

Improving protection of medium voltage networks

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Abstract. This paper presents an efficiency analysis of medium-voltage distribution network protection and considers directions for improving protection characteristics based on synchronized phasor measurement technology (SPM). The authors propose protection algorithms based on two- and multi-sided measurements of voltage and current synchrophasors and cite the advantages of combining local protection with centralized protection and wide area protection.

1 Introduction

The reliability of medium voltage (MV) networks largely depends on the types of protection used. It is observed that 6-10 kV electrical networks, primarily urban and rural, often have protection relays based on overcurrent principles [1]. At the same time, due to the significant length and branching of MV networks, such protections generally do not provide the required sensitivity. In this regard, there is a need to develop new algorithms for protecting MV electrical networks.

One of the ways to improve the main characteristics (sensitivity, selectivity, tripping speed) of the MV network protection is the implementation of synchronized phasor measurement technology [2-3]. Synchrophasor technology provides advantages for improving simple types of protection on the overcurrent principle due to the implementation of two- and multi-sided measurements. In addition, SPM ensures the improvement of more complex protections, for example, distance and differential protections [4-5].

This paper considers 6-35 kV networks that operate with an isolated neutral or with a neutral grounded through an arc-suppression reactor. Such networks also require the implementation of selective protection against single-phase ground faults (SGF). Overcurrent SGF protection is widely used at present, but it has some disadvantages that are associated with its incorrect operation at low zero sequence (ZS) currents and in networks with arc-suppression reactors, where the SGF current decreases [6]. The authors propose several new SGF protection algorithms based on measuring the ZS current and voltage synchrophasors. These algorithms are intended for different types of protection: local feeder protection, centralized switchgear protection, wide area protection [7-8]. In some cases, a combination of these protections allows obtaining the most significant effect.

2 Analysis of MV network protection

Implementation of MV network protection requires consideration of some features, primarily due to the low level of urban and rural 6-10 kV network automation. Cable and overhead networks are traditionally radial and have a one-way power supply. Short-circuit protection is most often overcurrent protection [1]. To increase the reliability of the network, automatic transfer switching (ATS), and automatic reclosing (AR, for overhead lines) are used. Thus, non-selective action of protection is allowed in the presence of ATS and AR [1]. SGF protection, as a rule, is performed based on measurements of ZS current and voltage of fundamental frequency.

Networks with a rated voltage of 20-35 kV have other features. They have the same types of neutral grounding as 6-10 kV networks, but much less often have a radial design. These networks are mainly ring-shaped. Therefore, overcurrent directional protections do not always provide the required sensitivity here [1]. In some cases, this problem is solved by using distance protection.

The characteristics of overcurrent protection largely depend on the power system operating modes, which change significantly over time. Below are summarized data on short-circuit currents in urban and industrial distribution networks of several regions of Russia (Table 1).

The network objects whose data are presented in the statistics (Table 1) are 6(10)/0.4 kV transformer substations (TS), 6-35 kV distribution points (DP) and 35-110 kV step-down substations. In Table 1, the parameter k is the ratio of the three-phase short-circuit current in the maximum power system mode to the two-phase short-circuit current in the minimum mode.

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Table 1. Maximum and minimum short-circuit currents.

Type	Parameter	Rated network voltage, kV							
		urban network				industrial network			
1	$I_{k,max}^{(3)}$, kA	16.9	13.1	32.1	16.5	2.73	9.61	16.5	
2	$I_{k,max}^{(3)}$, kA	1.97	0.98	1.2	1	1.06	4.95	-	
1	$I_{k,min}^{(2)}$, kA	13.9	8.06	5.19	9.35	0.98	3.7	4.63	
2	$I_{k,min}^{(2)}$, kA	1.7	0.82	0.24	6.06	0.63	2.13	-	
	k_{max}	1	1.63	.	.	2.79	.	3.56	
	k_{min}	1.16	1	.	1	1.68	.	-	

*1 – location near power source, 2 – furthest network location

The maximum power system operating mode means that all possible power sources are simultaneously connected to the network and, accordingly, the short-circuit power is the highest. The minimum power system operating mode corresponds to those repair or emergency network circuits when the short-circuit current is minimal for the specified locations (Table 1).

Data analysis shows that short-circuit currents vary significantly depending on the location of the short-circuit (near the power source or in the furthest network location), network topology (urban or industrial), and rated voltage. In some cases, the coefficient k differs by several times, so the operating conditions for overcurrent protections change significantly. In addition, the coefficient k gradually increases with increasing rated voltage.

Based on the expressions for calculating the tripping current of overcurrent protection and assessing its sensitivity [1], it can be proven that, in general, for the correct operation of overcurrent protection, the following condition must be met:

$$\frac{|\underline{z}_{c,max} + \underline{z}_L|}{|\underline{z}_{c,min} + 0.2\underline{z}_L|} \geq k_1, \quad k_1 = \frac{2}{\sqrt{3}}k_r, \quad (1)$$

where $\underline{z}_{c,min}$, $\underline{z}_{c,max}$ - impedance of the equivalent power system in minimum and maximum mode, \underline{z}_L - line impedance, k_r - protection reserve coefficient.

If we designate as λ the relative protection zone (from 0 to 1), then based on expression (1) we can obtain an equation describing the dependence of λ on the coefficient k , the maximum short-circuits current $I_{k,max}^{(3)}$ and the line length L :

$$\lambda^2 + \lambda \frac{2kX_{cmax}X_\mu}{LZ_\mu^2} + \frac{(k_1^2k^2 - 1)X_{cmax}^2 - 2LX_\mu X_{cmax} - L^2Z_\mu^2}{k_1^2L^2Z_\mu^2} = 0, \quad (2)$$

where X_μ , Z_μ - line parameters per km.

Positive real roots of equation (2) characterize the protection zone depending on various conditions. Figures 1-2 show the corresponding values of λ for 10 kV cable and overhead lines for various combinations of k , $I_{k,max}^{(3)}$, L and the line cross-section (mm^2).

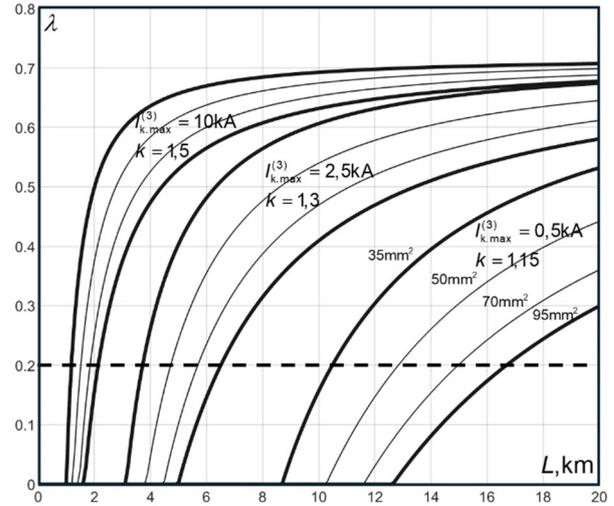


Fig. 1. Relative protection zone for 10 kV overhead lines

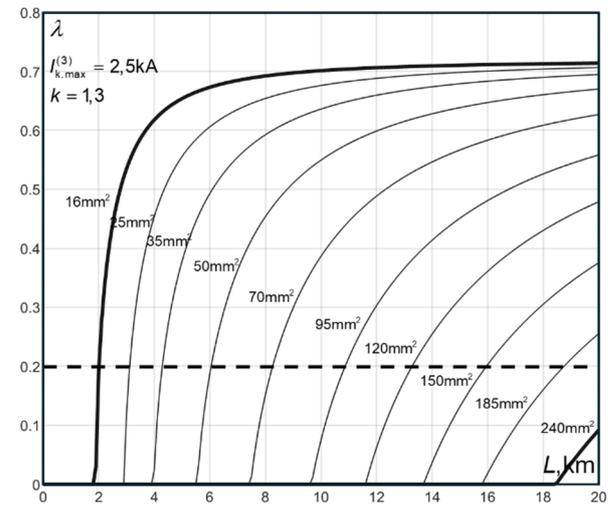


Fig. 2. Relative protection zone for 10 kV cable lines

Data analysis (Fig. 1-2) shows that for 10 kV networks there is a significant dependence of the parameter λ on the line cross-section; at low short-circuit currents it varies within wide limits. In addition, for many combinations of parameters k , $I_{k,max}^{(3)}$ and L the required condition $\lambda > 0.2$ is not met. Similar conclusions based on the analysis of equation (2) correspond to networks of other rated voltages. The lowest efficiency of overcurrent protection is observed for 35-110 kV overhead lines, since here the line impedance weakly depends on the line cross-section, and the coefficient k varies within the widest limits.

Expressions similar to (1) and (2) can be obtained for other types of current protection. In general, it can be concluded that the efficiency of overcurrent protection is quite difficult to ensure in MV networks with a branched structure, for example, when a long line has a short adjacent line, or when a line has taps. Increasing the number of current protection types can partially improve sensitivity [1] but does not solve the problem completely.

In modern conditions, the analysis of MV network protection requires considering such features as the development and significant increase in networks with distributed generation and renewable energy sources [9]. In such networks, it is practically impossible to

ensure the effectiveness of overcurrent protection, as well as in 20-35 kV ring networks. In this regard, new approaches to the development of MV network protection are required.

3 Improving protection against phase-to-phase short circuits

Synchrophasor technology provides conditions for the development of new approaches and algorithms for protecting MV networks [2-3]. Based on current and voltage synchrophasors, network operating mode parameters can be calculated, and network element parameters can be assessed. In addition, it becomes possible to use sets of these parameters for faster and more accurate fault detection.

There are two main directions for improving protection based on synchrophasor technology: the first direction concerns the development of classical protection principles (overcurrent protection, differential protection); the second direction is based on the development of the synchrophasor technology theory, first of all, this is the analysis of differential equations of the protected object (line, transformer) in voltage and current synchrophasors during electromechanical and electromagnetic transient processes. This direction is especially promising for improving distance protection [4].

The advantage of the SPM technology for current protection is the possibility of using multi-sided measurements, when the protection uses measurements from different objects to form additional signs of recognizing the fault type and fault location. In many cases, a simple principle of logical selectivity is effective, when the presence of synchrophasor measurements of other substation feeders ensures the correct operation of overcurrent protection. In this case, for current protection with time delay, such principle can be the most effective, since in this case the protection does not have high speed, which allows using various communication channels to transfer data between protection devices.

Two- and multi-sided synchrophasor measurements allow implementing new differential protection algorithms. It is most in demand for providing protection for busbars and power transformers [5].

One of the most promising areas of synchrophasor technology is the improvement of distance protection. This can be classical local distance protection based on one-sided measurements or protection based on two-sided measurements of current and voltage synchrophasors.

Based on the analysis of the line differential equation in the transient synchrophasors, the authors proposed algorithms for improving the line distance protection [4]. The general expression for one-sided measurement:

$$\hat{z}(t) = \frac{\dot{U}(t)}{\dot{I}(t) + k\dot{I}'(t)}, \dot{I}'(t) = \frac{dI(t)}{dt}, k = \frac{L_\mu}{z_\mu} \quad (3)$$

In many cases, the line short circuit is an arc fault. For distance protection, the nonlinear arc resistance introduces additional error into the line impedance

estimate. The following expressions allow one to consider the effect of the arc resistance:

$$\hat{R}_a(t) = \text{Re}[\hat{z}(t)] - \text{Im}[\hat{z}(t)] \frac{R_\mu}{L_\mu}, \hat{z}_1(t) = \hat{z}(t) - \hat{R}_a(t), \quad (4)$$

where $\hat{z}_1(t)$ - estimation of line impedance without arc resistance for one-sided measurements.

If there are measurements of current and voltage synchrophasors at both ends of the line (side 1 and side 2), then the impedance of the line during a short circuit on side 1 will be estimated using the following expression:

$$\hat{z}_{12}(t) = \frac{\dot{U}_1(t) - \dot{U}_2(t) + z\dot{I}_2(t) + L\dot{I}'_2(t)}{\dot{I}_1(t) + \dot{I}_2(t) + k(\dot{I}'_1(t) + \dot{I}'_2(t))}. \quad (5)$$

Expression (5) allows us to proceed to estimating the distance to the fault location:

$$\hat{l}_{12}(t) = \frac{\dot{U}_1(t) - \dot{U}_2(t) + z\dot{I}_2(t) + L\dot{I}'_2(t)}{z_\mu(\dot{I}_1(t) + \dot{I}_2(t)) + L_\mu(\dot{I}'_1(t) + \dot{I}'_2(t))}. \quad (6)$$

An important feature of the proposed algorithms (4) - (6) is the provision of an accurate and stable estimate of the line impedance when combining various electromagnetic and electromechanical transient processes (Fig. 3).

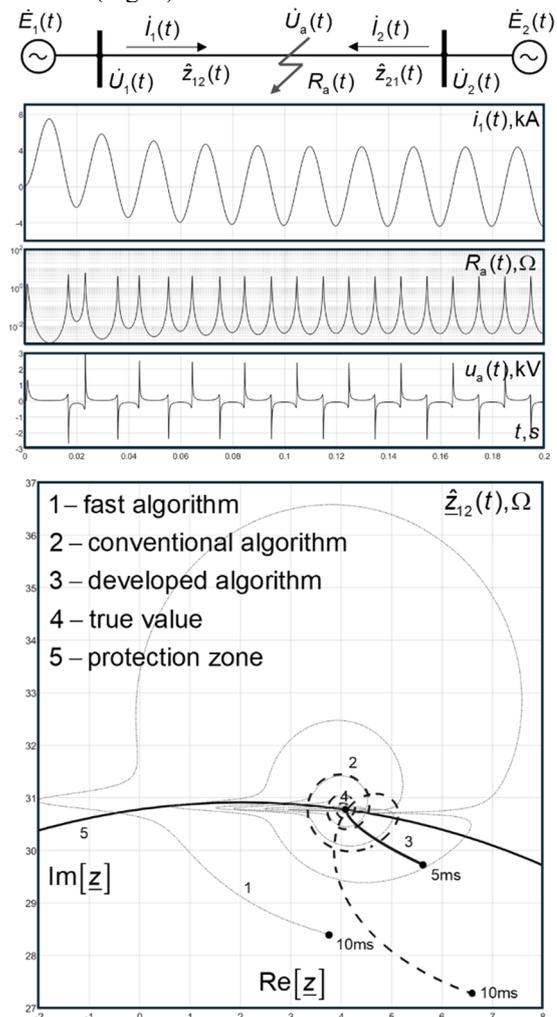


Fig. 3. Distance line protection based on synchrophasors

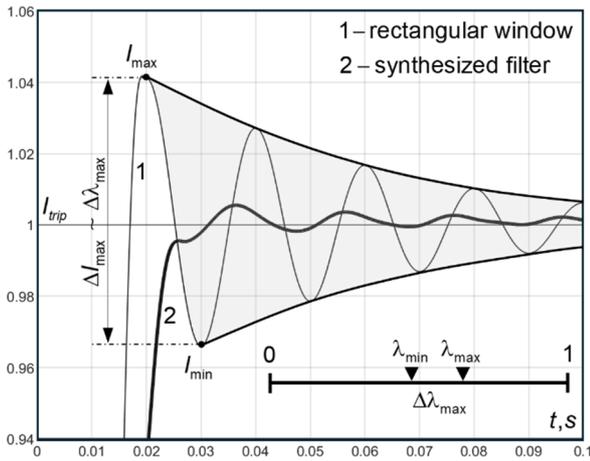


Fig. 4. Effect of signal processing on overcurrent protection

Fig. 3 shows the process of an arc short circuit in the line and the results of the line impedance estimation by different algorithms. Algorithm 1 (without averaging) assumes direct impedance calculation based on instantaneous values of voltage and current (the so-called "fast" algorithm, using two consecutive signal samples). This algorithm gives the largest error due to the presence of nonlinear arc resistance, which changes very quickly. Traditional algorithm 2 based on a filter with a rectangular window gives a more accurate estimate, but the time when the impedance estimate becomes stable is about 20-30 ms. In this case, the arc resistance can be taken as a constant value when selecting protection characteristics [10]. The developed algorithm 3 based on expressions (4) - (6) gives an accurate estimate of the line impedance already after 5-10 ms from the beginning of the short circuit.

For some power system time constants, a rectangular window filter can cause significant fluctuations in the estimated signal magnitude in the first 30-40 ms from the onset of a short circuit, which significantly affects overcurrent protection (Fig. 4). Therefore, the synthesis of digital filters for microprocessor protection devices and the use of synchrophasor technology [11] is a promising direction for improving the characteristics of both simple overcurrent protection and differential and distance protection.

4 Improving protection against single phase ground faults

Improvement of the SGF protection corresponds to various scientific directions [12-13]. One of the most promising ways of developing SGF protection algorithms is measuring ZS current and voltage synchrophasors [7-8].

Synchrophasor technology provides various principles of SGF protection: local, when synchrophasors are measured for one feeder; centralized, when synchrophasors of several feeders at a substation are measured and compared; wide area, when protection devices at different facilities can exchange synchrophasors with each other. All of the above directions for improving SGF protection are promising, since the conditions and level of network automation are always different.

The SGF protection on synchrophasors can have various algorithms that involve the assessment of certain parameters [7-8]. The simplest protection method is to measure the ZS current synchrophasors of the fundamental frequency. Their comparison by network segments ensures the operation of the centralized SGF protection. This protection method has been implemented at several 10 kV electrical network facilities and has proven its effectiveness [3].

However, the disadvantage of this method is less efficient operation of protection in networks with low capacity and installed arc-suppression reactors to compensate for the SGF current. Therefore, this method is more efficient in cable networks than in overhead ones.

A more advanced method of SGF protection involves the assessment of equivalent harmonic synchrophasors (EHSP) [7]:

$$I_{oc}(t) = \sum_{m=1}^M I_{0(2m+1)}(t), \quad U_{oc}(t) = \sum_{m=1}^M U_{0(2m+1)}(t),$$

$$\dot{U}_{0mc}(t) = \sum_{m=1}^M (2m+1) \dot{U}_{0(2m+1)}(t), \quad (7)$$

where $I_{oc}(t)$, $U_{oc}(t)$, $\dot{U}_{0mc}(t)$ - equivalent harmonic synchrophasors of ZS current and voltage.

The advantage of this method (7) is its independent operation from the level and composition of harmonics and the possibility of implementing different principles of SGF protection (Fig. 5).

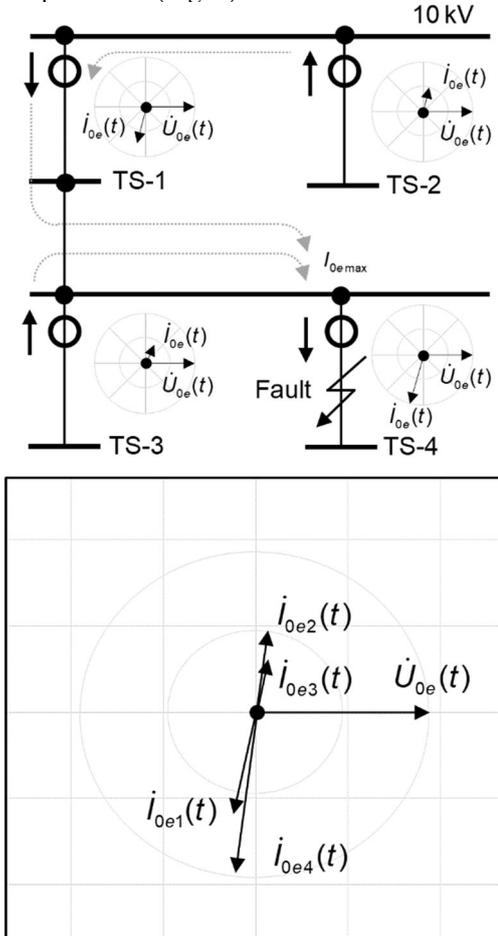


Fig. 5. SGF protection on equivalent synchrophasors

Fig. 5 shows that fault location is characterized by the equivalent current synchrophasor with the highest magnitude and a phase that differs from the phases of other network segments by 180°.

Another method of SGF protection on synchrophasors involves estimating the admittance or capacitance of the feeder [8]:

$$\widehat{C}_0(t) = \frac{I_{0e}(t)}{j\omega_0 \dot{U}_{0me}(t) + \dot{U}'_{0e}(t)}. \quad (8)$$

This method is most suitable for local protection, since an assessment of the feeder capacity is necessary to select the protection setting relative to the theoretical line parameters. The admittance principle of the SGF protection is an analogue of the distance principle, only in this case it is not the impedance that is assessed, but the line admittance/capacity (Fig. 6).

Fig. 6 shows the SGF protection characteristic, which allows dividing the zone with the parameters of undamaged feeders and the zone with the parameters of the damaged feeder (fault zone). The admittance principle provides a flexibly adjustable protection characteristic depending on many influencing factors, for example, on the measurement error.

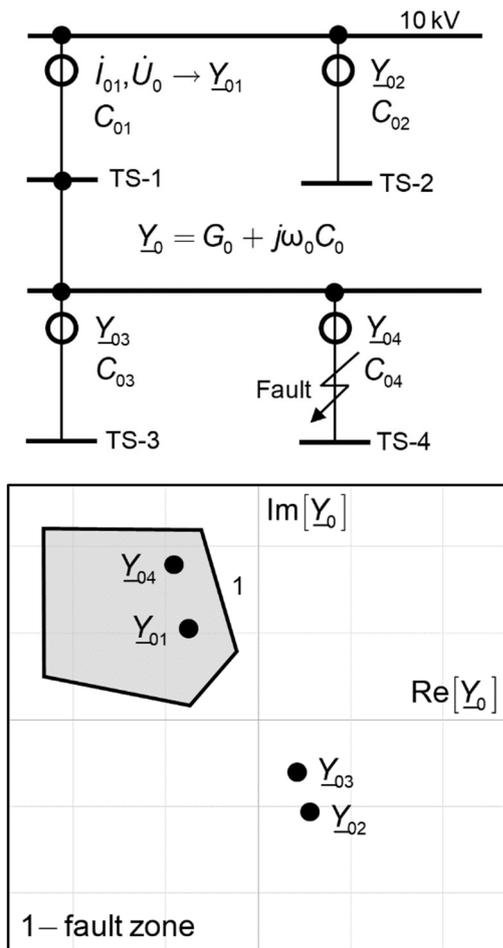


Fig. 6. SGF admittance protection

Synchrophasor technology also provides a centralized principle for the SGF localization system. This method has been successfully tested on mathematical models and on several electrical network facilities [2, 5].

5 Conclusion

Analysis of protection of medium-voltage electric networks shows that common overcurrent protections in many cases do not provide the required level of sensitivity. In addition, the development of networks with distributed generation and renewable energy sources requires the use of more advanced protections.

Synchrophasor technology is one of the promising areas for improving MV network protection. The research results confirm that measuring current and voltage synchrophasors in protection devices provides significantly better characteristics of overcurrent protection and allows the use of more advanced protection, such as differential and distance protection.

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