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Instrument current transducer for measurements in asymmetrical conditions in three-phase circuits with upper harmonics

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A B S T R A C T

The theme of the article is protection of electrical circuits against negative sequence currents both with sinusoidal and trapezoidal waveforms. The suggested solution is enhancement of instrument current transducers used in industrial relaying and control applications. The instrument negative sequence current transducer connected to Rogowski coils designed by the authors is presented in the article. To protect circuits with extremely non-sinusoidal currents (such as trapezoidal waveforms), instrument transducers with 2nd order low pass filter are suggested. In the presence of higher-order harmonics in the protected three-phase circuit the low pass filter will reduce the THD in the output voltage of instrument negative sequence current transducer (as compared to harmonics in currents of the protected circuit) and compensate for the differentiation effect typical of such transducer schemes.

The paper may be of interest for investigators and engineers engaged in research, design and commissioning of protection and control equipment, current instrument and measurement devices used in industrial applications, and also for undergraduate and postgraduate students in electrical engineering.

Introduction

Instrument negative sequence current transducer (INSCT) is the main connecting link between the protective relaying system and the protected installation. Improvements in INSCT characteristics very often help to increase the reliability of equipment at complex manufacturing facilities.

Electrical installations at industrial plants may work in different operating conditions when electrical parameters (e.g. input currents, voltages, or impedances) change within broad ranges. The changes of electrical values may be due to both normal switching events causing transients (starting and plugging of motors, energization of transformers, voltage interruptions, etc.) and different faults and abnormal conditions. Currents may change within especially large ranges under these circumstances. They can reach 12–15 times the nominal values not only under fault conditions, but also during normal switching operations (e.g. frequent plugging of electric motors) [1,2]. So the overcurrents due to such operations are inevitable during normal operation and the protections must not operate under such conditions, while the overcurrents during short circuits, open phase mode or other faults are usually regarded as sudden dangerous conditions and must be eliminated by protective relaying equipment [3–5].

Thus the operating conditions for primary transducer devices (current transformers and Rogowski coils) in protection and control applications are not the same as those for instrument circuits. The latter usually require primary transducers of a certain accuracy class at primary current no greater than nominal in steady-state condition. But the primary current transducers for relaying applications must very often operate at currents that are much greater than the nominal current, such as transient currents in open phase modes [6,7].

It should also be mentioned that INSCTs often have to work in presence of transient *dc* components in primary currents. These components are transformed to the secondary side of transducers (current transformers or Rogowski coils) with error that depends on their decay rate [8,9].

Modern electrical systems are characterized by increase of attenuation time constants up to tenths of seconds, decrease of relay operating times up to 0.02 s (or faster), and fault tripping times up to 0.06 s [8]. This results in larger influence of transients on instrument transducers and protective relaying applications as a whole. As a general rule, transients in primary circuits and in instrument transducers as such will affect the normal transformation of current that is observed in steady-state conditions.

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Neglecting such influence may result in slow or unwanted operation of protective relaying equipment.

Therefore, the design and implementation of instrument transducers must be aimed at providing reliability and accuracy both in steady-state and transient conditions.

Instrument negative sequence current transducer for measuring non-sinusoidal currents in the protected circuit

Instrument negative sequence current transducer with 2nd order low pass filter

The Far Eastern Federal University (Vladivostok, Russia) has recently carried out a research to increase the sensitivity of protections against negative sequence currents. The result of this research is a new design of INSCT which uses Rogowski coils as primary instrument transducer [10].

However the disadvantage of this INSCT is its limited application domain, for it can be used only for detection of imbalance condition with sinusoidal currents and are not suitable for relays intended to protect equipment with current waveforms close to trapezoidal. The selectivity and sensitivity of INSCT decrease as the level of higher-order harmonics rises in the currents measured. For example, when there is no negative sequence in the fundamental harmonic the output voltage of INSCT is not zero due to the higher-order harmonics. If the amplitudes of such harmonics are not high, the sensitivity of the protection to the negative sequence component in the fundamental harmonic must be reduced in order to avoid false operations (e.g. during open phase mode in the circuit to which INSCT is connected). When the higher-order harmonics' amplitudes are high, it is impossible to provide the required selectivity of the protection connected to INSCT.

The harmonics are generated by equipment whose components have non-linear characteristics, e.g. uncontrolled or controlled rectifiers with large inductive reactances in load circuits. The phase input current of such rectifiers is alternating sequence of pulses with waveform close to trapezoidal [11,12]. The only difference from "ideal trapezoid" is that the leading and trailing edges of such trapezoids are formed by segments of sinusoids instead of straight lines [13–15]. The Rogowski coils, which measure the rate-of-change of currents instead of currents as such, will transform each trapezoid into two pulses whose duration equals the duration of the leading and the trailing edges of the trapezoid. The form of emf induced in Rogowski coils in this case will change from that close to triangle (when controlled rectifier thyristor control angle equals zero) to that close to rectangle (when the control angle is close to $\pi/2$). The duration of pulses is several degrees only. Such form of emf applied to INSCT inputs is far from sinusoidal. Therefore, in steady-state mode, when the input currents are completely symmetrical, the output voltage of instrument transducer (INSCT prototype) is not zero [10].

The problem addressed by this article is to broaden the application range of this scheme, i.e. to suggest using the instrument negative sequence current transducer for detection of imbalance conditions with both sinusoidal and trapezoidal current waveforms.

The result achieved during solution of this problem is the following: the negative sequence component of current for both sinusoidal and trapezoidal waveforms is measured with a device which contains low pass LC-filter, compact negative sequence voltage filter and compact instrument transducers that transform three-phase currents into voltages. The output of this device is connected to a load with large impedance (e.g. ADC).

In the proposed solution the instrument negative sequence current transducer contains a 2-nd order low pass filter whose amplitude-frequency characteristic maximum corresponds to nominal frequency of the source. The corresponding structure is shown in Fig. 1. The schematic diagram of instrument negative sequence current transducer is shown in Fig. 1a. The low pass filter is shown in Fig. 1b. The filter constitutes an active 2nd order low-q circuit with two loop feedback.

Parameters and characteristics of instrument negative sequence current transducer

Output voltage of negative sequence voltage filter (NSVF) for three-phase sinusoidal currents

The parameters of elements in instrument negative sequence current transducer are determined by the following relations. Mutual inductance M between Rogowski coil 1 and the conductor of phase A equals mutual inductance between Rogowski coil 2 and the conductor of phase B. The inductances L_k of these coils are the same. At angular frequency of the source ω_1, which equals the angular frequency of the first harmonic of currents in phases A and B, inductances X_k of Rogowski coil 1 and Rogowski coil 2 and their mutual inductances X_m with conductors of phases A and B will be determined as $X_k = \omega_1 L_k$ and $X_m = \omega_1 M$. The active resistances of the two Rogowski coils are negligible as compared to impedance of negative sequence voltage filter (NSVF) and can be neglected. At angular frequency of the source ω_1 the relation between the capacitance $-jX_1$, resistance R_1 and inductive reactance of Rogowski coil is given by: $X_1 = R_1/\sqrt{3} + X_k$. At angular frequency of the source ω_1 the relations between the capacitance $-jX_2$, resistances R_2, R_3 and inductive reactance of Rogowski coils X_k are given by: $X_2 = \sqrt{3}R_3$ and $R_2 = \sqrt{3}X_k$.

The instrument negative sequence current transducer works as follows.

The instantaneous values of emf e_A and e_B induced in Rogowski coils are determined by mutual inductance M multiplied by rate-of-change of currents $\frac{di_A}{dt}$ and $\frac{di_B}{dt}$ for phases A and B.

Let us consider a case where phase currents and emf induced in Rogowski coils by these currents are caused by connecting a non-distorting load to the voltage source. In steady-state mode the values are sinusoidal and emf phasors $\underline{E}_A$ and $\underline{E}_B$ induced in Rogowski coils by currents $\underline{I}_A$ and $\underline{I}_B$ are given by:

$$\underline{E}_A = jX_m\underline{I}_A, \underline{E}_B = -jX_m\underline{I}_B, \tag{1}$$

where j is imaginary unit which denotes turn of phasor $\underline{E}_A$ by an angle of $\pi/2$ in positive direction relative to phasor $\underline{I}_A$. The negative sign preceding the second equation means that the output of Rogowski coil 2 (not its input) connects to an input of NSVF, while the input of Rogowski coil 1 connects to another input of NSVF. Therefore phasor $\underline{E}_B$ rotates by $\pi/2$ in negative direction relative to phasor $\underline{I}_B$.

During analysis of NSVF operation the following values can be neglected: active resistances of Rogowski coils and input admittance of low pass filter. The voltages $\underline{U}_a$ and $\underline{U}_b$ on the first and third inputs of NSVF in relation to the second input (considering the above relations between NSVF parameters) are given by:

$$\underline{U}_a = \frac{\sqrt{3}}{2}X_m\underline{I}_A \exp\left(\frac{\pi}{2}+\frac{\pi}{6}\right), \underline{U}_b = \frac{\sqrt{3}}{2}X_m\underline{I}_B \exp\left(-\frac{\pi}{2}-\frac{\pi}{6}\right). \tag{2}$$

If the measured currents $\underline{I}_A$ and $\underline{I}_B$ are positive sequence components, the current in phase B lags the current in phase A by an angle of $2\pi/3$, i.e. $\underline{I}_B = \underline{I}_B \exp(-2\pi/3)$. In this case the phasors of voltages at first and third inputs of NSVF will be equal: $\underline{U}_a = \underline{U}_b = \frac{\sqrt{3}}{2}X_m\underline{I}_A \exp\left(\frac{2\pi}{3}\right)$. The input voltage of low pass filter $\underline{U}_{ab} = \underline{U}_a - \underline{U}_b$ equals zero. Therefore, in this case the output voltage of the low pass filter is also zero.