Research on the influence of large-scale electric vehicles access to transmission grid considering cascading trip events

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Abstract. This paper researches the impact of large-scale charging electric vehicles on power system with considering cascading trip events. Firstly, with the analysis of the relationship between the branches and the nodes in the power system after the branch with initial failure tripped, this paper proposes the corresponding equation that can reveal the relationship. Then, by combining that equation, this paper analysis the influences of large-scale electric vehicles when they access to the power system on the transmission grid. Finally, some examples are performed on IEEE-39 bus test system and verify the rationality of the analytical method in the paper.

1. Introduction

It is likely to cause the complex cascading failures, even large-scale blackout in the power system when the cascading trip events of power grid occurrence, the problem was noted constantly and globally in recent years[1, 2, 3]. Researchers have done a lot of work on the study of cascading trip events and cascading failures, and also have obtained many research results.

In general, the initial failure of power system that cause a cascading trip failure is just a simple fault, the classic appearance is: after a line, which is the first step failure, is tripped. Then due to the cascading disturbance, some running branches of the power system are tripped by the action of the relay or automatic gear. This is the second step failure and then more lines or electrical equipment in running are tripped as the third step failure, and so on. In general, with the development of cascading trip failure, the dynamic process gets more complicated.

Obviously, the earlier block of cascading trip failure is better for the operation of power system than considering from the defense of cascading trip failure. In addition, from the emergency control considerations, some measures should be taken when the first step failure occurs which is the cascading trip usually.

Generally speaking, the cascading trip phenomenon of the power system is intimately related to the electrical parameters of the cascading disturbed branch after the redistribution of the power flow and the setting of the backup relay protection of the cascading disturbed branch. Combining these factors in this paper, the relationship is analyzed which between the cascading disturbed branch and the nodal power injection. Then the nodal power injection influence on the cascading trip is analyzed anteriorly as well as the impact of the large-scale electric vehicle charging in the power system on the cascading trip. At the end of this paper, simulations performed on IEEE-39 bus test system drawing some further analysis and meaningful validation.
Connection between nodes and branches after initial fault tripped

Suppose that a branch $L_k$ tripped due to an initial failure, then the power flow of the power system is re-distributed, the transmission power of the branch $L_i$ of the new power system is changed from $P_{i(0)}$ to $P_i$ when only consider the active power in approximately, namely:

$$P_i = P_{i(0)} + \lambda_k(i)P_{i(0)}$$

(1)

Where, $P_{i(0)}$ is the transmission power of the branch $L_k$ before failure, $\lambda_k(i)$ is the parameters that decided collectively by the composition of the power system and the reactance parameters of the branches, $\lambda_k(i)$ reflects the share of the previously transmission power distributed in the branch $L_i$ when the $L_k$ tripped. Suppose that a power system with $l$ branches and $n$ nodes, also include branch $L_k$, the combination of the transmission power of each branch of the power system in terms of Eq. (1) that can be formed as the Eq. (2) abbreviated matrix form:

$$P_L = P_{L(0)} + P_{k(0)}\lambda$$

(2)

Where, $P_L$ is the branch power vector that branch $L_k$ tripped which contains $l$ elements, $P_{L(0)}$ is the branch power vector before the branch $L_k$ tripped, and $\lambda$ is a vector that formed by $\lambda_k(i)$ of each branch.

According to the DC power flow method, before the branch $L_k$ tripped, the relationship between $P_{L(0)}$ in Eq. (2) and the voltage phase angle vector $\theta_0$ of every nodes of power system is known as [4]:

$$P_{L(0)} = S\theta_0$$

(3)

Where, the voltage phase angle of the datum node in $\theta_0$ is $\theta$, $S$ is a branch-node association matrix, in which each element is recorded as $s_{ij}$ ($i=1, 2, \ldots, l; j=1, 2, \ldots, n$), $s_{ij}=0$ when the branch $L_i$ and node $j$ are not connected, $s_{ij}=1/x$ when the power of the branch $L_i$ flows from node $j$, else $s_{ij}=-1/x$, and $x$ is the reactance of branch $L_i$.

The vector of the rest of the nodes except the reference node in the $\theta_0$ named as $\theta_0^\prime$, Eq. 4 shows that the relationship between $\theta_0^\prime$ and the nodal power injection vector by the DC Flow method [5]:

$$\theta_0^\prime = (B_0^\prime)^{-1}P_n^\prime$$

(4)

Where, $B_0^\prime$ is a $n-1$-order node susceptance matrix that before branch $L_k$ tripped which does not contain the datum node, $P_n^\prime$ is a node power injection vector which does not contain the datum node. $(B_0^\prime)^{-1}$ is extended by add a row and a column that the values of each element are taken as "0", the row and column numbers correspond to the number of the datum node, the remaining rows and columns are numbered separately from each of the remaining nodes, and named it as $B_0$. Named row $k$ of $l \times l$ unit array as $I_k$, ulteriorly:

$$P_L = [SB_0 + \lambda I_k SB_0]P_n = R_p P_n$$

(5)

Where, $P_n$ is a nodal power injection vector that including datum node. $R_p$ is a coefficient matrix composed of $SB_0 + \lambda I_k SB_0$, each element of which is recorded as $r_{ij}(i=1, 2, \ldots, l; j=1, 2, \ldots, n)$.

According to the assumptions of the DC power flow method and the relationship between the branch current and the transmission active power, the current of the remaining branches when the branch $L_k$ tripped are:
\[ I = R_p P_n \]  

Where, Eq. (6) is the relationship between the nodal power injection and the current of each branch when the branch \( L_k \) tripped.

By Eq. (8) can be seen, after the branch \( L_k \) tripped, the current branch \( L_i \) is:

\[ I_i = \sum_{j=1}^{n} r_{ij} P_j \]  

Any element \( r_{ij} P_j \) \( (j=1,2,\ldots,n) \) of the right of Eq. (7) represents the actual contribution of node \( j \) to the branch \( L_i \), while \( r_{ij} \) represents the sensitivity of the node \( j \) to the branch \( L_i \).

### 3. Effect of nodal injection to cascading trip

Suppose that a branch \( L_k \) tripped due to an initial failure, then the power flow of the power system is re-distributed, according to the configuration of the backup relay protection, the branch \( L_i \) of the new power system can be defined as the following variables to measure the branch trip:

\[ I_{i-dist} = I_i - \text{set} \]  

Where, \( I_{i-dist} \) is the parameter that to measure the electrical distance between \( I_i \text{lim} \) and \( I_i \), the meaning is: When \( I_{i-dist} \leq 0 \), the branch \( L_i \) tripped by the backup relay protection, \( I_{i-dist} \) is the setting of the backup relay protection, \( I_i \) is the current of the branch \( L_i \) after the branch \( L_k \) tripped.

By Eq. (8) can be seen, without considering the uncertainty of the relay protection action and other locking conditions, considering from the cascading trip, the value of \( I_{i-dist} \) is essentially reflects the severity of the disturbance of the branch \( L_i \) after the initial failure tripped as the impact of the cascading and \( I_{i-dist} \) is determined by the \( I_i \), by Eq. (7), \( I_i \) is determined by the nodal power injection.

### 4. Grid impact of charging electric vehicles

According to Eq. (6), (7) and (8), it can be deduced that the node \( j \) which the power injection changed dramatically and some elements \( r_{ij} \) are large will have a significant impact on the branch \( L_i \) when the initial fault branch tripped.

The node \( j \) that will have a large power injection which will give a powerful impact on the branch \( L_i \) when the large-scale electric vehicle charging in it.

Whether the branch \( L_i \) cascading trip is related to other nodes and the coefficient \( r_{ij} \) is associated with other nodes that can be found by Eq. (8).

### 5. Case Study

In this paper, the simulations are performed on IEEE 39-bus test system, which contains 10 generators, 19 loads and 46 lines, the wiring diagram of IEEE 39-bus test system is shown in Fig.1.

The program that according to the algorithm step and the simulating system is written with the language MATLAB, in this program, the per-unit value is calculated by valuing the base capacity of 100 MVA.

The branch \( i \) is defined as disturbed branch heavily if \( I_{i-dist} \leq 0.01 \) after initial failure tripped.

#### 5.1. Case 1

In this case, the initial fault branch is set to the branch \( L_{26-27} \) that connecting node 26 and node 27.

By calculating, a total of 4 branches were seriously disturbed that may occur cascading trip after the branch \( L_{26-27} \) tripped, these branches are the branch \( L_{3-18} \), \( L_{9-39} \), \( L_{14-15} \), and \( L_{17-27} \).

Fig.2 shows the data of \( r_{ij} \) and \( r_{ij}P_j \) of branch \( L_{3-18} \).

As seen from Fig.2, the elements \( r_{ij} \) of the nodes which related to the branch \( L_{3-18} \) are similar, the elements \( r_{ij}P_j \) of the nodes which related to the branch \( L_{3-18} \) are differ greatly. Some nodes with large
power injection which impact on the branch $L_{3,18}$ tripped, mainly includes node 20 and node 33 and node 35, etc.

Fig. 3 shows the data of $r_{ij}$ and $r_{ij}P_j$ of disturbed branch $L_{9,39}$.

Figure 1. Diagram of the example system

Figure 2. Data of $r_{ij}$ and $r_{ij}P_j$ of disturbed branch $L_{3,18}$ in case 1

Figure 3. Data of $r_{ij}$ and $r_{ij}P_j$ of disturbed branch $L_{9,39}$ in case 1
The meaning of ordinate and horizontal axis in Fig. 3 is same as in Fig. 2.
As seen from Fig. 3 which similar to Fig. 2, the elements $r_{ij}$ of the nodes which related to the branch $L_{9,39}$ are similar, the elements $r_{ijP_j}$ of the nodes which related to the branch $L_{9,39}$ are differ greatly. Some nodes with large power injection which impact on the branch $L_{3,18}$ tripped, mainly includes node 20 and node 37 and node 38, etc.

The above case show that if the correlation coefficients ($r_{ij}$) of the remaining branches of the power system to those of the rest nodes of the power system after the initial failure tripped are similar, some nodes with heavy power injection will have a severe impact on the power system, it should to be taken seriously when these nodes with the load of electric vehicles.

5.2. Case 2
In this case, the initial fault branch is set to the branch $L_{21,22}$.
By calculating, a total of 4 branches were seriously disturbed that may occur cascading trip after the branch $L_{21,22}$ tripped, these branches are the branch $L_{16,24}$, $L_{17,27}$, $L_{22,23}$, and $L_{23,24}$.

Fig.4 shows the data of $r_{ij}$ and $r_{ijP_j}$ of disturbed branch $L_{16,24}$, the meaning of ordinate and horizontal axis in it is same as in Fig. 2.

![Figure 4. Data of $r_{ij}$ and $r_{ijP_j}$ of disturbed branch in case 2](image)

![Figure 5. Data of $r_{ij}$ and $r_{ijP_j}$ of disturbed branch in case 1](image)

The Fig. 4 shows that when the branch $L_{21,22}$ tripped, the correlation coefficient ($r_{ij}$) between the branch $L_{16,24}$ and the node 24, and the correlation coefficient ($r_{ij}$) between the branch $L_{16,24}$ and the node 36 are both very large, correspondingly, the corresponding data $r_{ijP_j}$ are also very large. In this
case, $r_{ij}$ approximately equal to $r_{ij}P_j$. It shows that it will have an impact on the cascading trip when the node 24 and node 36 are both with the light load of electric vehicles.

Fig. 5 shows the data of $r_{ij}$ and $r_{ij}P_j$ of disturbed branch $L_{17-27}$, the meaning of ordinate and horizontal axis in it is same as in Fig. 2.

Through Fig. 5 can be found that the branch $L_{17-27}$ is also mainly affected by some key nodes that is basically similar as branch $L_{21-22}$, it will have a major impact on the cascading trip when those key nodes with the heavy load of electric vehicles.

6. Conclusion

The phenomenon of cascading trip of the power system is related closely to the relay setting of the cascading disturbed branch. The bearing after initial fault tripped between the branch current and the nodal power injection is calculated by DC power flow method in this paper and the impact of the nodal power injection on the cascading trip of power system is illustrated by combining with the action-setting equation of relay. The analysis and case studies in this paper show that after the initial fault resection of the power grid, the cascading trip of any branch is related to the nodal power injection but it is not dependent on any single node. When large-scale electric vehicles charging in the power system, the cascading trip of any branch is bearing on the state of every nodal power injection and the interconnection of every nodal power injection with it. The charging of electric vehicles will be the crucial impact on the cascading trip of the power system only when the interconnection of the branch and the node with charging electric vehicles is very tight and the coupling relationship with other nodes distantly.

The case studies show that the analysis presented in this paper is effective and can provide reference for further research.

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