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A Hybrid On-line Verification Method of Relay Setting

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Abstract. Along with the rapid development of the power industry, grid structure gets more sophisticated. The validity and rationality of protective relaying are vital to the security of power systems. To increase the security of power systems, it is essential to verify the setting values of relays online. Traditional verification methods mainly include the comparison of protection range and the comparison of calculated setting value. To realize on-line verification, the verifying speed is the key. The verifying result of comparing protection range is accurate, but the computation burden is heavy, and the verifying speed is slow. Comparing calculated setting value is much faster, but the verifying result is conservative and inaccurate. Taking the overcurrent protection as example, this paper analyses the advantages and disadvantages of the two traditional methods above, and proposes a hybrid method of on-line verification which synthesizes the advantages of the two traditional methods. This hybrid method can meet the requirements of accurate on-line verification.

1. Introduction

The relay protection is the guarantee of the safe operation of the power system. Currently, the setting value of relay protection is obtained in the offline state according to the expected maximum and minimum operation mode, and remains the same when the system operates. That will lead to a problem that the setting value obtained in the offline state is not the best under the current mode, and will degrade the performance of protections [1-3]. Under some special operation mode, the protection may not be able to meet the requirements of sensitivity and selectivity, which may cause protections to mal-operate or fail.

There have been many examples showing that power outages which involve a wide range are usually caused by relay protection incorrect actions [4-6]. Thus, it is very important to verify the setting values of protections. Selectivity verification is the key point of verification. The focus of on-line verification is real time, so improving the verifying speed is a top priority. The existing method of comparing the protection range takes too much time to calculate the protection range, it's hard to meet the real-time requirement. The method of comparing calculated setting value takes only a little time to finish the verification task, but the verifying result is conservative to some extent [7-8]. On the basis of analysing the advantages and disadvantages of the present methods, this paper proposes a new hybrid on-line verification method. It can effectively improve the speed and accuracy of on-line verification. Overcurrent protection is taken as example to explain the principle of the hybrid verification method.

2. Analysis on the present verification methods

2.1. The method based on comparing protection range

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Use the system shown in Fig. 1 to demonstrate the basic principle of selectivity verification by comparing protection range. The protection to be verified is zone 2 of R1.

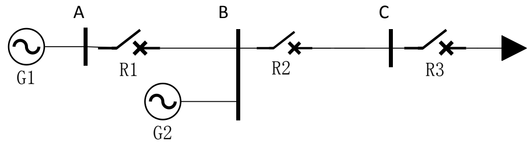

Figure 1. Structure of a simple example system

Firstly, find out two zones of the next protection, which the action time of R1 zone 2 is among them. Assuming that the two zones are zone 1 and zone 2 of R2, $t_2^{I} < t_1^{II} < t_2^{II}$.

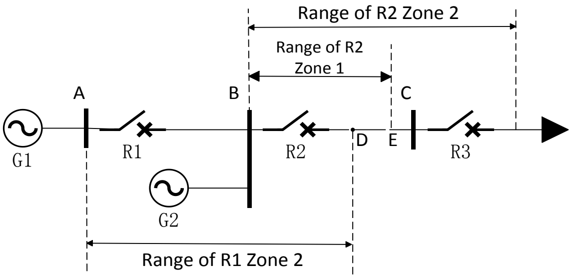

Figure 2. Selectivity meets requirement

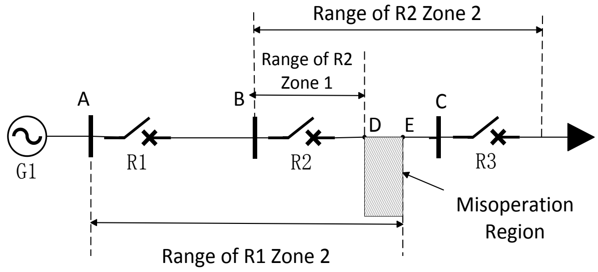

Figure 3. R1 loses selectivity with R2

Precisely calculate every protection range. In Fig.2, the range of R1 zone 2 isn't beyond R2 zone 1, R1 meets selectivity requirement with R2. In Fig.3, the range of R1 zone 2 is beyond R2 zone 1, but not more than R2 zone 2, R1 will lose selectivity with R2.

We can see that: this method is "quantitative verification", the biggest advantage is the verification result is quantitative and accurate. But there are also drawbacks as follows:

(1) The verifying speed is slow due to the large amount of calculation. If using this method to verify all the protections, it can hardly satisfy the real-time requirement.

(2) If the structure of the grid is complicated, especially when the grid contains lots of irregular lines, such as teed lines, the verifying speed will be greatly slowed down.

2.2. The method of comparing calculated setting value

This method is "qualitative verification". Setting calculation formulas are used to get the protection setting value under the current operation mode, which is called "calculated setting value". The calculated setting value meets selectivity requirement because it is obtained under the current operation mode. By comparing the calculated setting value with the actual setting value of protection, we can realize qualitative verification of protections. Analysis is still based on the system in Fig.1.

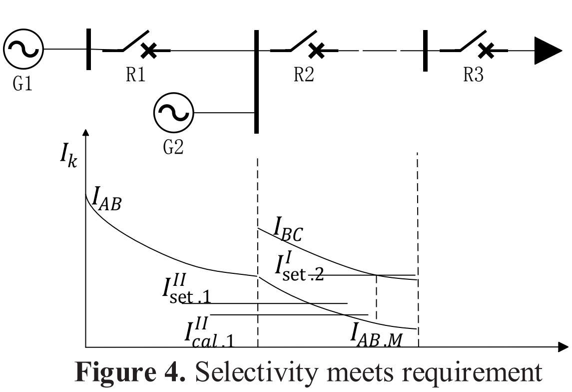

Figure 4. Selectivity meets requirement

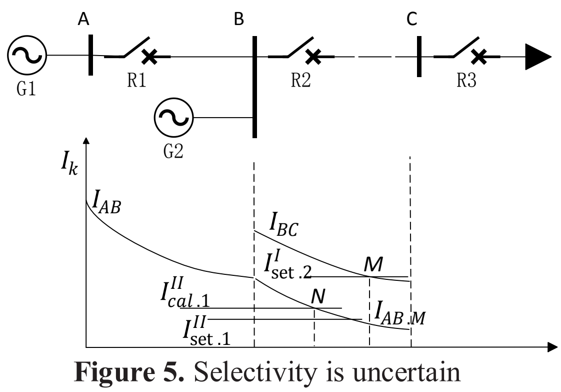

Figure 5. Selectivity is uncertain

According to the setting calculation formula, the calculated setting value of R1 zone 2 is:

$$I_{cal.1}^{II} = \frac{K_{rel}^{II}}{K_{b.min}} I_{set.2}^{I} \tag{1}$$

$K_{b.min}$ is the branch coefficient under the current mode. From Fig.4, the condition that the actual setting value meets selectivity requirement is:

$$I_{set.1}^{II} > I_{cal.1}^{II} \tag{2}$$

In Fig.4, $I_{set.1}^{II} > I_{cal.1}^{II}$, the actual protection range of R1 zone 2 isn't beyond the range of calculated setting value, we can judge that R1 meets selectivity requirement.

But if $I_{set.1}^{II} < I_{cal.1}^{II}$, it is uncertain whether the protection meets selectivity requirement or not. In Fig.5, although $I_{set.1}^{II} < I_{cal.1}^{II}$, the actual range of protection R1 zone 2 is beyond the range of its calculated setting value (point N), but it isn't beyond the range of R2 zone 1 (point M). So we can't simply think that protections lose selectivity when $I_{set.1}^{II} < I_{cal.1}^{II}$.

So this method is qualitative and conservative. In some extreme operation modes，the range of calculated setting value may be too narrow, namely, point N is too close to bus B, it will make protections verified by this method very hard to meet selectivity requirement ($I_{set.1}^{II}$ is hard to be greater than $I_{cal.1}^{II}$), which will make the verification result more conservative and inaccurate.

3. Hybrid verification method

As the comparison of calculated setting value is qualitative verification, fast but not accurate, we can conduct a preliminary screening for all the protections by comparing calculated setting value, distinguish which protections are certain to meet selectivity requirement, and which are uncertain. Define those protections whose selectivity is uncertain as "suspicious protections". After the preliminary screening, we can compare protection range to accurately verify the selectivity of "suspicious protections". Synthesizing the above features, a hybrid verification method is proposed, detailed steps are as follows:

① Conduct a preliminary screening for all the protections needed to be verified with the comparison of calculated setting value. Put the protections meeting selectivity requirement into set A. Put the other protections defined as "suspicious protections" into set B.

②According to the definition of protection range: the electric parameters detected by the protection are equal to the protection setting value when a fault occurs at the terminal of protection range. Calculate each protection range of the protections in set B.

③Conduct accurate verification on the suspicious protections in set B by comparing protection range. Put those suspicious protections which meet selectivity requirement into set C. Then protections in set A∪C are the whole protections meeting selectivity requirement.

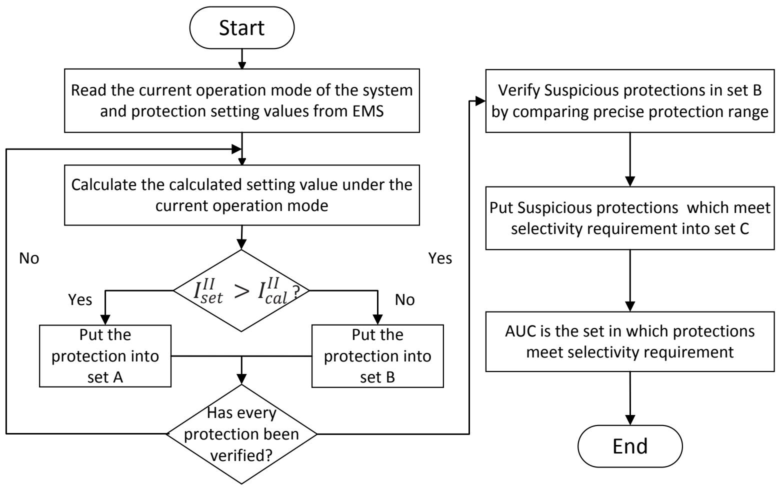

Figure 6. The flow chart of the hybrid verification method

The flow chart is shown in Fig.6. Practice shows that in most cases when the system is disturbed and the operation mode changes, most protections still meet the performance requirements for relay protection. The hybrid verification method can screen most protections which still meet selectivity requirement after the operation mode changes with preliminary screening. A small number of suspicious protections left are verified by comparison of protection range. It can be seen that with the hybrid verification method, only the protection ranges of suspicious protections need to be calculated, rather than all the protections. The amount of calculation is greatly reduced and the accuracy of verification result is improved.

4. Fast calculating method for range of current protection

In order to further improve the performance of on-line verification, it's necessary to further improve the speed. The main calculation amount is from calculating the ranges of suspicious protections. The calculation amount of preliminary screening is small. So we can seek a faster calculating method to get the protection range. Traditional algorithms usually use loop iteration algorithms such as golden-section method and split-half method, or use the graphical method, which all need a great deal of tedious and repetitive calculation [9].

As the system node impedance matrix remains the same during the process of verification [10-11], and calculating positive sequence values doesn't need to consider the mutual inductance, this paper proposes a method based on positive sequence impedance matrix to quickly calculate the range of overcurrent protection. It can simplify tedious calculation as the solution of a unary quadratic equation, further improve the verifying speed.

4.1. Range of protection zone 1

Assume that the terminal of the protection in bus b is point f. Use the system in Fig.7 to calculate protection range. Suppose that bf/bc=k,（$0\leq k \leq 1$）,the impedance of line bc is z_{bc}.
Set a phase-to-phase fault at point f.

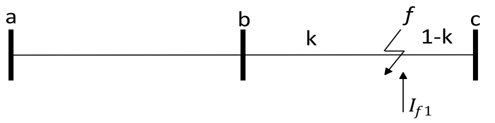

Figure 7. Short circuit fault at point f

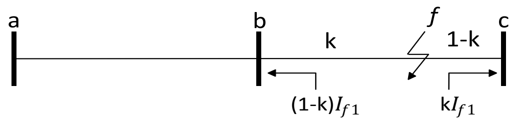

Figure 8. Equivalent model

According to the reciprocity theorem, voltage at any point m can be expressed as:

$$U_m^{(f)} = U_f^{(m)} = (1-k)U_b^{(m)} + kU_c^{(m)} = (1-k)U_m^{(b)} + kU_m^{(c)} \tag{3}$$

Equation (3) indicates that the injected current I_{f1} is equivalent to injecting $(1-k)I_{f1}$ and kI_{f1} into the two endpoints of the line respectively. The equivalent model is shown in Fig.8.

Inject unit current into point f:

$$\frac{\dot{U}_f - \dot{U}_b}{kz_{bc}} + \frac{\dot{U}_f - \dot{U}_c}{(1-k)z_{bc}} = \frac{Z_{ff} - Z_{bf}}{kz_{bc}} + \frac{Z_{ff} - Z_{cf}}{(1-k)z_{bc}} = 1 \tag{4}$$

$$Z_{fm} = (1-k)Z_{bm} + kZ_{cm} \tag{5}$$

Z_{ff} can be deduced from (4) and (5):

$$Z_{ff} = (1-k)^2 Z_{bb} + k^2 Z_{cc} + k(1-k)(2Z_{bc} + z_{bc}) \tag{6}$$

In Fig.8, the equivalent positive sequence current on line bc is:

$$I_{bf1} = -(1-k)I_{f1} + \frac{\dot{U}_{b1} - \dot{U}_{c1}}{z_{bc1}} = [-(1-k) + \frac{Z_{bf1} - Z_{cf1}}{z_{bc1}}]\, I_{f1} \tag{7}$$

$$Z_{bf1} = (1-k)Z_{bb1} + kZ_{bc1}\,,\ Z_{cf1} = (1-k)Z_{bc1} + kZ_{cc1} \tag{8}$$

$$I_{f1} = \frac{-1}{Z_{ff1} + Z_{ff2}} = \frac{-1}{2Z_{ff1}} \tag{9}$$

The phase current through the protection is $\sqrt{3}$ times of the positive sequence current. The setting per unit value of the protection in bus b is $I_{dz.b}^{I}$. Substitute $I_{bf1}=\frac{I_{dz.b}^{I}}{\sqrt{3}}$ into (7):

$$\frac{I_{dz.b}^{I}}{\sqrt{3}}=[-(1-k)+\frac{Z_{bf1}-Z_{cf1}}{z_{bc1}}]I_{f1} \tag{10}$$

Substitute (8) and (9) into (10), a unary quadratic equation can be obtained:

$$\begin{aligned}&k^{2}\left(2Z_{bb1}+2Z_{cc1}\text{-}4Z_{bc1}\text{-}2z_{bc1}\right)\times\frac{I_{dz.b}^{I}z_{bc1}}{\sqrt{3}}+k[(-4Z_{bb1}+Z_{bc1}+2z_{bc1})\frac{I_{dz.b}^{I}z_{bc1}}{\sqrt{3}}\\&+(2Z_{bc1}\text{-}Z_{bb1}\text{-}Z_{cc1}+z_{bc1})]+2Z_{bb1}\times\frac{I_{dz.b}^{I}z_{bc1}}{\sqrt{3}}+Z_{bb1}\text{-}Z_{bc1}\text{-}z_{bc1}=0\end{aligned} \tag{11}$$

Equation (11) is a unary quadratic equation of the unknown k:

$$Ak^{2}+Bk+C=0 \tag{12}$$

Figure out the unary quadratic equation, the protection range k is obtained.

4.2. Range of protection zone 2

$$I_{ab1}=\frac{\dot{U}_{a1}-\dot{U}_{b1}}{z_{ab1}}=\frac{(Z_{af1}-Z_{bf1})I_{f1}}{z_{ab1}} \tag{13}$$

Substitute $I_{ab1}=\frac{I_{dz.a}^{II}}{\sqrt{3}}$ into (13):

$$\frac{I_{dz.a}^{II}}{\sqrt{3}}=\frac{(Z_{af1}-Z_{bf1})I_{f1}}{z_{ab1}} \tag{14}$$

$$Z_{af1}=(1-k)Z_{ab1}+kZ_{ac1}\ ,\ Z_{bf1}=(1-k)Z_{bb1}+kZ_{bc1} \tag{15}$$

Substitute equation (9) and (15) into (14), a unary quadratic equation can be obtained:

$$\begin{aligned}&k^{2}\left(2Z_{bb1}+2Z_{cc1}\text{-}4Z_{bc1}\text{-}2z_{bc1}\right)\times\frac{I_{dz.a}^{II}z_{ab1}}{\sqrt{3}}+k[(-4Z_{bb1}+4Z_{bc1}+2z_{bc1})\times\frac{I_{dz.b}^{I}z_{bc1}}{\sqrt{3}}\\&+(Z_{ac1}\text{-}Z_{ab1}\text{-}Z_{bc1}+Z_{bb1})]+2Z_{bb1}\times\frac{I_{dz.a}^{II}z_{ab1}}{\sqrt{3}}\text{-}Z_{bb1}+Z_{ab1}=0\end{aligned} \tag{16}$$

Solve the unary quadratic equation (16), k is the range of protection zone 2 in bus a.

5. Case study

A district power grid is taken to validate the hybrid verification method. Choose four protections from the grid as example and conduct selectivity verification on them. The setting values are shown in Table 1. All the protections zone 2 needed to be verified are cooperative with protections zone 1 of the next lines. Table 1 shows the preliminary screening result:

Table 1. Preliminary screening result: "√" means the protection meets selectivity requirement, "×" means the protection is a suspicious protection.

Protection	Setting value of zone 2/A	$K_{b.min}$	zone 1 of next protection/A	Calculated setting value/A	Result
R1	1339	1.32	1638	1240.9	√
R2	761	2.39	2040	853.6	×
R3	952	1.83	1563	854.1	√
R4	768	1.91	1367	715.6	√

From table 1, R2 is a suspicious protection. On the basis of the preliminary screening, conduct accurate verification on suspicious protection R2 by comparing protection range:

Table 2. Result of accurate verification after preliminary screening by comparing protection range: "√" means the suspicious protection meets selectivity requirement

Protection	Range of zone 2	Range of zone 1 of next protection	Verification Result
R2	66% on the next line	75%	√

From table 2, by comparing protection range, the range of zone 2 of R2 is 66% on the next line, the range of zone 1 of the next protection which cooperates with R2 is 75%. We can see that the range of zone 2 of R2 isn't beyond the range of zone 1 of the next protection. So we can judge that the suspicious protection R2 also meets selectivity requirement.

6. Conclusion

This paper proposes a hybrid on-line verification method for protective relaying, which synthesizes the advantages of traditional methods. A fast algorithm based on positive sequence impedance matrix to calculate protection range is used to further improve the performance of the hybrid verification method. Comparing with the existing traditional verification methods, the hybrid verification method has the following advantages:

①The hybrid method only needs to calculate the range of a few protections instead of all the protections ②The verifying speed is greatly improved and the result is more accurate ③It can be applied to online/offline verification calculation.

On the basis on this paper, the following aspect can be further researched: further improve the verification principle of protections, reasonably assign workload to the two steps of the hybrid method, to get the best performance.

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