A Method of Evaluating Cascading Tripping in Power Grid Considering the Action of the Relay Protector and the Nodal Injection Power

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Abstract. Cascading tripping accidents are main causes of complex cascading outages in power system. This paper proposes a method of predicting whether cascading tripping will occur according to the nodal injecting power. In order to give the theoretical foundation of this method, this paper verifies that the injecting power of a power network plays a decisive role for the cascading tripping according to the general behavior of cascading tripping and the action of backup relay protector. As to backup relay protector, the type of current and distance are concerned in this paper. On the basis of the theoretical foundation, a method for predicting whether the cascading tripping by using pattern recognition technology is proposed. In this method, the nodal injecting power is taken as input, and whether the cascading tripping will occur is taken as output. By using this method, to a specific initial faulted line, as long as the nodal injection power is given, whether the power network will suffer from cascading tripping accident will be given. In order to prove the rationality and effectiveness of this method, an example in IEEE39 system is illustrated and the result of the example is satisfactory.

Introduction

Cascading outages are the main causes of blackout in power network, and they are concerned by more and more researchers in recent years. The scholars research the method of simulating the cascading outages, the mechanism of cascading outages, and the effect of the grid structure on the cascading outages[1-3], and achieve many beneficial research results which provide a lot of references for the further study on the cascading outages of power system.

The most common case of cascading outages in power network is cascading tripping, especially in the early stage of cascading outages. The common process of cascading tripping is that after an initial faulted line is removed, the power flow of the power network will be redistributed, and then the other lines may be cut down by their backup relay protectors. In the last two decades, some blackout accidents happened every a few years in the world. Features of cascading outages are common in blackout accidents. In the early stages of cascading outages, the usual feature of cascading outage performance is that it acts as cascading tripping.

With the development of modern computer, communication and control technology, the automation level of power system have greatly improved. And then, cascading tripping and the occurrence of cascading outage show that people do not pay enough attention to the importance of cascading tripping and cascading outage.

Cascading Tripping of the power grid is closely related to the action of backup relay protector in general[4].After the initial fault line is removed, the power flow is redistributed, and whether the power grid will have cascading tripping is closely related to the operation state of the power grid before the initial failure. In this paper, the common action behavior of current and distance backup relay protector is considered. Based on that, the relationship between cascading tripping and node injection power is analyzed, and a method of cascading tripping evaluation based on pattern recognition is proposed. In this method, the node injection power of the power network is regarded as the feature input, and the occurrence of cascading tripping is the output. The classifier is constructed by using sample data, and the power vectors can be injected according to the input nodes to evaluate whether the power grid will have cascading tripping because of an initial failure. Finally, this article uses the IEEE39 system to carry on the demonstration. In this example, the method of Cascading Tripping evaluation based on pattern recognition is very accurate. The results show that the method is effective.

Analysis of Cascading Tripping Behavior in Power Grid Considering Backup Relay Protector

Cascading tripping of the power system is usually caused by the redistribution of the power flow after the initial failure, and the process is slow, so the circuit of Cascading tripping is usually removed by backup relay protector. In the high voltage transmission network, the line is equipped with tree zone distance protector. The third-zone unit of a distance relay is mainly used as the delay action to remove the fault. In the process of power flow transfer after the initial fault, The third-zone unit of a distance relay is one of the possible protector of the possible action. In addition to distance protector, some power grid is also configured with overload protector. Overload protector may send out the warning information, and may also delay the tripping. If the time delay tripping is adopted, this kind of backup protector may also move in the process of power flow transfer after the initial fault.

Whether overload protector or the third-zone unit of a distance relay, we can use the unified expression form to measure whether there is cascading tripping on the corresponding branch according to its action equation. An initial fault in a power network is located at the branch L_{ij}(The branch between the node i and the node j, other branches in this paper are the same as this).When the power flow of the power grid is redistributed, the case of any branch L_{st} in the residual system of the power grid can be considered in combination with the action equation of the backup protector. The voltage and current of the branch L_{st} after the power flow re distribution is shown in Figure 1.

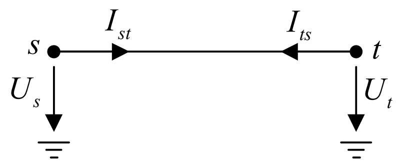


Fig. 1 voltage and current of branch L_{st}

For the backup protector of the s side of the L_{st}, Formula(1) can be used to determine whether the occurrence of cascading tripping[5].

$$\omega_{s\cdot dist} = |\omega_{s\cdot lim}| - |\omega_s| \quad (1)$$

In formula (1), $\omega_{s\cdot lim}$ is a parameter made up of a protective fixed value in the action equation of the backup protector of the s side of the branch L_{st}. ω_s is a parameter made up of protected and measured values in the s side backup protector action equation of the branch L_{st}. The $\omega_{s\cdot dist}$ is a parameter to measure the electrical distance between $\omega_{s\cdot lim}$ and ω_s. When $\omega_{s\cdot dist} \le 0$, the backup protector of the s side of the branch L_{st} will move. When $\omega_{s\cdot dist} > 0$, s side branch L_{st}t backup protector will not tripping. Formula (1) is given by the protector of s side in branch L_{st}.. For the protector of t side in branch L_{st}, the form of the judgment is consistent with the formula (1). The corresponding subscript letters are changed from s to t, such as the ω_s to the ω_t. The corresponding formula is expressed by the formula (2).

$$\omega_{t\cdot dist} = |\omega_{t\cdot lim}| - |\omega_t| \quad (2)$$

When backup protector is overloaded protector, $\omega_{s\cdot lim}$ is a current fixed value $I_{s\cdot \mathrm{set}}$ for overload protector on the s side of the branch L_{st}; ω_s is a current I_{st} that flows through the branch L_{st}.

Accordingly, for the backup protector of t side of L_{st}, $\omega_{t\cdot lim}$ can be regarded as the current value $I_{t\cdot \mathrm{set}}$ of overload protector of branch t on L_{st} side, while ω_t can be regarded as current I_{ts}.
For the case where backup protector is the third-zone unit of a distance protector, if backup protector is the distance protector for the offset circle characteristic, referring to reference 6, the specific form of parameter s s Lim in the s side protector of branch L_{st} is recommended as follows:

$$\omega_{s\cdot lim} = \left(Z_{s\cdot set1} - Z_{s\cdot set2}\right)/2 . \tag{3}$$

In formula (3), $Z_{s\cdot set1}$ and $Z_{s\cdot set2}$ are defined as fixed value of the s side of the third-zone unit of a distance protector in the branch L_{st}. At this point, the specific forms of the ω_s can be taken respectively as

$$\omega_s = Z_{s\cdot m} - \left(Z_{s\cdot set1} + Z_{s\cdot set2}\right)/2 . \tag{4}$$

In formula (4), $Z_{s\cdot m}$ is the impedance measurement of the s side of the third-zone unit of a distance protector in the branch L_{st}. Combined with figure 1, the volume can be given by formula (5).

$$Z_{s.m} = U'_{s.m} / I'_{st.m} . \tag{5}$$

$U'_{s.m}$ and $I'_{st.m}$ are the measurement voltage and current measurement of the s side of the third-zone unit of a distance protector in the branch L_{st}, respectively.
The third-zone unit of a distance protector for t side of branch L_{st} can be similar to (3), (4), (5) corresponding processing.
If the protector is a distance protector with a directional circular characteristic, the specific form of the parameter $\omega_{s\cdot lim}$ is recommended as[5]:

$$\omega_{s\cdot lim} = Z_{s\cdot set}/2 . \tag{6}$$

In formula (6), $Z_{s\cdot set}$ is defined as fixed value of the s side of the third-zone unit of a distance protector in the branch $L_{st.}$ And in this case, Z_s is taken as [5]:

$$\omega_s = Z_{s\cdot m} - Z_{s\cdot set}/2 . \tag{7}$$

In formula (7), the meaning and acquisition of $Z_{s\cdot m}$ is in agreement with the formula (4) and (5).
Similarly, the third-zone unit of a distance protector of the t side in the branch L_{st} can be similar to the formula (6) and (7).
If the protector is a distance protector with full impedance characteristics in the circular direction, the specific form of the parameter $\omega_{s\cdot lim}$ is recommended as:[5]:

$$\omega_{s\cdot lim} = Z_{s\cdot set} . \tag{8}$$

And in this case, Z_s is taken as

$$\omega_s = Z_{s\cdot m} . \tag{9}$$

Similarly, the third-zone unit of a distance protector of the t side in the branch L_{st} can be similar to the formula (8) and (9).
In addition, if the third-zone unit of a distance backup protector with other forms of action characteristics, we can give the values of ω_s and $\omega_{s\cdot lim}$ according to the above methods.

Analysis of the Main Determinants of Cascading Tripping

From the above analysis, after the branch outage because of the initial failure, whether there is cascading tripping happening in branch L_{st} is mainly determined by $\omega_{s\cdot dist}$. According to the knowledge of relay protector, the measured current and measurement voltage of backup protector of branch L_{st} are mainly determined by the voltage of node s and node t and the current passing through

branch L_{st} after the redistribution of power. When the parameters of the branch L_{st} are fixed, the current flowing through the branch L_{st} is mainly determined by the voltage of the node s and the node t. According to the above analysis, whether or not the cascading tripping of any branch L_{st} of the power grid is mainly determined by the voltage of the node s and the node t after the redistribution of the power flow.
Based on the knowledge of power flow calculation, it is known that after the branch outage because of the initial failure occurs, the equation of the power network is:

$$Y'\dot{U}' = \left(\widetilde{S}/\dot{U}'\right)^{*}. \tag{10}$$

In formula (10), Y' is the power grid node admittance matrix after the outage of the branch L_{ij}. $\dot{U}'$ represents the node voltage vector after outage of the branch L_{ij}. In the case of a specific grid and a specific initial fault branch L_{ij}, Y' is a matrix with a fixed value element. Through the above analysis, we can know that the $\dot{U}'$ in the type (10) is mainly determined by the node injection power $\widetilde{S}$. If we ignore the change of the node injection power before and after the branch L_{ij} outage, the $\widetilde{S}$ remains invariant. Thus, $\dot{U}'$ is mainly determined by the power grid node injection powers $\widetilde{S}$ before the branch L_{ij} outage.
In summary, after the branch outage because of the initial failure, whether there is any branch L_{st} tripped is mainly determined by the power grid node injection powers. In other words, when the power grid structure, element parameters and protector fixed value is fixed, the node injection power is the main factor for the occurrence of cascading tripping of any branch L_{st} after the initial failure occurs.

Thought and Algorithm of Evaluation for Cascading Tripping in Power Grid

We can get two revelation from the above analysis:firstly, there is a tight mapping between the power of node injection and the occurrence of cascading tripping; Secondly, If you want to check whether a grid cascading tripping occurs due to the initial failure, the conventional approach is checked by flow calculation. Because the grid has different node injection power state, so this verification method has a lot of calculation. Given these two points, it is simple and convenient to use pattern recognition technology to determine whether or not cascading tripping occurs in power network. The relationship between the cascading tripping and the node injection power is reconstructed in order to form a classifier. And then, the node injected power in a certain state input to the classifier to determine whether the power grid cascading tripping. Below, this paper gives the basic idea of using pattern recognition technology to carry out the evaluation of cascading tripping.
The input and output variables of the evaluation. According to the previous analysis, the node injection power plays a decisive role in the occurrence of cascading tripping. In the process of the evaluation by using pattern recognition technology, the node injection power can be used as the input quantity and the results of whether or not cascading tripping occurs can be used as the output quantity. Using S'to represent input. There are n nodes in the power grid, which can be written in the form of vector:

$$\boldsymbol{P} = \left[P_1, Q_1, \cdots, P_j, Q_j, \cdots, P_n, Q_n\right]^T. \tag{11}$$

In formula (11), the element P_j and Q_j of the vector P indicates that the injected active power and injected reactive power of each node j respectively. By the formula (11) we can know that the vector P has $2n$ dimension.

Using y to represent output. In order to determine whether the cascading tripping occurs and facilitate the quantitative analysis, which involves all the branches of the remaining system, the formula (1) is extended to the formula (12).

$$D = \min\left(\omega_{st \cdot dist}\right). \tag{12}$$

After a certain branch circuit in the power grid is shut down due to an initial fault, if the system meet to the $D>0$, then the power grid will not happen cascading tripping. At this time desirable $y=0$; If D is less than or equal to 0, at least a branch occurring cascading tripping or at the boundary of the cascading tripping. At this time desirable $y=1$.

The idea of evaluation. Based on the standard form of expression of the input and output data, the input amount of P and output y are combined to form a sample data as shown in formula (13).

$$\boldsymbol{S}_i = \left[P_1, Q_1, \cdots, P_j, Q_j, \cdots, P_n, Q_n, y\right]^T. \tag{13}$$

In formula (13), S_i represents a sample i. Obviously, S_i is a column vector with $2n+1$ dimension. If there are N samples, then $i=1, 2, \ldots N$.

According to the general idea of pattern recognition, it is concluded that the idea of cascading tripping evaluation is: Firstly, a classifier is formed by training a part of sample data. And then a part of the sample data is used to test the trained classifier. If the test accuracy meets the requirements, the classifier can be used to assess the cascading tripping. In other words, based on each node injection power state, the P input to the power state of the node is input to the classifier, and then the power grid is evaluated according to the output result. Put P in the classifier which represents node injection power state. The results of the output are used to evaluate whether the cascading tripping occurs. If the classifier does not meet the requirements of the test, then re training until it meets the requirements. Among them, when the sample data is formed, it is needed to pay attention to the configuration of the actual backup protector in the power system. Whether the grid configuration of the current type of backup protector, or distance type backup protector, or both, when the y value in formula (12) is formed, it should be strictly corresponding to the actual configuration of the power grid.

The above gives a basic idea of cascading tripping evaluation based on pattern recognition technology. As for what kind of specific pattern recognition techniques are used in practice, which can be based on the actual needs and specific circumstances to be chosen, this article does not discuss in detail. In this paper, an evaluation method based on BP neural network is presented in study section.

Example

In this paper, the IEEE39 node system is used as the example to carry out example analysis.The wiring diagram of the used IEEE39 node system is as shown in Fig. 2.

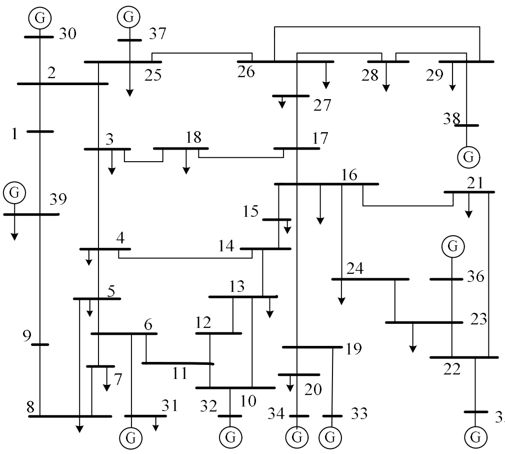


Fig. 2 Wiring diagram of the example system

In the example, the analysis program is compiled in the MATLAB. The program mainly includes sample data formation and classifier training and testing parts. In the example, the paper presents a numerical example for the three cases of the power system configuration, which is based on the current type backup protector, distance protector and current protector and distance protector. In third cases the paper called the mixed type.
In the form of the sample data, the main steps of this paper are as follows:
(1) setting the initial failure.
(2) to obtain the node injection power state.
The node injection power state is obtained by adding a ΔP and ΔQ each time randomly based on typical data of IEEE39 system. The typical active injection power of any PV node in a IEEE39 system is P_i^0, the typical active power of any PQ node is P_j^0, and the reactive power injection is Q_j^0. The specific operation is: firstly, as shown in formula (14) to obtain a ΔP and a ΔQ.

$$\Delta P = \Delta Q = 50 \times rand(1,1). \tag{14}$$

In formula (14), the *rand* is a function of obtaining a random number in the (0,1) interval on MATLAB. And then operate on any of the PV nodes in accordance with formula (15).

$$P_i = P_i^0 + \Delta P. \tag{15}$$

Operate on any of the PQ nodes in accordance with formula (16).

$$\begin{cases} P_j = P_j^0 + \Delta P \\ Q_j = Q_j^0 + \Delta Q \end{cases}. \tag{16}$$

If the original data of the node is P=Q=0, this paper will no longer press formula (16) to operate, still keep it as P=Q=0. After this operation, a new node injection power state and its corresponding node injection power vector P are obtained.
(3)acquisition values of Y and the formation of samples.
Based on the set initial fault, it can determine whether the occurrence of cascading tripping through the power flow calculation of the disconnection the power grid and formula (12). According to the occurrence of cascading tripping, the y will be taken as 1, otherwise, take y as 0. And then according to the formula (13) combine P and y to form a sample.
Repeat the above operation until a sufficient number of samples are obtained.
Next, train and test the samples.This paper uses the MATLAB toolbox function. The initialization function is *newff*, and its call form is:

$$net = newff\left(input, output, 8\right). \tag{17}$$

In the formula (17), input and output respectively for the input and output, respectively, here are P and y.
The train in the MATLAB toolbox is used as the training function, which calls for the form of:

$$net = train\left(net, input, output\right). \tag{18}$$

Accordingly, for some of the parameters in train, in this example, *trainParas.epochs* is taken as 500, *trainParas.lr* is 0.1, *trainParas.goal* is 0.002. Other parameters use their default values.
The train in the MATLAB toolbox is used as the test function, which calls for the form of:

PreOutput=sim(net,input_test). (19)

In formula (19), *input_test* is used to test the input data, *PreOutput* is the predictive output.The calculation example selected *mapsinsax* for the normalization of input P.
Figure 3 is an example of a power grid configuration with current protector. The initial fault branch is the branch $L_{4\text{-}5}$. The total sample data is 200, 120 of which are used for training, and 80 samples are

used for testing. The correct rate for the test is 98.75%. The test results are to meet the requirements, if 90% of the criteria are used as the standard.

Figure 4 is an example of a power grid configuration with distance protector. The initial fault branch is the branch $L_{21\text{-}22}$. The total sample data is 200, 120 of which are used for training, and 80 samples are used for testing. The correct rate for the test is 99.17%. Obviously, the training results are satisfactory.

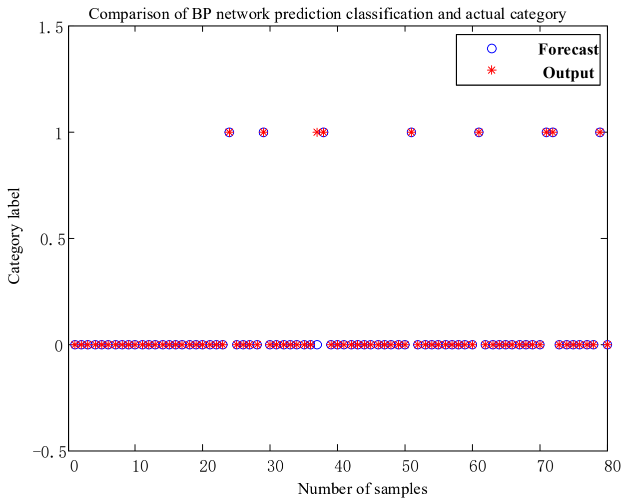
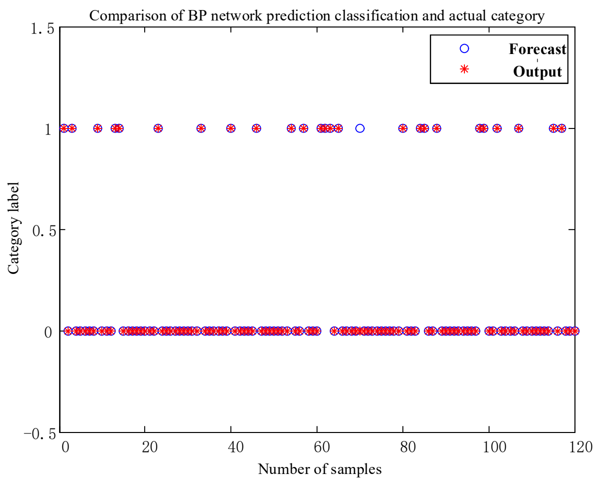


Fig. 3 a power grid configuration with current protector when the classifier is tested

Fig. 4 a power grid configuration with distance protector when the classifier is tested



In the example shown in Figure 4， the third-zone unit of a distance relay is the distance protector with the direction of the circle characteristic. In the course of using the formula (12) to judge the cascading tripping, the method is based on the scanning of the branch circuit. In fact, the direction of distance protector has been taken into account.

Figure 5 is an example of a power grid configuration with the mixed type distance protector. The initial fault branch is the branch $L_{21\text{-}22}$. The total sample data is 300, 210 of which are used for training, and 90 samples are used for testing. The correct rate for the test is 97.78%. Obviously, the training results are satisfactory.

In the example of Figure 5, when the sample data is formed, the action of distance protector and current type protector should be considered. In these two kinds of protector, there is any kind of protector action which is regarded as the occurrence of cascading tripping events. For distance protector, the characteristics of the whole impedance circle are still considered.

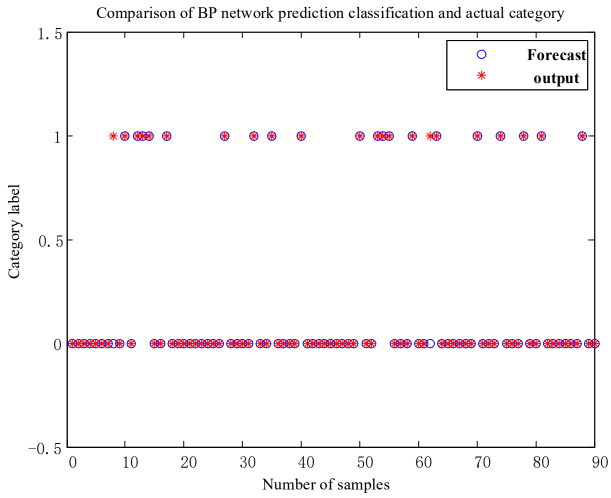


Fig. 5 a power grid configuration with the mixed type distance protector when the classifier is tested

The results of the classifier given by Figure 3, 4 and 5 are quite satisfactory. Of course, the classifier can also be further improved, such as adjusting the training parameters of the classifier, the use of other pattern recognition technology, etc. Limited space, this article is no longer in-depth discussion.

Conclusions

The cascading tripping of power grid is related to the backup protector action of the circuit, the structure of the power network and the operation status of the power grid. The main conclusions of this paper are as follows:

(1) when grid structure, component parameters and line backup protector fixed valueare are fixed, regardless of the backup protector is current type or distance type, or is the current distance backup protector, whether the power grid is trippingped due to the given initial failure, the main factor is the node injection power.

(2) whether the grid line configuration is current type or distance protector, is not only the current type but also has distance backup protector, it can assess cascading trippingping by pattern recognition technology.

(3)After getting the satisfactory classifier, we use the pattern recognition method to evaluate the cascading tripping of the grid, which makes the evaluation of the cascading tripping become concise. Input the corresponding node power vector can be evaluated without the need to calculate the power flow after the initial fault is removed for any one node injection power state.

The conclusions obtained in the paper and the evaluation method of cascading tripping based on pattern recognition technology can provide some references for further research and practical operation of power grid.

Acknowledgements

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