Chapter 2
The new method of measuring the complex value of short circuit loop impedance

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The article presents the basic assumptions of a new method of measuring the complex value of short circuit loop impedance by the polynomial approximation method. It involves determining the module value and the loop impedance angle and is later based on calculating the resistance and reactance values of the short circuit at the measuring point.

Index terms: measurement of short circuit loop impedance, complex values of short circuit loop impedance, fault resistance and reactance.

The Purpose of Measuring Short Circuit Loop Impedance

The most common means of protection against electric shock in the event of damage is self-acting power-off. It is intended to protect against electric shock as well as to protect the installation and electrical devices against disturbances in their operation or destruction. Protection by self-acting power-off is effective if, in the event of a phase wire short circuit to the enclosure (connected to the protective wire):

a) a protective device (fuse, over-current circuit-breaker, residual current circuit-breaker) automatically switches off the power supply in the required time;

b) permissible for regulations of the value of allowable long-term touch voltage UL is not exceeded.

The maximum allowable power switch-off time in TN network systems was specified in PN-HD 60364-4-41: 2009 [1] and is 0.4 s (for a rated value of phase voltage equal to 230 V). This switch-off time applies to plug-in circuits with a rated current of not more than 63 A, and for the circuits supplying loads which are permanently installed, the rated current cannot be more than 32 A. For distribution circuits, this time may be longer than 0.4 s, but it cannot exceed 5 seconds.

To check compliance (concerning the conditions of protection against electric shock by self-acting power-off) of real systems with the provisions of the PN-HD 60364-4-41 standard should be:

1) measure (according to PN-HD 60364-6 [2]) the value of fault loop impedance,
2) check compliance of the protective device rating data.

The short circuit loop in a properly made TN system includes a transformer winding, electric wires and cables (on the transformer – load section) and a metal enclosure of the device (Fig. 2.1).

To check the effectiveness of the protection against an electric shock by self-acting switching off the power supply in the TN system, it is necessary to determine whether the measured value of short circuit loop impedance meets the condition [1]:

$$Z_S \leq \frac{U_0}{I_a} \qquad (2.1)$$

where:

Z_s – short circuit loop impedance in the tested system,
I_a – current of the protection causing power-off in due time,
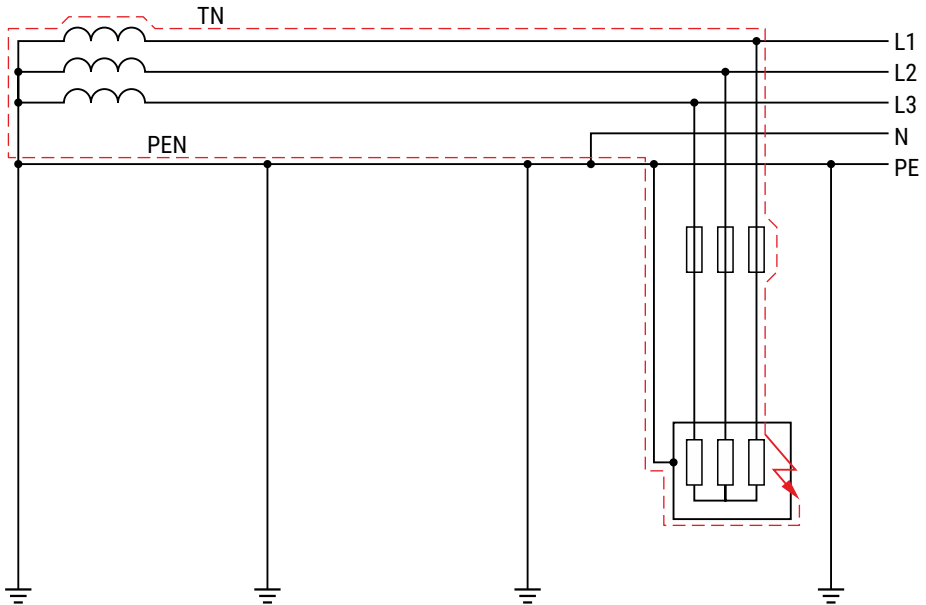U_0 – rated voltage of the network relative to the earth.

FIGURE 2.1. Short circuit loop L − PE in the TN system [3]

Knowable Methods
of Metering Short Circuit Loop Impedance

1. Measurement of short circuit loop impedance using the technical method

The measurement of short circuit loop impedance using the technical method, i.e. using a voltmeter and an ammeter, is shown in Figure 2.2. In this method, the values of resistance R_x and reactance X_x of the tested short circuit loop should be measured separately. The searching impedance of the short circuit loop Z is then the geometric sum of the measured values of resistance and reactance X_x:

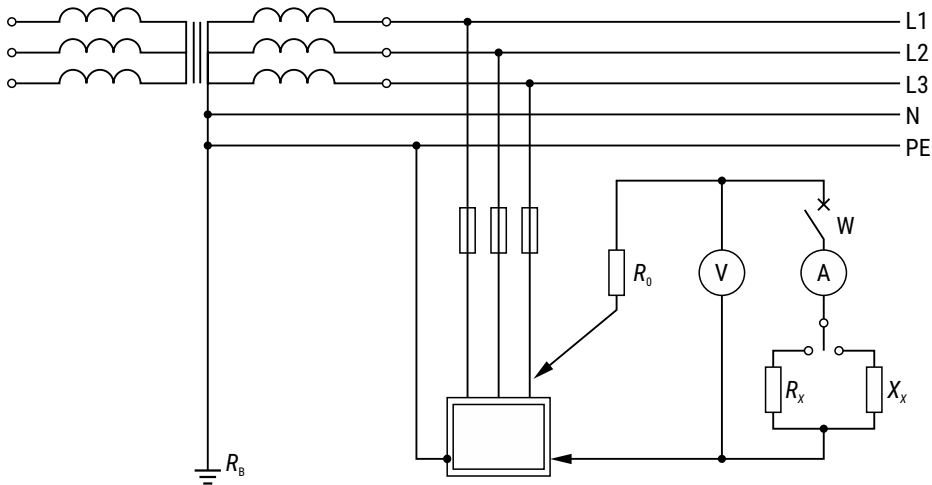$$Z_S \leq \sqrt{R_X^2 + X_X^2} \qquad (2.2)$$

FIGURE 2.2. Measurement of short circuit loop impedance by technical method [3]

When using this method in TN–C systems, there is a risk of dangerous contact voltage loads appearing on the conductive parts. It may occur as a result of a break in the PEN protective conductor.

The technical method of measuring short circuit loop impedance is currently used very rarely.

2. Measurement of short circuit loop impedance using voltage drop method

The circuit for measuring short circuit loop impedance by the voltage drop method (using the so-called "artificial fault") is shown in Figure 2.3. This is currently the most common way of defining the value of short circuit loop impedance.
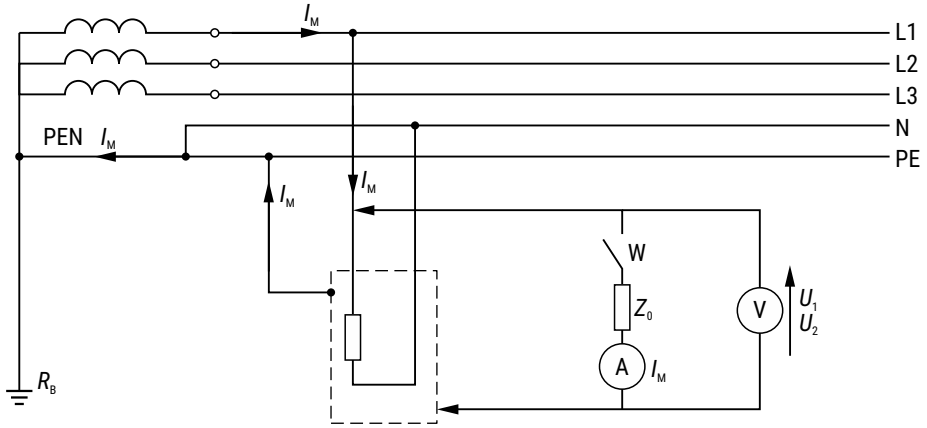
FIGURE 2.3. **Measurement of short circuit loop impedance by voltage drop method [3]**

In this method, short circuit loop impedance of the studied circuit is defined by switching on, for a short time, of the load with known impedance Z_0. Then the two voltage values should be measured: U_1 before the measuring load and U_2 – after switching on. The sought value of short circuit loop impedance Z could then be calculated by the formula:

$$\underline{Z} = \underline{Z}_0 \frac{\underline{U}_1 - \underline{U}_2}{\underline{U}_2} = \underline{Z}_0 \left(\frac{\underline{U}_1}{\underline{U}_2} - 1 \right) \tag{2.3}$$

where:
Z – measured impedance,
Z_0 – metering load impedance,
U_1 – voltage measured before switching on the metering load,
U_2 – voltage measured after switching on the metering load.

There are two basic ways to measure the searched values: direct and indirect.

The indirect measurement consists of two stages. In the first stage, using the resistive load, resistance of the investigated circuit is determined. In the second case, reactance of the circuit is determined using the reactance load. The main disadvantage of this method is the complexity of measurement as well as the large size of the measuring instruments, resulting from the release of a significant amount of heat in the resistance during the flow of the measuring current through it. An extension of this method of performing measurements is the use of a resistance-reactance load. The disadvantage of this type of solution is not only the weight and size of the device itself but also time-consuming measurements, resulting from the need to make at least three readings for different sets of *X/R* values.

The second group of short circuit loop impedance measurement methods includes methods based on a direct measurement of the difference or ratio of the voltage of a tested network in loaded and unloaded conditions. The first way to directly measure the impedance of a short circuit loop is that in one voltage period, the tested circuit is loaded with metering current, and in the next period, the system is without the load. Such measuring cycles are repeated several times, measuring the difference or ratio of the voltage in a loaded and unloaded measuring period, and the phase of the measuring current is adjusted to obtain the highest value of this difference (ratio). The disadvantage of this solution is primarily a step regulation, which introduces a variable measurement error, depending on the value of the measured impedance.

Another method of direct measurement of short circuit loop impedance is the way based on comparing the voltage between the phase wire and the protective wire, with the metering load being on or off. The value of the searched resistance or impedance of the circuit is obtained by dividing the maximum value of the voltage occurring in the system loaded with metering impedance during the one-half period to the peak value of the voltage occurring in the unloaded system measured during one or several half-periods.

Another method to directly measure short circuit loop impedance in low voltage electrical installations is to measure the voltage difference (or ratio) over two half-periods or entire periods of the testing system voltage in which the test circuit alternately loads or does not load the test circuit with the metering current. The measured voltage is saved in a metering system that detects the differences and maximum values of voltage occurring at a metering load or no metering load. The number of load cycles of the system should be selected during the measurement so that the measurement of short circuit loop resistance or impedance takes place within the allowable transient state limits.

The method of direct measurement of short circuit loop impedance, in which the measurement sensitivity to supply voltage distortion is limited consists of measuring, with the metering load being switched off, the values of instantaneous voltages at time t and $t+T/2i$ (where T is the period of supply voltage, and i – harmonic order), from which sums are made and which are the orthogonal component of the unloaded voltage. These operations are repeated as many times as much we want to eliminate harmonics.

To sum up, short-circuit loop impedance measurement systems known to date consist of a measuring load element composed of series-connected thyristor switch and load impedor, to which a measurement and control system element is connected in parallel. The measurement consists of determining the maximum difference (ratio) of voltages in unloaded conditions and under load with the metering current. However, a common disadvantage of such solutions is the uncertainty of measurement strictly dependent on the degree and type of the load occurring in the network and the complexity of the metering systems.

The New Method
for Measuring Short Circuit Loop Impedance

The method of metering the complex value of short circuit loop impedance proposed by the authors [4] is based on the measurement of the RMS value of the investigated network voltage, in which the studied system is loaded in one period, and in the second period, the investigated circuit is not loaded by the metering current. During the measurement, an impedor composed of three different known (from module and phase) impedances (Fig. 2.4) is connected to the studied system. The complex value of the sought short circuit impedance of the tested system is determined using a second-degree polynomial.
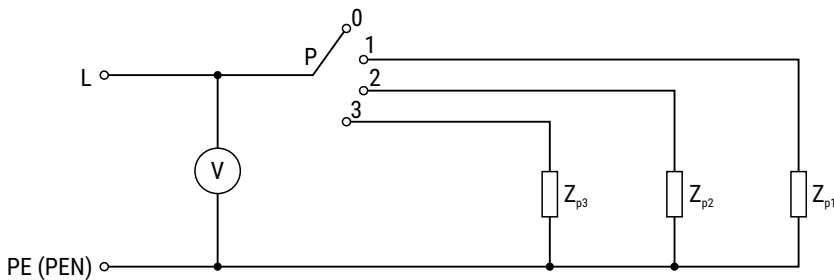

FIGURE 2.4. Scheme showing the idea of measuring short circuit loop impedance [4]

At the first moment of measurement, the RMS value of the low voltage E_{11} is measured over the full period, after which the first measuring branch with impedance Z_{p1} is switched on. After t_1 time has elapsed since switching on the first load impedance (where t_1 is the time of transient states resulting from switching on impedance), the first RMS value of voltage U_{p1} is measured for the full period. Then after the measuring time T (where T is the voltage period of the investigated system), the first impedance is switched off. After t_1 time, from switching off the measuring impedance, the RMS value of the low voltage network E_{12} is measured again. If $E_{12} \neq E_{11}$, the measurement is repeated from the beginning. If $E_{12} = E_{11}$, the RMS value of measuring voltage U_{p1} and the voltage of the network $E_1 = E_{12}$ is saved, and the second measuring branch, with impedance Z_{p2}, is switched on. After t_1 time, from the moment of switching on the second measuring impedance, the second RMS value of voltage U_{p2} is measured for the full period. The same applies to the remaining measuring branches. Based on the measured RMS values the of voltages of the tested network (E_1, E_2, E_3) and the RMS values of voltages (U_{p1}, U_{p2}, U_{p3}) obtained for individual measuring members, the modules of short circuit loop impedance Z_{si} are determined (where $i = 1, 2,$ and stands for the number of the metering branch).

$$\begin{cases} Z_{s1} = Z_{p1} \cdot \dfrac{E_1 - U_{p1}}{U_{p1}} \\[2ex] Z_{s2} = Z_{p2} \cdot \dfrac{E_2 - U_{p2}}{U_{p2}} \\[2ex] Z_{s3} = Z_{p3} \cdot \dfrac{E_3 - U_{p3}}{U_{p3}} \end{cases} \qquad (2.4)$$

The relationship of the value of the module of short circuit loop impedance (Z_{si}) as a function of the measuring impedance angle (ψ_{pi}) is approximated by a second-degree polynomial:

$$Z_{si}(\psi_{pi}) = a \cdot \psi_{pi}^2 + b \cdot \psi_{pi} + c \qquad (2.5)$$

Polynomial's coefficients (a, b, c) are determined based on phase angles values (ψ_{pi}) of metering impedances and calculated short circuit loop impedances (Z_{si}) for three measurement points, solving the following system of equations:

$$\begin{cases} a \cdot \psi_{p1}^2 + b \cdot \psi_{p1} + c = Z_{s1} \\ a \cdot \psi_{p2}^2 + b \cdot \psi_{p2} + c = Z_{s2} \\ a \cdot \psi_{p3}^2 + b \cdot \psi_{p3} + c = Z_{s3} \end{cases} \qquad (2.6)$$

By using the Cramer method to solve the system of equations (6), determinants of the matrix of system coefficients are obtained, and then the values of the polynomial's coefficients are determined.

The searched, the actual value of the short circuit loop impedance module (Z_s) of the investigated circuit is the maximum of function $Z_{si}(\psi_{pi})$:

$$Z_s = max\{Z_{si}(\psi_{pi})\} \qquad (2.7)$$

The argument (ψ_r) at which the maximum of function $Z_{si}(\psi_{pi})$ occurs is also the actual angle of short circuit loop impedance:

$$\psi_r = \frac{-b}{2a} \qquad (2.8)$$

The authentic value of the short circuit loop impedance module (Z_s) is determined based on the relationship:

$$Z_s = a \cdot \psi_r + b \cdot \psi_r + c \qquad (2.9)$$

Thus, the real complex value of short circuit loop impedance (Z_s) for the investigated low voltage circuit is:

$$\underline{Z}_s = Z_s \cdot e^{j\psi_r} = Z_s (\cos \psi_r + j \sin \psi_r) \qquad (2.10)$$

A system for measuring the complex value of short circuit loop impedance, in which the measuring terminals are connected to the input terminals, consisting of load impedance and a breaker, controlled by the central unit (built from the control, measuring and counting part). The factor of the measurement result, according to the invention, is characterized in that three input load elements are connected to the input terminals, in which the thyristor controlled switch is connected in series with the impedance. The input terminals are also connected in parallel to the main input of the central control-measuring-counting unit, whose control outputs are coupled with controlled switches and the measurement result display, which is also connected in parallel to the input terminals. The block diagram of the meter implementing the proposed method of metering the complex value of short circuit loop impedance is shown in Figure 2.5.
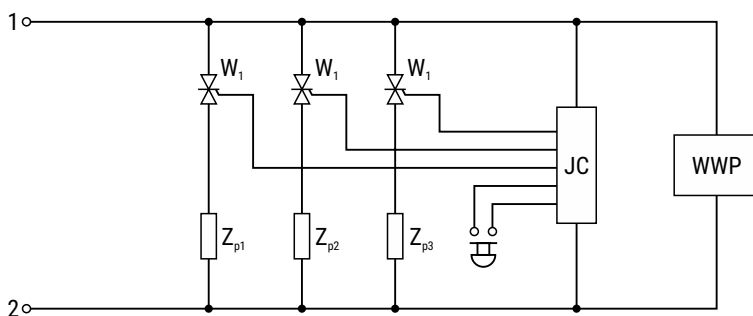

FIGURE 2.5. **Block diagram of the meter implementing the proposed method of measuring the complex value of short circuit loop impedance [4]**

Conclusions

Measuring short circuit loop impedance is necessary to determine the effectiveness of the protection against an electric shock by the self-acting power-off. There are two basic methods for determining it, i.e. the technical method (rarely seen today), and the voltage drop method (with direct or indirect measurement). The method proposed by the authors also belongs to the group of direct methods. The advantage of this method primarily involves the elimination of the influence of system operating loads on measurement accuracy. The simplicity of measurements is also important, as well as the fact that the complex value of short circuit loop impedance is determined based on measurements of RMS values of currents and voltages. Also, it is not required to maintain the same value of the modules of metering impedances.

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