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On Methods of Checking Digital Out-Of-Step Protection Devices

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Abstract. The article addressed the issue of commissioning task that must take place before putting out-of-step protection into operation. Most of the developers of digital out-of-step protection devices utilize control of impedance vector locus parameter during transient in a power system to detect its out-of-step operation, however checking the setting of such protection in the field conditions using existing means is often a challenging work. To facilitate the commissioning of such devices and provide means to automatize the process so as to rid of human factor the authors suggest means of simulating impedance vector locus with the desired parameters on the complex plane to check distance out-of-step protection. The means for checking current-oscillation based out-of-step protection is also considered. The results of a transient simulation representing instantaneous values of currents and voltages are saved in the international oscillography recording format COMTRADE, which makes it possible to carry out comprehensive verification of emergency control equipment using any kind of testing equipment that is able to generate the corresponding electrical signals stored in such format.

1 Introduction

Out-of-step protection (OOSP) is one of the most important types of emergency control automation designed to prevent the development of an emergency situation caused by a loss of dynamic stability of a power system. Basically, OOSP can be based on different principles of operation: current, distance and angular OOSP [1]. At present, each design organization is developing its own OOSP operation algorithm based on one or another concept of detection of out-of-step operation, which undoubtedly increases the reliability of the power system operation [2-14]. However, OOSP algorithms simultaneously control many parameters of the electric power network, and therefore are very difficult to implement, and checking their settings in the process of commissioning is labor-consuming. Usually verification of such automation is carried out with use of "*RL-model of the power system*" software which is included in the set of basic programs of the RETOM device (hardware-software testing equipment manufactured by research-and-production company "*Dinamika*"). However, the lack of available methodological materials on the selection of model parameters for commissioning of a specific device complicates the performance of such work. Thus, the relevant task is to obtain easy-to-use means of checking OOSP. The means should allow to simulate power system in the loss of synchronism conditions and in the case of stable power swings. The creation of such tools would not only reduce labor costs, but also improve the quality of commissioning. The widespread use of such approach is recommended by the standard [15]. To achieve the task set, it is necessary to use mathematical simulation.

2 Materials and Methods

Distance OOSP is the most common type of OOSP in Russian power systems [16]. Current OOSP are also somewhat widespread. For this reason, the work addresses the means of checking current and distance OOSP. The protection should form a control action aimed at tie-tripping only in the case when only two parts of the power system loss the synchronism (note that none of the generators in these parts experience loss of excitation) [17]. Therefore, to compile a mathematical description of the considered conditions, a basic model of an electrical network consisting of two power systems is used (Fig. 1). In Fig. 1, the following designations are assumed: $\underline{E}_1$, $\underline{E}_2$ are EMFs of the two power systems; $\underline{Z}_1$, $\underline{Z}_2$ are complex impedances from the side of power system 1 and 2 respectively; the protection P is between the power systems and controls the current $\underline{I}_r$ flowing through a tie-line.

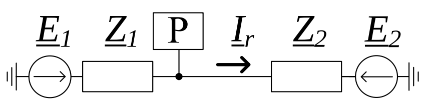

Fig. 1. Electrical drawing of the power system for the calculations.

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2.1 The development of the mathematical model for checking the current OOSP

The features of the implementation of OOSP algorithms differ depending on the manufacturer. Therefore, from this point onward, it is assumed that we deal with OOSP algorithms developed by *Institute of Power System Automation* JSC [3]. To use the method for different algorithms, the described approach can be slightly adjusted without changing its basic essence.

When checking the correct functioning of the current OOSP, it is necessary to establish the following: reliable inaction of the protection in case when the value of the current flowing through the measuring unit is equal to 90% (or lower)of the set pick-up value; reliable operation of the protection when the RMS current value is equal to 110% (or higher) of the set pick-up value; the protection must not operate if current lowers below the drop-away setting (when it previously raised above the pick-up value) and vice-versa.

For the computational model (Fig. 1), we assume that under the conditions of the loss of synchronism, the EMF vector $\underline{E}_1$ rotates relative to the vector $\underline{E}_2$, *i.e.* the angle δ_1 of the EMF vector $\underline{E}_1$ over time remains unchanged, and the angle δ_2 of the EMF vector $\underline{E}_2$ changes over time according to the law:

$$\delta_1(t) = \delta_{10} \pm \omega_s t, \tag{1}$$

where δ_{10} is the initial value of the phase of the vector $\underline{E}_1$, rad; ω_s is the slip frequency, rad/sec. In the process of loss of synchronism, the current through the power transmission line changes from a certain maximum I_{max} to a minimum value I_{min}. The maximum I_{max} and minimum I_{min} values of the current are derived from the given settings of the protection [3] among the values describing behavior of asynchronous running and the behavior of protection in time domain (for example, duration of a cycle, time delay before tripping, and *etc.*). The parameters $\underline{Z}_1$ and $\underline{Z}_2$ are set by the user at will. Then, with the given values of I_{max}, I_{min} and $\underline{Z}_1$, $\underline{Z}_2$, we obtain the following relation for the model under consideration, which makes it possible to determine the value of $\underline{E}_1$:

$$\begin{cases} q = (I_{max} - I_{min})/(I_{max} + I_{min}); \\ \underline{E}_1 = I_{max} \cdot ((\underline{Z}_1 + \underline{Z}_2)/(1-q)); \\ |\underline{E}_2| = q \cdot |\underline{E}_1|. \end{cases} \tag{2}$$

Here, the sum of resistances to the right ($\underline{Z}_2$) and to the left ($\underline{Z}_1$) from the place of installation of the protection P is taken as a constant, and therefore does not affect the formation of instantaneous values of currents.

In the considered model, all the parameters are now determined, which allows (taking into account the required duration of normal and emergency conditions, and also taking into account the specified parameters of the operation of the protection in time) to obtain the matrices of vector values of EMFs, currents and voltages in the place of the installation of the device P. From this, the matrices the instantaneous values of currents and voltages for normal and emergency conditions are derived afterwards.

The obtained instantaneous values of currents and voltages are stored in the COMTRADE format which allows to reproduce the obtained electrical signals by using a software-and-hardware testing equipment of any manufacturer (the only requirement is that equipment has a function to read COMTRADE files and generate the mentioned signals which is a common function for such devices).With sufficient information about a specific protection algorithm and its settings it is possible to predict the behavior of the protection under test.

2.2 Mathematical model for testing distance OOSP

Distance OOSP controls the behavior of the vector of complex impedance, measured at the place of installation of the protection P. When checking such an OOSP, it is necessary to make sure of its reliable non-operation in case of external asynchronous run or in case of stable power swings and a short-circuit fault and reliable operation in case of internal asynchronous run with a given slip period.

Unlike the process of obtaining the method for checking the current OOSP, where the setpoint is set directly for the controlled value, when considering the formation of instantaneous values of currents and voltages for testing a distance OOSP, it is important to control the location of the locus of the impedance vector $\underline{Z}_p$ on the complex plane.

For the assumed model of the power system (Fig. 1), the time dependence of the measured impedance vector $\underline{Z}_p$ at the place of installation of the protection is determined as [18]:

$$\begin{cases} \underline{Z}_p = (\underline{Z}_2 + \underline{q}(t)\underline{Z}_1)/(1 - \underline{q}(t)); \\ \underline{q}(t) = \underline{E}_2(t)/\underline{E}_1(t). \end{cases} \tag{3}$$

With a constant ratio of the EMFs moduli, the locus of the $\underline{Z}_p$ corresponds to a circle on the complex plane with a radius R_0 and a center $\underline{Z}_0$:

$$\begin{cases} \underline{Z}_0 = -\left(q^2 \underline{Z}_1 + \underline{Z}_2\right) \Big/ \left(q^2 - 1\right); \\ R_0 = -q\left|\underline{Z}_1 + \underline{Z}_2\right| \Big/ \left|q^2 - 1\right|; \\ q = \left|\underline{E}_2\right| / \left|\underline{E}_1\right| = const. \end{cases} \tag{4}$$

Let's suppose that the values q, R_0, $\underline{Z}_0$ are determined (the parameter q is determined arbitrarily, and the remaining parameters are uniquely determined by the protection settings), then the values of $\underline{Z}_1$ and $\underline{Z}_2$ can be found by expanding the modules in the system of equations (4). The sought values of $\underline{Z}_1$ and $\underline{Z}_2$ are satisfied by solutions of two systems of equations:

$$\begin{cases} \underline{Z}_1 = \dfrac{1}{q^2-1}\left(-\underline{Z}_0(q^2-1)+\dfrac{R_0\left|q^2-1\right|}{q}\right); \\ \underline{Z}_2 = -\dfrac{R_0\left|q^2-1\right|}{q}-\underline{Z}_1. \end{cases} \quad (5)$$

$$\begin{cases} \underline{Z}_1 = \dfrac{1}{q^2-1}\left(-\underline{Z}_0(q^2-1)-\dfrac{R_0\left|q^2-1\right|}{q}\right); \\ \underline{Z}_2 = \dfrac{R_0\left|q^2-1\right|}{q}-\underline{Z}_1. \end{cases} \quad (6)$$

System (4), with the impedance values found according to either (5) or (6) makes it possible to obtain a circular locus, however, the region with the highest density of samples (corresponds to the region where the speed of movement of the impedance vector along the locus is the lowest) cannot be determined by a user.

The desired distribution of samples on the locus can be achieved in 2 stages, making the following transformations. First, when calculating the values of impedances $\underline{Z}_1$, $\underline{Z}_2$ according to (5) or (6), instead of the previously used value of $\underline{Z}_0$, it is necessary to substitute its corrected value $\underline{Z}'_0$which is equal to

$$\underline{Z}'_0 = \underline{Z}_0 e^{j\varphi_{cor}} \quad (7)$$

where φ_{cor} is the correction angle with which the desired location of the maximum sample density on the locus is shifted along the locus relative to the initially obtained location.

Secondly, in the formula (4) it is necessary to substitute the values of resistances $\underline{Z}_1$, $\underline{Z}_2$ not obtained by (5) or (6), but their corrected values $\underline{Z}'_1$, $\underline{Z}'_2$, which are:

$$\begin{cases} \underline{Z}_1' = \underline{Z}_1 e^{-j\varphi_{cor}}; \\ \underline{Z}_2' = \underline{Z}_2 e^{-j\varphi_{cor}}. \end{cases} \quad (8)$$

Let's consider a numerical example. Suppose it is necessary to obtain the impedance locus centered at the point $\underline{Z}_0$ = 100 + j75 Ohm and with the radius R = 80 Ohm. Let us also take q = 0.95 and φ_{cor} = –45 degrees, and calculate the impedance by expression (6). Then, in accordance with the procedure presented above, we get:

$$\underline{Z}_0' = \underline{Z}_0 e^{j\varphi_{cor}} = 123.74 - j17.68 \text{ Ohms.}$$

The values of $\underline{Z}1$, $\underline{Z}2$ calculated according to (6) for the given value of $\underline{Z}'0$ are equal to:

$$Z_1 = -39.53 + j17.68\,Ohms,$$
$$Z_2 = 47.74 - j17.68\,Ohms.$$

New values of these impedances after transformations (8) are equal to:

$$Z'_1 = -40.45 - j15.45\,Ohms,$$
$$Z'_2 = 46.26 + j21.26\,Ohms.$$

The obtained values of complex impedances $\underline{Z}'_1$ and $\underline{Z}'_2$ are substituted into the power system model (Fig.1) and the loss of synchronism simulation begins according to equation (1). The result of the simulation is the time dependence of the vector values of the voltage supplied to the relay $\underline{U}_p$ (t) and the measured current $\underline{I}_p$ (t). From this, instantaneous values of current and voltage are formed(as imaginary components of complex values for the considered moment in time t) and COMTRADE files format are made.

In the example under consideration, maximum RMS values of currents and voltages are 1.17 Amps and 55.49 V, respectively (the value of EMF $\underline{E}_1$ equal to 7 V was taken). These values can be changes while the locus parameters remain the same. The way to do so is to change either parameter q, or the value of EMF $\underline{E}_1$, or use system of equation (5) instead of (6).

One of the important parameters of the described method is the correction angle φ_{cor}, it allows to set the region where the speed of impedance vector is the lowest, as it's illustrated in Fig. 2, 3.

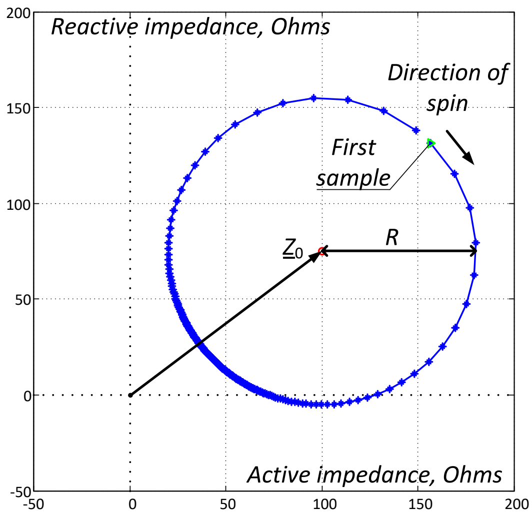

Fig. 2. Impedance locus with given characteristics, φ_{cor} = –45°.

Another test that has to be performed when checking the settings of distance OOSP is its inaction the during stable power swings in the power system. For a comprehensive check, it is necessary to make changes to redefine the value of the angle of EMF $\underline{E}_1$.

Assume that at the initial moment of time the phase shift between the vectors $\underline{E}_1$ and $\underline{E}_2$ is δ_{12}, while in the process of power swings the angle δ_1 deviates from its initial position by δ_{1m} clockwise and by δ_{2m} counterclockwise, as shown in Fig. 4a.

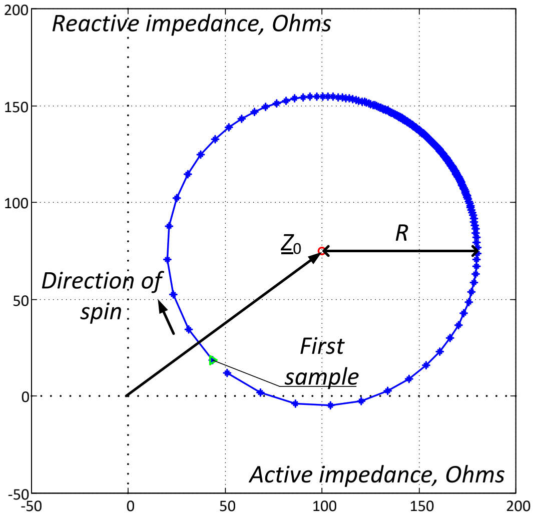

Fig. 3. Impedance locus with given characteristics, $\varphi_{cor} = 135°$.

Suppose that the change in the angle δ_1 occurs according to a sinusoidal law, as shown in Fig. 4b. In this case, the law of variation of the angle δ_1 (t) looks as follows (9):

$$\begin{cases} \delta_1(t) = \left(A_0 + \delta_{12}\right) + A_1 \sin\left(2\pi f_{sw} t - \arcsin\left(A_0 / A_1\right)\right), \\ A_0 = 0{,}5(\delta_{1m} - \delta_{2m}), \\ A_1 = 0{,}5(\delta_{1m} + \delta_{2m}), \end{cases} \tag{9}$$

where the parameter f_{sw} characterizes the speed of power swings. In system (9), it is taken into account that the numerical values of δ_{1m} and δ_{2m} should be substituted with a plus sign, then the upper limit of the angle δ_1 will be $\delta_{12} + \delta_{1m}$, and the lower one is, respectively, $\delta_{12} - \delta_{2m}$.

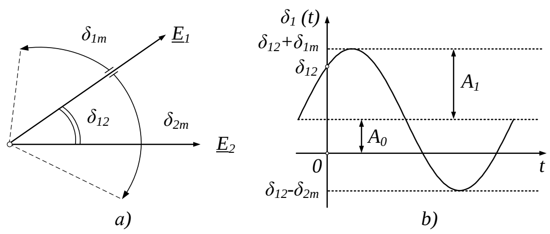

Fig. 4. The change in the mutual angle between power systems during power swings: a) phasor diagram; b) change in δ_1 over time.

An example of a locus of power swings is shown in Fig. 5, which also shows the settings of distance relay of OOSP in accordance with the algorithm [3].

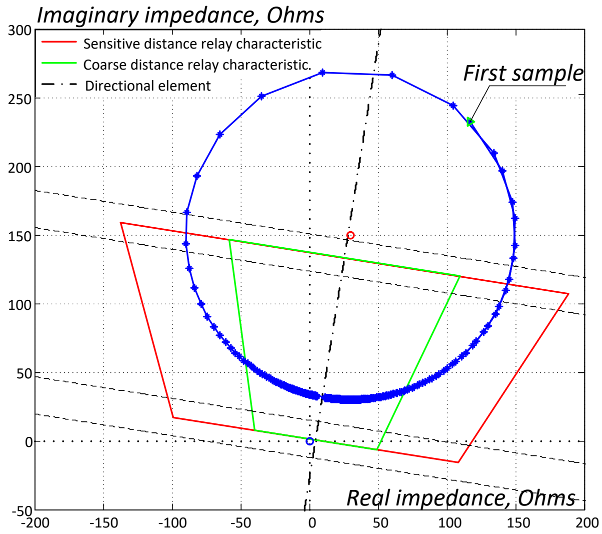

Fig. 5. Impedance locus obtained by simulating power swings in the case of $\delta_1 = 179°$, $\delta_2 = 100°$, $\delta_{12} = 1°$ and $\varphi_{cor} = -81°$.

3 Results and Discussion

Experience has shown the possibility of using the developed method in practice. Experimental studies of the current-type and distance-type OOSP were carried out on the basis of the multifunctional emergency control system series KPA-M produced by *Power Systems Automation Institute* JSC using the RETOM software-hardware testing equipment. Analysis of the data recorded by the terminal as a result of the experiments carried out confirms the complete correctness of the considered method, as well as the similarity of the parameters of the simulated locus with the real one observed in the power systems. Some experimental results are shown in Fig. 6-10. Thus, proposed means have more functional abilities and are more easy-to-use that presented in [19] or in [20].

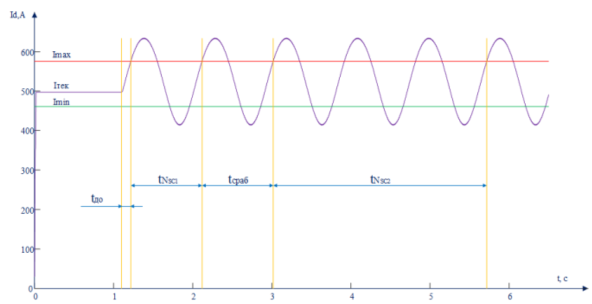

Fig. 6. Visualization of simulation results in the MatLab software: operation of the current OOSP during the check of pick-up current in specified time delay after the beginning of asynchronous running.

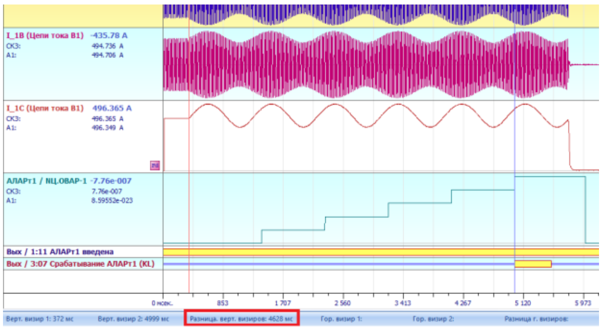

Fig. 7. The record of the test report in the specialized FastView software: the operation of current OOSP after the specified cycles of asynchronous run at the certain pick-up current setting.

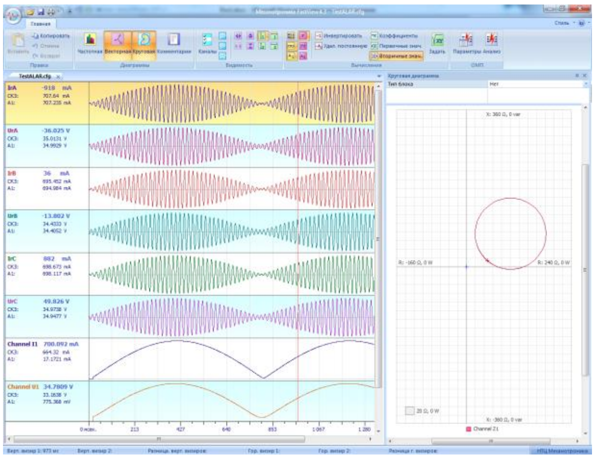

Fig. 8. The oscillography of current and voltages forming impedance locus shown in Fig.2. The record is processed with the tools available in the specialized FastView software. Currents and voltages are on the left side of the figure; the locus of positive sequence impedance is presented on the right side.

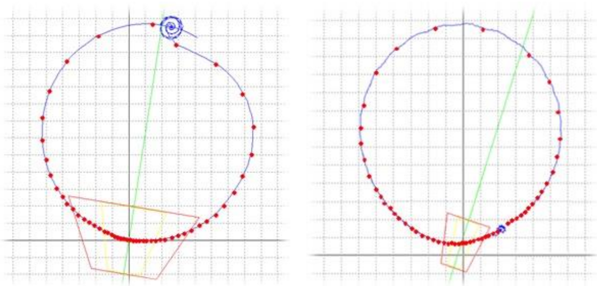

Fig. 9. The impedance locus recorded by digital terminal KPA-M (the reddots on the locus show the sequential position of the impedance vector $\underline{Z}_p$ at time intervals equal to the terminal sampling period): checking of the settings of the distance OSSP device installed at Ust-Ilimsk HPP (left) and the locus obtain in the process of certification trial of the distance OOSP device by using a RTDS (right).

4 Conclusion

The developed algorithms form a full-fledged basis for checking the settings of OOSP of different type in case of the asynchronous run and power swings.

It is important that the given approach makes it possible to test OOSP devices without being bound to a specific type of test equipment, the only requirement for which is the ability to read and reproduce signals saved in a COMTRADE file.

The proposed algorithms for the formation of input signals for checking the OOSP are now actively used in the commissioning tasks of emergency control devices series KPA-M. This use significantly reduces the time required to complete commissioning and improves its quality.

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