The impact of current transformer saturation on the performance of differential protection of generators and motors at frequencies below 50 Hz

A V Bessolitsyn*, A V Golgovskich and A V Novikov
Faculty of Electrical Engineering, Vyatka State University, Kirov, Russia

* E-mail: bessolitsin@vyatsu.ru

Abstract. At present, low-frequency modes are widely used in the operation of electric generators and engines. Relay protection should ensure the implementation of its functions even at a frequency below the rated by tens of percent. Signals from current transformers go to inputs of current relay protection devices, and their performance deteriorates significantly at frequencies below industrial. The article experimentally investigates the impact of the core saturation of a current transformer that occurs at low frequency on the value of the differential current in the differential relay protection circuit of a generator or motor. The authors analyze how the burden of current transformers, the value of the current and its frequency affect the value of the differential current. They show the possibility of both a false response and a failure in the operation of the differential protection at low frequency. Moreover, the authors give practical recommendations on ensuring emergency protection of equipment at a frequency below 50 Hz.

1. Introduction
Differential current protection is widely used to protect generators and powerful motors due to its absolute selectivity and speed. When using current transformers to form a differential protection circuit, the amount of current in the relay is determined by the errors of at least two current transformers. The amount of error in current transformers is affected by the following factors: the value of the current, the burden of the transformer and the frequency of the signal. A large number of works consider the error of current transformers operation intended for using in power circuits at a frequency of more than 50 Hz [1–5]. With the wide use of variable-frequency drive current transformers can operate at frequencies significantly less than the rated [6, 7]. In the case of using electric braking of synchronous generators or motors [8, 9], the amount of electric current is controlled up to a frequency of about 0.5 Hz. However, the impact of current transformer errors on the operation of differential protection at a frequency below 50 Hz hasn’t been studied enough.

The purpose of this article is to examine the influence of various factors determining the radio error of current transformers on the amount of current in the current relay of differential protection at low and extra-low frequencies. Differential current in case of external and internal damage is determined experimentally by measuring the sum and difference of secondary currents of two practical current transformers connected in accordance with the longitudinal differential protection circuit.
2. The principle of the current transformer operation

To consider the features of the current transformer is easier if we use the equivalent circuit and the phasor current diagram [10]. When analyzing practical problems, we can neglect the voltage drop across the active resistance and the leakage resistance of the primary and secondary windings [1]. Figure 1 shows the simplified equivalent circuit of the current transformer.

![Figure 1. The equivalent circuit of the current transformer.](image)

An ideal transformer connects the primary and secondary sides of a current transformer. The number of turns of the primary winding is \( N_1 \), of the secondary one is \( N_2 \). The secondary current \( I_2 \) can be brought to the primary side:

\[
I'_2 = \frac{N_2}{N_1} I_2
\]

Figure 1 shows that in a real transformer the primary current is not equal to the reduced secondary current, as in the case with an ideal transformer. This phenomenon is due to the presence of a no-load current \( I_0 \). The no-load current has two components. The first one is a component of magnetization, which creates a magnetic flux in the transformer core. The second component is active, which takes into account the active power losses in the core for eddy currents and hysteresis. The reactive component of the no-load current is modeled by the inclusion in the equivalent circuit of reactance \( X_M \). The active component is modeled using the active resistance \( R_M \) in the equivalent circuit.

The vector diagram in Figure 2 shows currents in the transformer.

![Figure 2. Current transformer vector diagram.](image)

The vector diagram shows that the cause of the error in the current transformer operation is the excitation current \( I_0 \). In the design and manufacture of current transformers, measures are taken to reduce the no-load current, and under rated conditions it is negligible. However, under the influence of some factors, the excitation current can have a significant impact on measurements [11–14] and on the operation of differential protection [15, 16].

A decrease in the current frequency leads to an increase in the current flowing through the \( X_M \) resistance of the equivalent circuit. The current transformer is saturated, since its core is made of ferromagnetic material with a nonlinear magnetization characteristic. The secondary current, reduced
to primary, is significantly different from the true current. Thus, saturation of current transformer cores leads to deterioration of the working conditions of the differential protection [11].

3. Test setup
To study the operation of current transformers in the differential protection circuit at frequencies below the rated, we used the test circuits shown in Figures 3 and 4.

Figure 3. Test setup for studying the impact of current transformers on the operation of the differential protection in normal mode and in case of external faults.

Figure 4. Test setup for studying the impact of current transformers on the operation of the differential protection in case of short circuit in reach.

The primary winding of the current transformer was connected to a alternating current source. For this purpose, test setup of relay protection RETOM-61 was used. An ammeter $A_1$ connected in parallel with the current shunt, is installed in the primary current circuit to measure the true primary current. The terminals of the secondary windings of current transformers are connected to the ammeter $A_2$ by signal cables. The cable with the total resistance of the forward and return wires $R_1$ leaves the transformer ST1. The total resistance of the cores of the cable leaving the transformer ST2 is $R_2$. The diagrams in Figures 3 and 4 differ in the method of connecting the ammeter $A_2$, which measures the current in the differential relay circuit. The diagram in Figure 3 shows the ammeter connected to the difference of the secondary currents of the current transformers, so it measures the current flowing through the differential relay in the normal mode and in the external short circuit mode. In the diagram shown in Figure 4, the ammeter is connected to the sum of the currents of the secondary windings of the transformers and measures the current flowing through the differential relay during a short circuit within the protected area. The scheme in Figure 4 allows to investigate only one particular case when, in the event of a short circuit in reach, the currents in the current transformers are equal to each other. However, it allows to obtain a qualitative assessment of the impact of the current transformer on the operation of the differential protection at a lower frequency.
This paper presents the results of a study of the impact of current transformers, type TKL-0.5T on the currents flowing in the differential protection relay at a lower frequency. The rated parameters of the transformers are given in Table 1.

Table 1. Parameters of current transformer TKL-0.5T.

| Parameter                        | Value  |
|----------------------------------|--------|
| Primary / secondary current (A)  | 15/5   |
| Rated voltage (kV)               | 0.66   |
| Rated frequency (Hz)             | 50     |
| Rated burden (VA)                | 5      |
| Accuracy class                   | 0.5    |
| Standard                         | GOST 7746-68 |

4. Measurement results
Field studies were performed in the laboratory of the department of power plants at Vyatka State University. Using the circuit shown in Figure 4, we obtained the dependences of the differential current on frequency for the case of a short circuit in the protected area. These dependences are shown in Figure 5. Using the circuit shown in Figure 3, we obtained the dependences of the differential current on frequency for the case of normal mode and an external short circuit. These dependences are shown in Figure 6. It should be noted that the dependences in Figures 5 and 6 were measured when the resistances of the wires connecting the secondary terminals of ST1 and ST2 transformers with the ammeter A2 were very small and equal to each other $R_1 = R_2 = 0.017$ Ohm.

The curves in Figure 5 show that when the frequency is lowered, the secondary current of the current transformer decreases significantly. It is due to the fact that when the frequency decreases, the core of the current transformer goes into saturation mode [11]. The current unbalance in normal mode and an external short circuit with decreasing frequency first increases due to an increase in the current error of the current transformer, and then decreases due to a decrease in the secondary currents of the transformers.

The study [11] shows that the degree of core saturation of the current transformer is determined by the value of the primary current and the magnitude of the secondary burden besides the frequency. To assess the impact of the current transformer burden on the operation of the differential protection, we measured the dependences of the differential current on frequency with an increased resistance of the signal cable of one of the current transformers. Figures 7 and 8 show the dependences of the differential current on the frequency in various modes, measured with resistance of conductors from ST1 equal to $R_1 = 0.017$ Ohm and resistance of conductors from ST2 equal to $R_2 = 0.08$ Ohm.
Comparing the dependences shown in Figures 5 and 7, it can be concluded that an increase in the burden resistance of the current transformer had little effect on the value of the differential current during a short circuit in the protected area. The analysis of the dependences shown in Figures 6 and 8 shows that an increase in the secondary burden of the current transformer leads to a sharp increase in the unbalance current in the normal mode and during an external short circuit.

5. Conclusion
A full-scale experiment has shown that the saturation of current transformers with decreasing frequency leads to a significant change in the value of the currents in the differential protection in both
normal and emergency modes. The degree of current change in the differential protection due to saturation of the transformer cores is determined by three factors: frequency, primary current value, and secondary burden of the transformer. With a high resistance of the secondary circuits of the transformers, the differential protection may give false operations in case of a decrease in frequency. At a frequency of several hertz, the differential protection becomes inoperative due to the reduction of the secondary current of the transformers.

In order to ensure the functioning of the differential protection, we can recommend: to select current transformers with a rated current several times higher than the rated current of the protected equipment, to reduce the secondary burden of the current transformer by all means. To avoid false operation, it is necessary to consider the need to block the differential in each case when equipment is operated at frequencies substantially below 50 Hz.

References

[1] Cataliotti A, Cara D, Emanuel A and Nuccio S. 2008 Influence of Current Transformers on the Measurement of Harmonic Active Power 16th IMEKO TC4 Symposium. Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements (Budapest) pp 1–4
[2] Jäschke C and Schegner P 2015 Metrological frequency response analysis of a high current instrument transformer 9th International Conference on Sensing Technology (Auckland) pp. 640–45
[3] Chen J C, Phung B T, Zhang D M and Blackburn T 2013 Frequency response of MV current transformers IEEE 2013 Tencon – Spring (Sydney) pp. 332–36
[4] Gallo D, Landi C and Luiso M 2014 Evaluation of metrological performance of electromagnetic current measurement transformers in non-sinusoidal conditions International Conference on Electromagnetics in Advanced Applications (Palm Beach, Netherlands Antilles) pp 671-674
[5] Kaczmarek M 2015 Operation of inductive protective current transformer in condition of distorted current transformation Modern Electric Power Systems (Wroclaw) pp 1–4
[6] Khan U, Voloh I and Robinson P 2016 Considerations for dependability of the motor protection on current transformers performance in VFD applications Petroleum and Chemical Industry Technical Conference (Philadelphia) pp 1–8
[7] D’Aversa A, Hughes B and Patel S 2013 Challenges and solutions of protecting variable speed drive motors 66th Annual Conference for Protective Relay Engineers (College Station) pp 250–56
[8] Zhang Y, Chen Y and Tao J 2017 Electric braking method in hydroturbine generating unit and transformation scheme Acta Technica 62 pp 145–54
[9] Ge B, Fu Y, Lv Y and Wang M 2010 Study on electrical braking of huge hydro-generator Asia-Pacific Power and Energy Engineering Conference (Chengdu) pp 1–4
[10] Harlow J H 2004 Electric power transformer engineering (Boca Raton: CRC Press) p 496
[11] Bessolitsyn A V, Golgovskich A V and Novikov A V 2017 Experimental study of current error of up to 50 hz current-measuring transformer International Conference on Industrial Engineering, Applications and Manufacturing (Saint-Petersburg) pp 1–4
[12] Radu R A, Micu D O, Micu D D and Ceclan A 2014 Analysis of inrush and fault currents measurement errors generated by the current transformer saturation 49th International Universities Power Engineering Conference (Cluj-Napoca) pp 1–5
[13] Kasztenny B, Mazereeuw J and Docarmo H 2008 CT Saturation in industrial applications - analysis and application guidelines IET 9th International Conference on Developments in Power System Protection (Glasgow) pp 418–25
[14] Ozgonenel O 2013 Correction of saturated current from measurement current transformer IET Electric Power Applications 7 pp 580–85
[15] Kasztenny B and Finney D 2005 Generator protection and CT-saturation problems and solutions IEEE Transactions on Industry Applications 41 pp 1452–57
[16] Lirvinov L I, Osintsev A A and Glazirin V E 2017 Characteristic features of internal and external faults for use in differential protection International Conference "Actual Issues of Mechanical Engineering" (Tomsk) pp 425–32