio of short circuit is adopted. As the interaction between new energy sites is not considered, the accuracy is reduced. At present, progress has been made in evaluating the grid carrying capacity of new energy grid connected systems considering small disturbance stability, and the small disturbance stability constraint has been transformed into a generalized short circuit ratio constraint, which is suitable for large-scale new energy grid-connected scenarios, new energy "black box" model scenarios and new energy grid-connected scenarios with grid type and grid structure type[13-14]. In the new energy grid-connected scenario, on the basis of the assumption that power electronic devices are all fed into the same AC network, the ratio of weighted short circuit and the short-circuit ratio composited are put forward in the literature [15-17], ignoring the relation between the devices with new energy grid-connected, which has certain limitations. Compared with the conventional DC multi-feed short-circuit ratio, the short-circuit ratio which is equivalent is proposed by the International Organization of Great Power Grids (CIGRE) [18].On the basis of the static voltage stability margin analysis, relevant short-circuit ratio is proposed in literature [19]. In an effort to evaluate the new energy grid-connected system strength, the literature put forward the short-circuit ratio about new energy multi-site and critical short-circuit ratio calculation method in the system with new energy grid connected[20-21], taking into account the interaction factors between the sites into the short circuit ratio definition. However, the power system structure is becoming increasingly diverse and complex. For systems containing DC input and new energy grid connection, the above indicators have not taken the impact of DC input on the new energy grid connection point short-circuit ratio into account, making it difficult to extend to actual complex scenarios containing DC. The usage scenarios are limited, and the accuracy of the short-circuit ratio is reduced.

Therefore, this literature constructs short-circuit ratio index suitable for DC-fed grid-connected system of new energy to evaluate system stability. Firstly, based on the superposition theorem, the physical nature of the system including DC-input and new energy grid connected system is analyzed, and the ratio index $SCR_{edi\text{-}U}$ defined by capacity and taking the influence of DC and other new energy junction points into account is proposed. On this basis, the ratio index of short circuit SCR defined in the voltage form is derived. The physical nature of the two is the same. Secondly, based on the mathematical derivation of the above short-circuit ratio index, the critical short-circuit ratio extreme value is obtained. It is suggested that the critical short-circuit ratio extreme value 2.683 should be used as the strength judgment standard for DC and new energy grid-connected systems. Finally, a model is built on the PSASP simulation platform, and effectiveness of the index proposed are verified by time domain simulation.

II. THE SHORT CIRCUIT RATIO OFTHE NEW ENERGY JUNCTION WITH DCFEED

A. System equivalent analysis

As for the grid-connected system of new energy with DC feed, the access of DC and new energy will cause the node voltage of AC system to change, and the stability of the system will also change. According to the superposition theorem, considering the effect of new energy and DC on AC system comprehensively, the system can be equivalent to the superposition of three parts, as shown in Figure 1.

The system node voltage equation is:

$$\boldsymbol{U} = \boldsymbol{U}_{ac} + \boldsymbol{\Delta U}_{e} + \boldsymbol{\Delta U}_{d} = \boldsymbol{Z}(\boldsymbol{I}_{ac} + \boldsymbol{I}_{e} + \boldsymbol{I}_{d}) \tag{1}$$

Where, $\boldsymbol{Z}$ is the node impedance matrix; $\boldsymbol{U}$ is the node voltage of the voltage column vector; $\boldsymbol{U}_{ac}$ is the node voltage of the AC system before DC connection and new energy to the grid; $\boldsymbol{\Delta U}_{e}$ is the change in node voltage caused by new energy; $\boldsymbol{\Delta U}_{d}$ is the change in node voltage caused by DC input; $\boldsymbol{I}_{ac}$ is the injection current of the synchronous machine before the connection of DC and new energy to the grid; $\boldsymbol{I}_{e}$ is the injected current of the new energy unit; $\boldsymbol{I}_{d}$ is the injected current into the DC line.

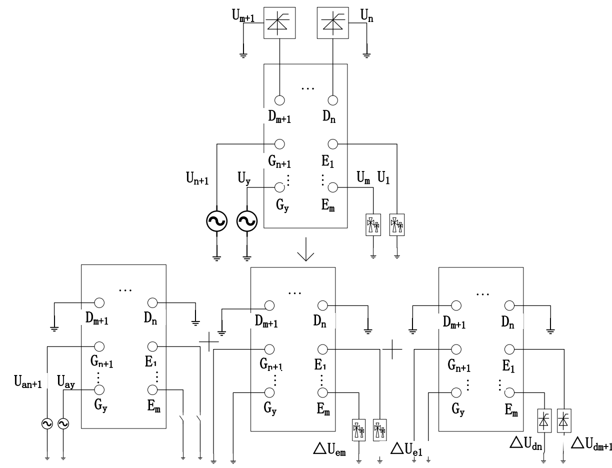

Figure 1. Equivalent analysis model of new energy grid connected system with DC input

B. AC system short circuit capacity

In AC system with new energy and DC grid-connected, node 1-m is new energy grid-connected node, node m+1-n is the DC feed node, and n+1-y is the synchro node. When calculating the capacity of AC system short circuit, the effect of DC and new energy injection current is ignored, only the node injection current of synchro is considered. The current injected into the AC system by each synchro node is $\dot{I}_{acn+1}, \dot{I}_{acn+2}, \cdots, \dot{I}_{acy}$,and the voltage equation of the system node is:

$$U_{ac} = \begin{bmatrix} \dot{Z}_{11} & \cdots & \dot{Z}_{1m} & \dot{Z}_{1m+1} & \cdots & \dot{Z}_{1n} & \dot{Z}_{1n+1} & \cdots & \dot{Z}_{1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{m1} & \cdots & \dot{Z}_{mm} & \dot{Z}_{mm+1} & \cdots & \dot{Z}_{mn} & \dot{Z}_{mn+1} & \cdots & \dot{Z}_{my} \\ \dot{Z}_{m+11} & \cdots & \dot{Z}_{m+1m} & \dot{Z}_{m+1m+1} & \cdots & \dot{Z}_{m+1n} & \dot{Z}_{m+1n+1} & \cdots & \dot{Z}_{m+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{n1} & \cdots & \dot{Z}_{nm} & \dot{Z}_{nm+1} & \cdots & \dot{Z}_{nn} & \dot{Z}_{nn+1} & \cdots & \dot{Z}_{ny} \\ \dot{Z}_{n+11} & \cdots & \dot{Z}_{n+1m} & \dot{Z}_{n+1m+1} & \cdots & \dot{Z}_{n+1n} & \dot{Z}_{n+1n+1} & \cdots & \dot{Z}_{n+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{y1} & \cdots & \dot{Z}_{ym} & \dot{Z}_{ym+1} & \cdots & \dot{Z}_{yn} & \dot{Z}_{yn+1} & \cdots & \dot{Z}_{yy} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \\ \dot{I}_{acn+1} \\ \vdots \\ \dot{I}_{acy} \end{bmatrix} \tag{2}$$

In equivalent impedance matrix with new energy and DC input, diagonal element $\dot{Z}_{ii}$ is self-admittance of node i, representing converted equivalent impedance of node i; The non diagonal element $\dot{Z}_{ij}$ is transadmittance between node i and node j, representing equivalent relation between nodes i and j.

The connecting point I open circuit voltage before the new energy is used to represent system potential of the AC point.

$$\dot{U}_{aci} = \dot{E}_{eqi} \tag{3}$$

The new energy short circuit current unit before grid-connection is:

$$\dot{I}_{sci} = \frac{\dot{U}_{aci}}{\dot{Z}_{ii}} = \frac{\dot{E}_{eqi}}{\dot{Z}_{ii}} \tag{4}$$

The short circuit capacity obtained from AC system looking at the new energy connection point i is:

$$\dot{S}_{aci} = \dot{I}_{aci} U_N = \frac{\dot{E}_{eqi} U_N}{\dot{Z}_{ii}} \tag{5}$$

The AC system short circuit capacity can reflect stability and system strength. The stronger the system is, it indicates the system owns a higher ability to withstand the short circuit current, has strong anti-disturbance ability, and can maintain stable operation facing external interference or failure. Therefore, in the design and operation of systems with new energy grid-connected, itis necessary to pay attention to capacity calculation of the AC system as to ensure system stability.

C. Equivalent grid-connected capacity

When calculating new energy units equivalent grid connected capacity, the injection current fed into the DC and AC systems is not considered, only the injection current of 1-m at the point of new energy grid connection is considered. The currents injected into the AC system by each new energy unit are $\dot{I}_{e1}, \dot{I}_{e2}, \cdots, \dot{I}_{em}$. The node voltage equation is:

$$\Delta U_e = \begin{bmatrix} \dot{Z}_{11} & \cdots & \dot{Z}_{1m} & \dot{Z}_{1m+1} & \cdots & \dot{Z}_{1n} & \dot{Z}_{1n+1} & \cdots & \dot{Z}_{1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{m1} & \cdots & \dot{Z}_{mm} & \dot{Z}_{mm+1} & \cdots & \dot{Z}_{mn} & \dot{Z}_{mn+1} & \cdots & \dot{Z}_{my} \\ \dot{Z}_{m+11} & \cdots & \dot{Z}_{m+1m} & \dot{Z}_{m+1m+1} & \cdots & \dot{Z}_{m+1n} & \dot{Z}_{m+1n+1} & \cdots & \dot{Z}_{m+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{n1} & \cdots & \dot{Z}_{nm} & \dot{Z}_{nm+1} & \cdots & \dot{Z}_{nn} & \dot{Z}_{nn+1} & \cdots & \dot{Z}_{ny} \\ \dot{Z}_{n+11} & \cdots & \dot{Z}_{n+1m} & \dot{Z}_{n+1m+1} & \cdots & \dot{Z}_{n+1n} & \dot{Z}_{n+1n+1} & \cdots & \dot{Z}_{n+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{y1} & \cdots & \dot{Z}_{ym} & \dot{Z}_{ym+1} & \cdots & \dot{Z}_{yn} & \dot{Z}_{yn+1} & \cdots & \dot{Z}_{yy} \end{bmatrix} \begin{bmatrix} \dot{I}_{e1} \\ \vdots \\ \dot{I}_{em} \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{6}$$

When calculating equivalent new energy unit grid-connected capacity, when electrical distance between the connecting point of synchronous unit and new energy unit is far away, injection current influence of the new energy unit on the synchronous unit can be ignored, and new energy unit influence on the DC can be ignored. On this basis, the above node voltage equation can be simplified, and the simplified equation is:

$$\begin{bmatrix} \Delta\dot{U}_1 \\ \vdots \\ \Delta\dot{U}_i \\ \vdots \\ \Delta\dot{U}_m \end{bmatrix} = \begin{bmatrix} \dot{Z}_{11} & \cdots & \dot{Z}_{1i} & \cdots & \dot{Z}_{1m} \\ \vdots & & \vdots & & \vdots \\ \dot{Z}_{i1} & \cdots & \dot{Z}_{ii} & \cdots & \dot{Z}_{im} \\ \vdots & & \vdots & & \vdots \\ \dot{Z}_{m1} & \cdots & \dot{Z}_{mi} & \cdots & \dot{Z}_{mm} \end{bmatrix} \begin{bmatrix} \dot{I}_{e1} \\ \vdots \\ \dot{I}_{ei} \\ \vdots \\ \dot{I}_{em} \end{bmatrix} \tag{7}$$

The new energy node i voltage variation under the other new energy influence units on the new energy node i is:

$$\Delta\dot{U}_{ei} = \dot{Z}_{ii}\dot{I}_{ei} + \sum_{j=1, j\neq i}^{m} \dot{Z}_{ij}\dot{I}_{ej} \tag{8}$$

The capacity which is equivalent grid-connected of the new energy merging point i is:

$$\dot{S}_{eqi} = \dot{U}_i I_{eqi}^* = \dot{S}_i + \sum_{j\neq i} \frac{\dot{Z}_{ij}^*}{\dot{Z}_{ii}^*} \frac{\dot{U}_i}{\dot{U}_j} \dot{S}_j \tag{9}$$

The capacity which is equivalent grid-connected of new energy reflects mutual influence between the new energy interconnection points, reflects the interactiveness between generation unit of new energy power and grid, and is also limited by the stability and grid transmission capacity, so the system safe operation must be ensured by precise calculation.

D. Equivalent DC transmission power

Multiple DC lines connected to the grid can also cause voltage fluctuations at system nodes. When calculating the equivalent DC transmission power, the synchronous injection current with new energy units not considering. The external injected currents at the grid connection points m+1-n of the DC line are $\dot{I}_{dm+1}, \dot{I}_{dm+2}, \cdots, \dot{I}_{dn}$.The node voltage equation is:

$$\Delta U_d = \begin{bmatrix} \dot{Z}_{11} & \cdots & \dot{Z}_{1m} & \dot{Z}_{1m+1} & \cdots & \dot{Z}_{1n} & \dot{Z}_{1n+1} & \cdots & \dot{Z}_{1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{m1} & \cdots & \dot{Z}_{mm} & \dot{Z}_{mm+1} & \cdots & \dot{Z}_{mn} & \dot{Z}_{mn+1} & \cdots & \dot{Z}_{my} \\ \dot{Z}_{m+11} & \cdots & \dot{Z}_{m+1m} & \dot{Z}_{m+1m+1} & \cdots & \dot{Z}_{m+1n} & \dot{Z}_{m+1n+1} & \cdots & \dot{Z}_{m+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{n1} & \cdots & \dot{Z}_{nm} & \dot{Z}_{nm+1} & \cdots & \dot{Z}_{nn} & \dot{Z}_{nn+1} & \cdots & \dot{Z}_{ny} \\ \dot{Z}_{n+11} & \cdots & \dot{Z}_{n+1m} & \dot{Z}_{n+1m+1} & \cdots & \dot{Z}_{n+1n} & \dot{Z}_{n+1n+1} & \cdots & \dot{Z}_{n+1y} \\ \vdots & & \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{y1} & \cdots & \dot{Z}_{ym} & \dot{Z}_{ym+1} & \cdots & \dot{Z}_{yn} & \dot{Z}_{yn+1} & \cdots & \dot{Z}_{yy} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \dot{I}_{dm+1} \\ \vdots \\ \dot{I}_{dn} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{10}$$

When calculating the equivalent DC transmissionpower, when the distance of electrical between the DC junction point and the synchronous unit is far away, the influence of the injection current of multi-fed DC on the synchronous unit can be ignored, but grid-connected DC influence on the unit of new energy will lead to the voltage change of the new energy junction point i, which cannot be ignored. On this basis, the above node voltage equation can be simplified, and the simplified equation is as follows:

$$\begin{bmatrix} \Delta\dot{U}_1 \\ \vdots \\ \Delta\dot{U}_i \\ \vdots \\ \Delta\dot{U}_m \\ \Delta\dot{U}_{m+1} \\ \vdots \\ \Delta\dot{U}_n \end{bmatrix} = \begin{bmatrix} \dot{Z}_{11} & \cdots & \dot{Z}_{1i} & \cdots & \dot{Z}_{1m} & \dot{Z}_{1m+1} & \cdots & \dot{Z}_{1n} \\ \vdots & & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{i1} & \cdots & \dot{Z}_{ii} & \cdots & \dot{Z}_{im} & \dot{Z}_{im+1} & \cdots & \dot{Z}_{in} \\ \vdots & & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{m1} & \cdots & \dot{Z}_{mi} & \cdots & \dot{Z}_{mm} & \dot{Z}_{mm+1} & \cdots & \dot{Z}_{mn} \\ \dot{Z}_{m+11} & \cdots & \dot{Z}_{m+1i} & \cdots & \dot{Z}_{m+1m} & \dot{Z}_{m+1m+1} & \cdots & \dot{Z}_{m+1n} \\ \vdots & & \vdots & & \vdots & \vdots & & \vdots \\ \dot{Z}_{n1} & \cdots & \dot{Z}_{ni} & \cdots & \dot{Z}_{nm} & \dot{Z}_{nm+1} & \cdots & \dot{Z}_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \\ \dot{I}_{dm+1} \\ \vdots \\ \dot{I}_{dn} \end{bmatrix} \tag{11}$$

The node I voltage variation of new energy under the input DC line influence on the newenergy node is:

$$\begin{aligned} \Delta\dot{U}_{di} &= \dot{Z}_{im+1}\dot{I}_{dm+1} + \dot{Z}_{im+2}\dot{I}_{dm+2} + \cdots + \dot{Z}_{in}\dot{I}_{dn} \\ &= \sum_{k=m+1}^{n} \dot{Z}_{ik}\dot{I}_{dk} \end{aligned} \tag{12}$$

The equivalent DC transmission power is:

$$P_{deq} = \sum_{k=m+1}^{n} \frac{\dot{Z}_{ik}^*}{\dot{Z}_{ii}^*} \frac{\dot{U}_i}{\dot{U}_k} P_k \tag{13}$$

E. New energy junction short circuit ratio index including DC feed

In summary, the short-circuit ratio index of thenew energy grid-connected system including DC feedis defined as:

$$SCR_{edi} = \frac{S_{aci}}{S_{eqi} + P_{deq}} = \frac{\left|\dfrac{U_N E_{eqi}}{Z_{ii}}\right|}{\left|\dot{S}_i + \sum_{j \neq i} \dfrac{\dot{Z}_{ij}^*}{\dot{Z}_{ii}^*} \dfrac{\dot{U}_i}{\dot{U}_j} \dot{S}_j + \sum_{k=m+1}^{n} \dfrac{\dot{Z}_{ik}^*}{\dot{Z}_{ii}^*} \dfrac{\dot{U}_i}{\dot{U}_k} P_k\right|} \tag{14}$$

If $|\dot{U}_i| = |\dot{U}_j| = |\dot{U}_k| = 1$ considered, there is:

$$SCR_{edi} = \frac{\left|\dfrac{U_N E_{eqi}}{Z_{ii}}\right|}{\left|\dot{S}_i + \sum_{j \neq i} \dfrac{\dot{Z}_{ij}^*}{\dot{Z}_{ii}^*} \dot{S}_j + \sum_{k=m+1}^{n} \dfrac{\dot{Z}_{ik}^*}{\dot{Z}_{ii}^*} P_k\right|} \tag{15}$$

The voltage variation of the new energy junction point i under common influence of DC feed lineand other new energy units is:

$$\Delta\dot{U}_i = \Delta\dot{U}_{ei} + \Delta\dot{U}_{di} = \dot{Z}_{ii}\dot{I}_{ei} + \sum_{j=1, j\neq i}^{m} \dot{Z}_{ij}\dot{I}_{ej} + \sum_{k=m+1}^{n} \dot{Z}_{ik}\dot{I}_{dk} \tag{16}$$

The ratio of the new energy grid connection point nominal voltage to the voltage change caused by the new energy and DC grid connection is:

$$\frac{U_N}{\left|\Delta\dot{U}_i\right|} = \frac{U_N}{\left|\Delta\dot{U}_{ei} + \Delta\dot{U}_{di}\right|} = \frac{U_N}{\left|\dot{Z}_{ii}\dot{I}_{ei} + \sum_{j\neq i} \dot{Z}_{ij}\dot{I}_{ej} + \sum_{k=m+1}^{n} \dot{Z}_{ik}\dot{I}_{dk}\right|} \tag{17}$$

The above formula is derived and transformed to obtain:

$$\frac{\left|U_N \dot{E}_{eqi}\right|}{\left|\Delta\dot{U}_i \dot{U}_i\right|} = \frac{\left|\dfrac{U_N \dot{E}_{eqi}}{\dot{Z}_{ii}}\right|}{\left|\dot{S}_i + \sum_{j \neq i} \dfrac{\dot{Z}_{ij}^*}{\dot{Z}_{ii}^*} \dfrac{\dot{U}_i}{\dot{U}_j} \dot{S}_j + \sum_{k=m+1}^{n} \dfrac{\dot{Z}_{ik}^*}{\dot{Z}_{ii}^*} \dfrac{\dot{U}_i}{\dot{U}_k} P_k\right|} \tag{18}$$

Therefore, the new energy junction short-circuitratio index including DC feed can also be defined bythe form of voltage ratio:

$$SCR_{edi-U} = \frac{\left|U_N \dot{E}_{eqi}\right|}{\left|\Delta\dot{U}_i \dot{U}_i\right|} \tag{19}$$

SCR_{edi-U} defined in terms of voltage ratio has thesame physical meaning as SCR_{edi} defined in terms ofcapacity ratio, and its physical nature is exactly thesame. SCR_{edi-U} is more convenient and intuitive inevaluating the system voltage support strength,and SCR_{edi-U} has higher accuracy in evaluating. Both of them are significant for new energy grid-connected system stability evaluation with DC feed and have practical engineering significance.

III. THE CRITICAL SHORT-CIRCUIT RATIO OF THE NEW ENERGY SYSTEM WITH DC FEED

A. The significancecriticalshort-circuit ratio

Critical Short-Circuit Ratio (CSCR) is an significant concept in power system stability evaluation. It builds a bridge between power system static voltage stability and short circuit ratio and establishes relationship between them. Under such conditions, the system maximum transmitted power is usually adopted as a criterion to measure the system maximum transmitted power. The voltage instability of system usually occurs when the system operating power is close to the maximum transmitted power. In the stage of maximum transmission power, the system operates in a critical state. At this time, even a slight increase in load can cause a sudden drop in system voltage and instability. As show in figure 2.

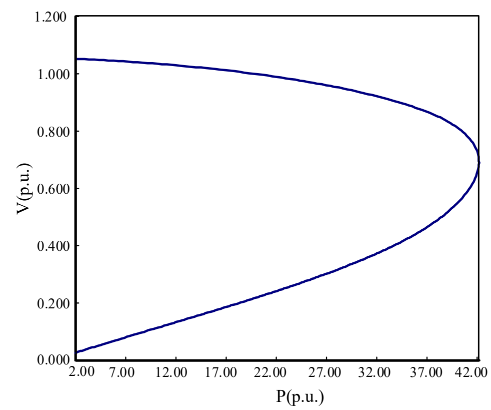

Figure 2. P-V Curve Equivalent Model

P-V curve is significant in measuring system stability. By calculating the P-V curve of each node in the receiving end system of grid-connected new energy, two important parameters related to voltage stability of the receiving end of the grid can be obtained. The ultimate transmission and critical voltage of the load, according to these two variables, the ability of the load node in system to maintain voltage stability in face of load fluctuations can be obtained, thus characterizing voltage stability margin of receiving end of grid.

B. Theoretical derivation of the criticalshort-circuit ratio

The critical short-circuit index indicates lowerlimit of the system index when system is in a critical stable operation state. The greater thedifference between the system index and the critical index, the more stable thesystem is, the less likely it is to cause voltage collapsedue to load fluctuations and other reasons, with agreater stability margin.

Based on ratio formula of short circuit about the new energy junction point with DC feed defined in the formof voltage, the mathematical derivation of the extremevalue of the critical index is carried out.In order to simplify the calculation, U takes unitvalue 1, and index formula defined inthe form of voltage is simplified as:

$$SCR_{ei-U} = \frac{\left|\dot{E}_{eqi}\right|}{\left|\Delta\dot{U}_i\dot{U}_i\right|} \tag{20}$$

Take the complex form of the AC system potential E_{eqi} of the junction point i and the actual voltage U_i of the junction point i, and obtain:

$$\begin{cases} E_{eqi} = e_x + je_y \\ U_i = u_x + ju_y \end{cases} \tag{21}$$

According to the value ofthe AC system potentia!and the new energy node i, the node voltage change ofthe new energy node i before and after grid connectioncan be calculated:

$$\Delta U_i = U_i - E_{eqi} = (e_x + je_y) - (u_x + ju_y) \tag{22}$$

The complex form of the voltage change of thenew energy junction point i is substituted into the ratio calculation formula of short circuit defined in the form ofvoltage, and the critical short-circuit ratio can be expressed as:

$$CSCR = \frac{\left|e_x + je_y\right|}{\left|(u_x{}^2 - u_y{}^2 - e_x u_x + e_y u_y) + j(2u_x u_y - e_x u_y - e_y u_x)\right|} \tag{23}$$

To simplify the calculation, Ee i takes the per unitvalue as 1, which can be obtained:

$$CSCR = \frac{1}{\left|(u_x{}^2 - u_y{}^2 - u_x) + j(2u_x u_y - u_y)\right|} \tag{24}$$

The critical short-circuit ratio extreme value is transformed into problem of findingthe maximum value of the function.

$$\begin{aligned} F(u_x, u_y) &= \left|(u_x{}^2 - u_y{}^2 - u_x) + j(2u_x u_y - u_y)\right|^2 \\ &= u_x^4 + u_y^4 + 2u_x^2 u_y^2 - 2u_x^3 - 2u_x u_y^2 + u_x^2 + u_y^2 \end{aligned} \tag{25}$$

Through calculation, the maximum value withinthe reasonable range of the function is 0.1389, andfinally, the extreme value of grid-connected system of new energy critical short-circuit ratio with DC feed is 2.683.

In order to ensure project robustness and take into account the uncertainties that may occur in the implementation of the project, it is suggested to set critical ratio thethreshold of the new energy connection point to 2.683 in the new energygrid-connected system with DC input. The difference between normal and critical short circuit ratio reflects stability margin ofthe receivingend system. On this basis, the stability of the system can be evaluated by the difference between the actual short circuit ratio of the new energy junction pointSC'Redi and the critical short circuit ratio.

IV. SIMULATION VERIFICATION

This paper builds a 10-machine 39-node model based on PSASP simulation platform, as shown in Figure 3, calculates each new energy node short-circuit index, besides, calculates the critical short-circuit ratio of new energy node based on the continuous power flow method using idea of limiting transmission power.

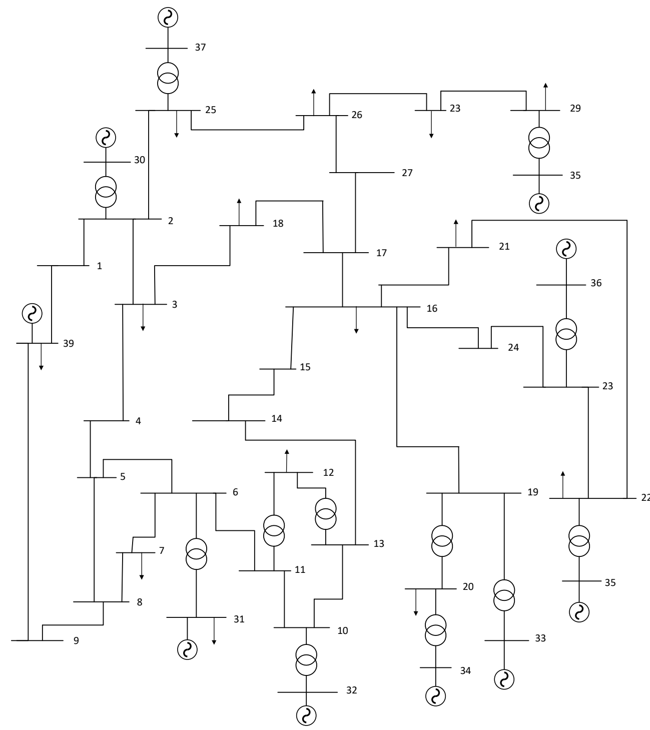

Figure 3. Simulation diagram of new energy grid connected system with DC input

To verify the rationality and feasibility of the short-circuit ratio index of the new energy grid connection point with DC input proposed in this article, as well as its representativeness for the system voltage support strength, simulation verification was carried out from several aspects, including relationship between the overvoltage short-circuit ratio and the short-circuit ratio at new energy unit terminal, the influence of new energy penetration rate on short-circuit ratio, the relationship between the DC input line and short-circuit index, and relationship between the short-circuit ratio and the voltage support strength.

A. New energyjunction criticalshort-circuit ratio calculation

Based on the new energy grid-connected system model with DC feed, the voltage stability simulation calculation of the model is carried out by using the method of obtaining the critical short-circuit ratio by limiting transmission power. The simulation results are combined with the short circuit ratio index definition formula proposed above to calculate the critical index value of each grid connection point of new energy.

Table 1 Short-circuit ratio and critical short-circuit ratio of each new energy grid connection point

Wind turbine	**Grid-connected bus bars**	**SCR$_{edi\text{-}U}$**	**Critical short circuit ratio**
G01	Bus1	3.404	1.831
G02	Bus2	3.486	1.810
G03	Bus3	2.649	2.089
G04	Bus4	3.115	1.657
G05	Bus5	3.019	2.578
G06	Bus6	3.299	1.764

It can be seen from the results of Table 1 that the short-circuit ratio of the new energy junction in the model built is greater than the critical short-circuit ratio based on the limit transmission power, which shows that these new energy junction points have high stability.

It can be seen that there is a certain error between the critical short-circuit ratio obtained based on the limiting transmission power and the critical short-circuit ratio obtained based on theoretical derivation in the above, mainly due to two reasons: First, the theoretical calculation model adopts some simplified assumptions and simplified data processing, while the simulation model contains more details of the equipment and parameters in the scenario of DC and new energy grid connection, and the solution algorithm is more complicated; Second, the calculation model only considers the steady-state conditions, and the simulation model can capture the transient response of the system, including more dynamic processes, and perform simulation calculations at different new energy interconnection points. The above factors will lead to the difference between the simulated critical short circuit ratio value and the theoretical calculation value, but the error is within a reasonable range, and will not have an essential impact on the conclusion.

B. Therelationshipbetweenterminalovervoltage and short-circuit ratio

For the system of new energy grid-connected with DC feed, after the system failure disturbance, the new energy unit overvoltage is closely related to the short circuit ratio of the new energy junction point. Based on the PSASP simulation program, for the DC and system of new energy grid-connected, a node is set to have a three-phase short circuit fault, and the relationship between the short circuit ratio of different new energy power generation equipment and new energy unit overvoltage after system fault disturbance is simulated.

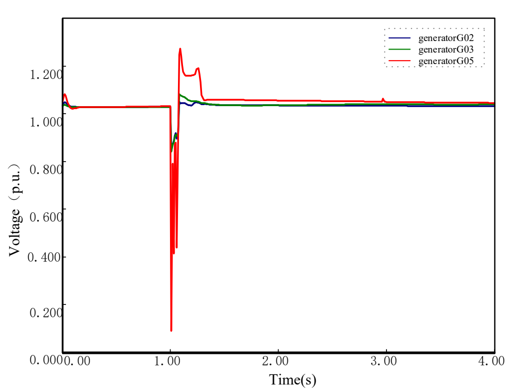

Figure 4. Overvoltage of different new energy units after system fault disturbance

As can be seen from Fig 4, the maximum overvoltage at end of G02 of new energy units is 1.049pu; The highest overvoltage of G03 of new energy unit is 1.079pu; New energy unit G05 machine end overvoltage is the highest 1.273pu.Under the same conditions of DC feeding, the smaller the new energy unit short-circuit ratio, the greater maximum overvoltage after fault the system disturbance, Conversely, the larger the new energy node short-circuit ratio, the smaller the maximum over voltage after the system fault disturbance. The simulation results show that the new energy unit with small short circuit is weak, and cannot effectively suppress the voltage fluctuation caused by the system fault; And the new energy units with relatively large short circuit have stronger dot strength, which can better control the voltage fluctuation after the fault.

C. The influence of new energy permeabilityon short circuit ratio

In the grid-connected grid scenario with DC feed,the new energy permeability also has a certain impacton the short-circuit ratio of the new energy units at theconnecting point. Based on the PSASp simulationplatform, the number of new energy units is changed,the permeability of new energy units is set to changefrom low to high, and the short-circuit ratio is simulatedand analyzed.

Table 2 New energy penetration rate of 20% of the new energy interconnection points short-circuit ratio

Wind turbine	**Grid-connected bus bars**	**SCR$_{edi\text{-}U}$**
G04	Bus4	3.199
G05	Bus5	3.056

Table 3 New energy penetration rate of 30% of the new energy interconnection points short-circuit ratio

Wind turbine	**Grid-connected bus bars**	**SCR$_{edi\text{-}U}$**
G03	Bus3	2.685
G04	Bus4	3.134
G03	Bus5	3.035

Table 4 New energy penetration rate of 40% of the new energy interconnection points short-circuit ratio

Wind turbine	**Grid-connected bus bars**	**SCR$_{edi\text{-}U}$**
G02	Bus2	3.391
G03	Bus3	2.648
G04	Bus4	3.059
G05	Bus5	3.017

As can be seen from the simulation results in Table 2, 3 and 4, under the condition that the DC feed condition is unchanged and only the new energy unit is connected to the grid is changed, the higher the new energy penetration rate of the system, the smaller the corresponding new energy junction point value, indicating that the increase of new energy permeability leads to the weakening of system strength and the decrease of resistance to disturbance. In system of actual power, new energy unit output can be controlled when necessary to avoid the stability problem because of the low short-circuit ratio of the system, and appropriate protection devices and control measures can be taken to increase the stability and reliability of the power system with ahigh proportion of new energy.

D. *The influence of DC feed on the shortcircuit ratio*

Compared with new energy system short circuit ratio proposed in past, the index proposed in this paper adds consideration factor of DC feed, and DC feed also has a certain impact on ratio of short circuit. Based on the PSASP simulation platform, new energy node short-circuit ratio is simulated and analyzed by comparing whether there is DC feed line.

Table 5 Short-circuit ratio of each new energy node in the scenario of no DC feed

Wind turbine	Grid-connected bus bars	SCR_{edi-U}
G01	Bus1	2.989
G02	Bus2	2.622
G03	Bus3	2.434
G04	Bus4	2.661
G05	Bus5	2.668
G06	Bus6	2.832

Table 6 Short-circuit ratio of each new energy junction under multi-DC feed scenario

Wind turbine	Grid-connected bus bars	SCR_{edi-U}
G01	Bus1	2.035
G02	Bus2	2.443
G03	Bus3	2.350
G04	Bus4	2.386
G05	Bus5	2.380
G06	Bus6	2.484

It can be seen from Table 5 and 6 that the new energy grid connection system has a significant impact on the new energy grid connection point short circuit ratio after DC line is fed into system. After DC is fed into the new energy grid-connected system, the short circuit ratio becomes smaller, strength of the system weakens, and resistance to fault disturbance decreases. In actual engineering, the system may need more complex and accurate control strategies to ensure the system safe and stable.

According to the critical short-circuit feeding ratio threshold value of the new energy junction with DC input proposed in 2.2, in the scenario of multi-new energy grid-connected, after DC input, the short circuit ratio of the selected new energy grid-connected nodes is all smaller than the critical short-circuit ratio. The critical index proposed above is derived from theoretical reasoning and is conservative to a certain extent. In practical engineering, the threshold of the critical short-circuit ratio should be adjusted according to the actual situation, so as to evaluate the stability of the system's new energy junction points more scientifically and accurately.

E. *Voltage support strength evaluation*

When the system is running stably, there is a certain difference between the actual short-circuit ratioand the critical short-circuit ratio, which is system stabilitymargin. When the grid-connectedcapacity of the system increases, the short-circuit ratiogradually decreases until it approaches the criticalshort-circuit ratio, and the system may collapse andcannot return to normal operation.In the PSASP simulation platform, for the newenergy grid-connected system with DC feed, select anew energy grid-connected node, increase whole system new energy grid-connected capacity,until the short circuit ratio of the new energyconnection point is close to the critical short circuitratio, set a node to have a three-phase short circuit fault and simulate point transient stability after the system failure.

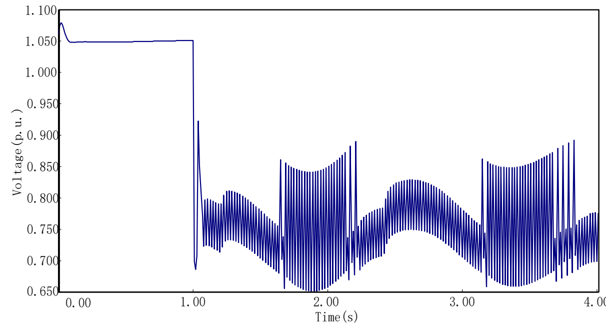

Figure 5. Transient stability of the system after fault disturbance under the limit grid-connected capacity of new energy

As shown in Fig.5, the simulation results show that when new energy is connected to grid with a high capacity, the system stability decreases and the system becomes unstable after fault disturbance. This indicates that the proposed index has a certain indicative effect on new energy grid stability connected systems with DC input. It is a quantitative indicator of the system voltage support strength, which helps to analyze the reactive power compensation system requirements, optimize the grid structure, and adjust control strategies, and has certain engineering significance.

V. CONCLUSIONS

This paper puts forward the short-circuit ratio index of new energy junction in grid-connected scenario with DC feed, and theoretically deduces the critical index based on proposed index to obtain extreme value of the critical ratio of short circuit, and rationality and feasibility of the short-circuit ratio index are verified by simulation. The specific conclusions are as follows:

(1) Based on superposition theorem, the new energy grid-connected system with DC feed is divided into AC system, new energy system and DC system super position. The node voltage equation is listed respectively, and AC system short-circuit capacity, grid-connected equivalent new energy capacity and the equivalent DC transmission power are obtained. The short-circuit ratio index SCR_{edi} is defined by short-circuit capacity ratio of the AC system and the sum of the equivalent grid-connected capacity of the new energy system plus the equivalent DC transmission power. The ratio between new energy grid connection point nominal voltage and voltage change caused by new energy grid connection is mathematically transformed, and the short-circuit ratio index SCR_{edi-U} defined in the form of voltage is obtained. The expression forms of above two ratios of short circuit indicators are different, but the physical meaning is the same, and the effect of system stability evaluation is the same.

(2) Based on ratio index of short circuit defined in the form of voltage, critical ratio of short circuit is mathematically derived, besides, extreme value of the critical short-circuit ratio is 2.683. In actual project, for the new energy grid-connected system with DC feed, it is recommended to set the threshold of new energy connection point critical short-circuit ratio to 2.683.

(3) The reasonableness of above index is verified by simulation. The smaller the index of the connecting point of the new energy unit, the higher the overvoltage of the machine end during the fault disturbance, and the ability to restrain the voltage fluctuation is weak. Under the same DC feeding conditions, the higher the penetration rate of new energy, the smaller the short circuit ratio of new energy junction, and the weaker the system strength; When more DC lines are fed into the new energy grid-connected system, the short circuit ratio becomes smaller and the system strength weakens. Increase new energy grid-connected capacity to the short-circuit ratio close to the critical index, and system will oscillate and lose stability after failure. The above simulation results show that ratio index of short circuit proposed in above literature is reasonable and feasible, and has a certain indication of the voltage support strength of the system.

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