1. Paweł LESZCZYŃSKI[1], 2. Tadeusz DASZCZYŃSKI[1], 3. Marcin SZEWCZYK[1]

Warsaw University of Technology, Electrical Power Engineering Institute, Division of Power Apparatus, Protection and Control
ORCID: 1. 0009-0009-0134-9152; 2. 0000-0002-6262-0286; 3. 0000-0003-3699-5559

doi:10.15199/48.2025.01.51

Implementability in the RLC classes of the peripheral current transformer model based on the measurements of its frequency characteristics

Abstract. *Along with the development of the power system, an increasingly important role is attached to its reliability and reducing installation costs, which is being observed to introduce intelligent transmission networks. They are aimed at reducing electricity consumption, ensuring safe transmission and distribution of this energy, and adapt to the demand of recipients, providing them with proper quality indicators. An indispensable element of such systems are current transformers, which are part of the measuring systems enabling monitoring of the power network and being an essential element of security systems. The most popular method of testing current transformers is the analytical and experimental method using the peripheral replacement model. The possibility of its use in various tests and simulations depends on the quality of the model as well as the correctness of the results obtained. The purpose of this article is to check the implementation of the peripheral model of the RLC class on the basis of measurements of its frequency characteristics. Work on these studies is to simplify the process of identifying the replacement circuit of the transformer and improve the quality of simulations carried out in a wide frequency band.*

Streszczenie. *Wraz z rozwojem systemu elektroenergetycznego coraz większą rolę przykłada się do jego niezawodności i redukowania kosztów instalacji, przez co obserwuje się trend do wprowadzania inteligentnych sieci przesyłowych. Mają one na celu ograniczenie zużycia energii elektrycznej, zapewnienie bezpiecznego przesyłu i rozdziału tej energii oraz dostosowanie się do zapotrzebowania odbiorców zapewniając im właściwe wskaźniki jakości. Niezbędnym elementem takich systemów są przekładniki prądowe, stanowiące część układów pomiarowych umożliwiających monitorowanie sieci elektroenergetycznej oraz będące zasadniczym elementem układów zabezpieczeniowych. Najpopularniejszą metodą badania przekładników prądowych jest metoda analityczno-doświadczalna wykorzystująca obwodowy model zastępczy. Od jakości modelu zależy możliwość jego zastosowania w różnego rodzaju badaniach i symulacjach oraz poprawność otrzymanych wyników. Celem niniejszej artykułu jest sprawdzenie realizowalności modelu obwodowego przekładnika w klasie RLC na podstawie pomiarów jego charakterystyki częstotliwościowej. Praca nad tymi badaniami ma uprościć proces identyfikacji obwodu zastępczego przekładnika oraz poprawić jakość przeprowadzanych symulacji w szerokim paśmie częstotliwości (**Implementowalność w klasach RLC modelu obwodowego przekładnika prądowego na podstawie pomiarów jego charakterystyk częstotliwościowych**).*

Keywords: current transformers (CT), vector fitting, equivalent circuit, frequency characteristics.
Słowa kluczowe: przekładnik prądowy, vector fitting, obwód zastępczy, charakterystyka częstotliwościowa.

Introduction

Current transformers enable the measurement of the main circuit tracker ensuring the galvanic insulation of the measuring circuit and reduce its value in proportion to the range of control. The patenting of the first transformer took place in the UK in 1882, in Poland the first transformers were produced in 1932 by the K. Szpotański Factory [1]. Intimnitled, problems with accuracy, transitional states as well as the impact of deformable primary signals on the value of measurement were not focused on. The first scientific articles about them began to appear.

Currently, many research groups focus on improving the quality and reliability of the device. As a result, unconventional constructions of transformers were also created, the principle of which often uses other physical phenomena (described in detail in [2-4]). However, induction transformers are most often used. A separate direction of research is also the work on the use of current transformers to predict the behaviour of the power grid, such as the occurrence of short-circuit states. Early detection of a short-circuit or high harmonic currents enables action to be taken to ensure system reliability and improve system quality.

The problem of modelling power transformers, current transformers or inductors is widely known. The biggest difficulty is to identify system correctly [5]. Models used in low-frequency applications are the most common in the literature [6-8]. Many of those digital models are intended for protective relay transient performance analysis.

One of the main problems in modelling was the appropriate consideration of the magnetic core and the physical effects caused by this core at different frequencies [9-12].

The problem considered in this paper is: based on the measurements of frequency characteristics and approximation of the obtained waveforms using the pole relocation method, it is possible to build a circuit model of the current transformer for the purpose of simulating its operation in eg short-circuit states. It should be noted that high-frequency modelling of current transformers is not only applicable to diagnostics. The construction of the model in a wide frequency spectrum also allows for the study of transient phenomena in the transformer, e.g. related to switching overvoltage, atmospheric discharges, insulation damage, nuclear explosions or resulting from the very principle of operation of the devices. These types of transients can be detrimental to the insulation system because the peak voltage at, for example, an overvoltage is much higher than the rated voltage of the device.

Determining mathematical models

The description of physical phenomena, objects and processes using mathematical models is an important element of research. The creation of models allows for better understanding of physical phenomena occurring in them, understanding the principles of action and the use of the created object to simulate its actions in conditions that very much achieved on a real object. These models are also brought to some simplification, especially when the phenomenon that interests us is too complex and its thorough analysis is impossible.

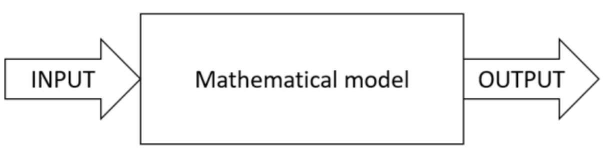

Fig. 1. Diagram of the mathematical model

Fig. 1 shows a diagram of the mathematical model. Relations between the output and input large -sized are described with mathematical functions, and the subject of the research is to identify these depends. They can be presented in the form of an equation, a system of diverse or with the help of a peripheral model consisting of basic passive elements. Many methods are used to designate mathematical models. The most common methods are:

1. The design of the balance circuit and its analysis,
2. The approximation of time characteristics,
3. The approximation of frequency characteristics.

Choosing one of them and a way to obtain the best result depending on the initial knowledge of the object and data obtained on the basis of its observation, measurement results. The first method is to analyse the object and present all phenomena with the help of mathematical equations. The more complicated the object or phenomenon, the harder it is to describe all dependent. However, in methods based on approximation, knowledge about the object is not necessary and the model is based primarily on measuring and observing its behaviour. Depending on the class of the object and its purpose, various tools can be used to construct models [13].

Often, Laplace transformers are used for descriptions of electrical or mechanical systems, whose application in many cases brings the problem of a differential equation to the problem of solid algebraic equation. In the case of electrical circuits, the ratio of Laplace transforms of the output signal to the Laplace transformation of the system input signal at zero initial conditions is presented as the operator transmittance (1).

(1) $$h(s) = \frac{Y(s)}{X(s)}$$

Depending on the input and output signals, four types of operator transmittants can be distinguished: voltage, current, voltage and current and current transmitting transmittance. Due to the measurement of the frequency characteristics of the transformer, it will be appropriate to use the operator impedance, which is characterized by the relationship between current intensity and voltage in alternating current circuits.

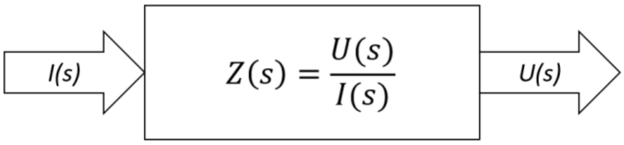

Fig. 2. Block diagram of the impedance operator function

The function shown in Fig. 2 determines the general properties of the linear system with one input and one output for any extortion. Thanks to the operator transmittance, it is possible to clearly describe the model of the examined object using a measurable function.

Basic models of current transformers

Basic one-phase model of current transformer can be seen as in Fig. 3. In this model primary elements and magnetic core resistance are ignored because they have only slight influence on behaviour, especially on 50 Hz [14]. At 50 Hz, eddy currents are usually neglected in transformer modelling. This is due to their negligible influence on the behaviour of the magnetic core at low frequencies. In principle, only the voltage drop and the electromotive force (emf) induced in the windings are taken into account. They are represented in circuit models by resistance *R* and inductance *L*.

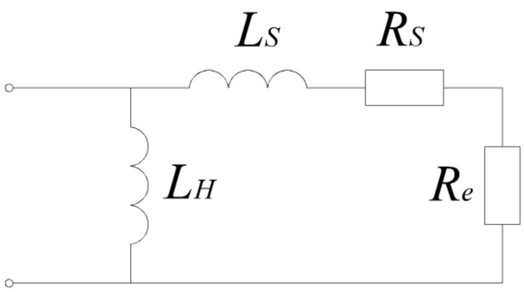

Fig. 3 One-phase model of current transformer

Modelling of the power system, and with it also transformers, basically has its beginnings with the construction of the first power lines at the end of the 19th century.

The bibliography on transformers and electrical machines was described by P. A. Abetti [15-17], starting his work in the 1950s. The literature collection of the publication includes 1265 items and it took the author almost 10 years to develop it (the first publication in 1958, the last one in 1964). The work of P. A. Abetti is a summary of the so-called I era of transformer modelling [18]. This era is associated primarily with the development of mathematical models and their physical interpretations. The second era, the beginning of which can be sought in the 1950s, is associated with the relatively widespread use of computers.

The first mathematical models of transformers began to appear at the end of the 1920s [19-21]. Complex substitute electrical circuits began to be used to solve insulation design problems. Basically, three solutions of transformer models [18] have been created, which are still being considered and improved:

1) Modelling windings as a power line.

2) Creating an equivalent electrical circuit with lumped parameters

3) Creating an equivalent electrical circuit with distributed parameters.

It is difficult to determine the "father" of modern transformer modelling, because the process of creating theories used in research or computer software is not a phenomenon that began suddenly. As early as 1919, L. F. Blume and A. Boyajian, in their publication [22], used an electrical circuit for modelling a transformer without resistance. They introduced the concept of distributed winding inductance and defined methods for determining this inductance. The presented idea was further developed by many scientists [23-25].

It is impossible to quote here all the publications and authors who contributed to the development of modern modelling. Nevertheless, the development of computer technology and software deserves special attention here. Since the 1960s, computing with computers has been solving theoretical problems with increasing speed and accuracy. The basic problem that scientists and developers of computer programs still face is the calculation of the inductance of systems with complex geometry. In fact, the most important and effective tool has become the Finite Element Method (FEM).

The main trends in computer modelling of power transformers for the purposes of transient state analysis can be classified as follows [18]:

1) Modelling based on self and mutual inductances
2) Modelling based on distributed inductances
3) Modelling based on the similarity of the description of magnetic and electric phenomena (principle of duality)
4) Modelling using a long line

5) Modelling based on measurement data (black-box modelling)
6) Modelling based on electromagnetic fields

Realability in RLC classes

A given immersion can be presented with a synthesis of passive doubles if it meets the conditions for the implementation in a given class of RLC elements. In order to check them, a substitute impedance should be presented in the form of a rational function (2).

$$h(s) \approx \frac{a_0+a_1s+a_2s^2+\dots+a_ns^n}{b_0+b_1s+b_2s^2+\dots+b_ns^n} \quad (2)$$

The described function (2) has real, positive AI coefficients, meter and denominator. The impedance determined by equation (2) is implemented in individual RLC classes if it meets the following conditions [26]:

<u>Realability in the class of RLC elements</u>

1. The coefficients of polynomials *L*(*s*) and *M*(*s*) are real and positive.
2. All zero and poles of immense are located in the left half-plane complex variable *s* or on the imaginary axis (in the last case single), and Residua in these poles is positive.
3. Degree *L*(*s*) and *M*(*s*) may vary a maximum of one.
4. For *Re*(*s*) ≥ 0 the condition is met *Re*[*Z*(*s*)] ≥ 0.

Laboratory setup

Figure 4 shows the current transformer used in the tests. It is a YHDC split-core low voltage transformer with a rated current of 20 A. Connected to the secondary terminals of the device, the built-in sampling resistor R_s enables the measurement of the voltage output signal in the range from 0 to 1 V, proportional to the primary current. Technical parameters of the transformer are presented in Table 1.

Fig. 4. Current transformer YHDC type SCT013

Table 1. Technical parameters of measured current transformer

Parameter	Value	Unit
Model	SCT013	---
Input current	0-20	A
Output type	0-1	V
Frequency range	50-1000	Hz
Core material	ferrite	---
Mechanical strength	the number of switching is not less than 1000 times(test at 25°C)	
Work temperature	-25°C～+70°C	

The HP 4192A LF impedance analyser was used to measure the frequency characteristics of the YHDC SCT013 current transformer. It is a device designed to measure eleven impedance parameters over a wide frequency range. The device measures, among others, resistance, reactance, phase shift and quality factor. The device has a communication interface GPIB enabling measurement control using a computer application, which was used to automate the measurement process in the MATLAB environment. The diagram of the measurement system is shown in Figure 5 and 6.

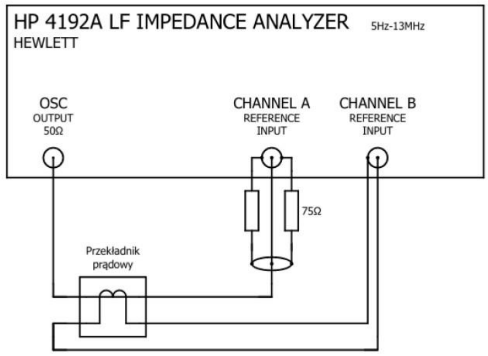

Fig. 5. The block diagram of a measurement system

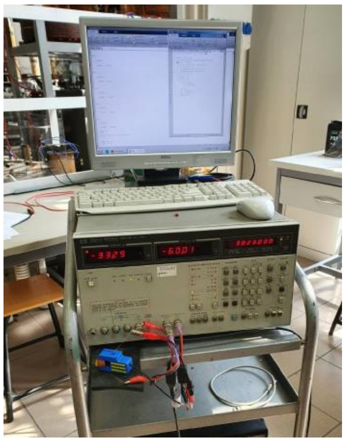

Fig. 6. The laboratory realization of block diagram of a measurement system

One terminal of the transformer's primary circuit was connected to the oscillating output of the analyzer, which generates a current signal of variable frequency. The second terminal is connected to channel A of the analyzer, where the value of the primary current is measured through the voltage across the terminating resistor. The second channel of the analyzer measures the voltage signal on the secondary side of the transformer.

Frequency response measurements

The measurement of the YHDC SCT013 transformer was carried out in the range from 10 Hz to 3 MHz. The developed results are presented in the Table 2.

Table 2. Measurements of YHDC SCT013 current transformer

Frequency [Hz]	Gain REAL	Gain IMAG	Gain MAGNITUDE [dB]	Phase
10	0,0741	0,0458	-21,2	0,5534
10,1271	0,0746	0,0454	-21,18	0,5468
10,2558	0,0751	0,0451	-21,15	0,5412
10,3862	0,0756	0,0448	-21,12	0,5353
…				
2982047,2090	0,0141	-0,0159	-33,45	-0,8454
3019951,7204	0,0190	-0,0174	-31,78	-0,7398

Figure 7 shows the obtained frequency characteristics of the current transformer YHDC type SCT013. The frequency is described on the abscissa axis, and the gain modulus on the ordinate axis, which corresponds to the current transformer impedance. It can be seen that in the operating range of the current transformer a constant gain value was obtained. Large changes appear for frequencies above 100 kHz where the system resonates.

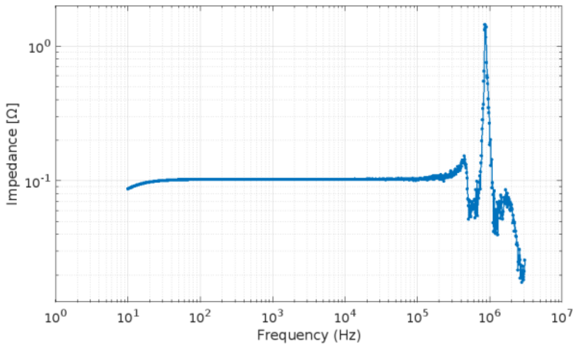

Fig. 7. Frequency characteristics of the current transformer YHDC type SCT013

Modelling of frequency characteristics

Linear systems with concentrated parameters can be modelled and identified on the basis of frequency response. In the frequency identification of the measured characteristics $h(j\omega)$ usually approximates by the rational function (2).

The function (2) is a nonlinear equation of the model parameters, so to create a linear equation type $Ax=b$ by multiplying both sides by denominator may lead to many errors [5].

Vector fitting method [27] has been found reliable and accurate for approximation of frequency characteristics different devices. Basically, this method takes some initial pole values, which are then improved in an iterative manner. This is achieved by repeatedly solving the linear problem until convergence is reached. The pole relocation method is formulated as an equation (3).

(3) $$h(s) \approx \sum_{m=1}^{N} \frac{r_m}{s-a_m} + d + sh$$

Unstable poles are shifted to the left half of the complex plane to make them stable. Thanks to this, the method is applicable to high-order systems and wide frequency bands. Vector fitting identifies rm poles, zeros am and d and h using the least squares method. The constants d and h take only real values and are optional for solving the equation. The poles are identified by solving a linear problem (4).

(4) $$\left(\sum_{m=1}^{N} \frac{\overline{r_m}}{s-\overline{a_m}} + 1\right) \cdot f(s) = \sum_{m=1}^{N} \frac{r_m}{s-a_m} + d + sh$$

where $\overline{a_m}$ are the set of initial poles. The poles are equal to the eigenvalue of the diagonal matrix A containing the elements $\{a_m\}$, so the zeros of $\sigma(s)$ are equal to $eig(A - br)$. The element b is a row vector containing the elements $\{r_m\}$, and b is a one column vector [28].

Thanks to the work on improving the pole relocation method, it was possible to eliminate the asymptoticity condition associated with the least squares method [29]. It is also proposed to take into account the time delay of the measurements in order to reduce the number of poles of the fitted function while maintaining the quality of the fitting [10]. In the MATLAB environment, the RF Toolbox extension is available, which contains an improved algorithm of the vector fitting method implemented (5).

(5) $$h(s) \approx \left(\sum_{i=1}^{N} \frac{c_j}{s-a_j} + D\right) e^{-s\cdot Delay}$$

Using the *rationalfit* function, it can use the basic form as well as with additional options providing better control over the efficiency and accuracy of the fit. In [30], the authors presented the influence of the number of poles on the quality of the match and the efficiency of the algorithm.

The *rationalfit* function takes two input arguments. The first one should be represented as a vector of length *M*, defining the frequency at which the function fits the object. The second element is the data to be fitted represented as a vector of complex numbers, the same magnitude as the frequency vector. Correctly entered data results in obtaining a solution to the equation in the form of vectors *A* and *C* containing, respectively, zeros and poles of the function and the constant *D*.

The result of fitting the VF approximation to the frequency response of the SCT013 current transformer is shown in Fig. 8. Good results were obtained for the number of matching poles equal to nine. The '*DelayFactor*' parameter was not used because it did not improve the approximation results. Vector fitting zeros and poles are shown in the Table 3.

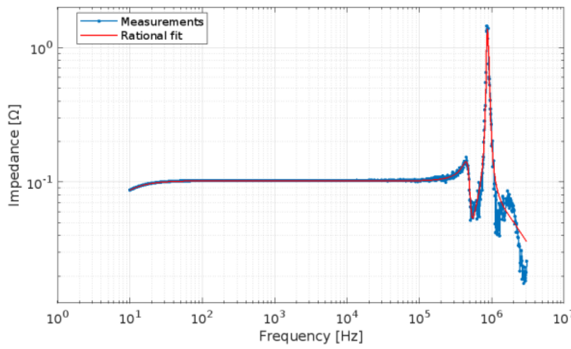

Fig. 8. Approximation of the frequency characteristic of the SCT013 CT for NPoles = 9.

Table 3. Calculated new zeros and poles of the SCT013 CT for NPoles = 9

No.	New POLE	New ZERO
1	$-8{,}8779 \cdot 10^6$	$5{,}5352 \cdot 10^5$
2	$(-0{,}2103 + 5{,}6177i) \cdot 10^6$	$(-0{,}3623 - 1{,}3941i) \cdot 10^5$
3	$(-0{,}2103 - 5{,}6177i) \cdot 10^6$	$(-0{,}3623 + 1{,}3941i) \cdot 10^5$
4	$(-0{,}1301 + 5{,}3423i) \cdot 10^6$	$(1{,}2928 + 0{,}7733i) \cdot 10^5$
5	$(-0{,}1301 - 5{,}3423i) \cdot 10^6$	$(1{,}2928 - 0{,}7733i) \cdot 10^5$
6	$(-0{,}3110 + 2{,}9434i) \cdot 10^6$	$(0{,}0129 - 0{,}2703i) \cdot 10^5$
7	$(-0{,}3110 + 2{,}9434i) \cdot 10^6$	$(0{,}0129 + 0{,}2703i) \cdot 10^5$
8	$-0{,}0157 \cdot 10^6$	$0{,}0001 \cdot 10^5$
9	-39,0295	-3,9790

Substituting the obtained results into the equivalent function (3), the form of the equivalent impedance Zeq was obtained, presented by the equation (5).

Construction and evaluation of the equivalent circuit model

According to the method of circuit synthesis described in [26], in the first step it is necessary to check whether the transmittance obtained on the basis of the approximation of the frequency characteristic of the current transformer (Table 3), is realizable in the class of RLC elements. For this purpose, the zeros and poles obtained as a result of the vector fitting method are shown in Figure 9 (Table 3).

Although all transfer function coefficients are real and positive, and the degree of the denominator and numerator differ by one, a given transfer function is not realizable in any class of RLC elements. This is due to the arrangement of zeros in the right half-plane of the complex variable *s*. For this reason, the conditions necessary to obtain the equivalent circuit are not met.

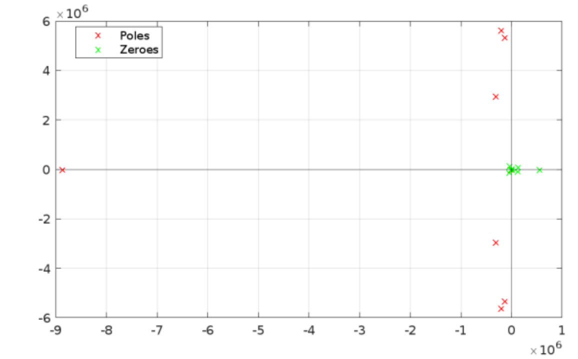

Fig. 9. Zeros and poles of the impedance of the SCT013 transformer shown on the complex plane.

The vector fitting method was used many times for different values of the parameters '*NPoles*', '*TendsToZero*', '*DelayFactor*'. Unfortunately, the obtained results also did not meet the criteria for presenting the equivalent transmittance in the form of a circuit model. An attempt was also made to approximate the measurements in a limited frequency range, in order to check whether the results of the fitting are affected by a wide frequency band. The range was selected so that the model included the first resonance peak. The results for the STC013 transformer are presented in the figures 10 and 11.

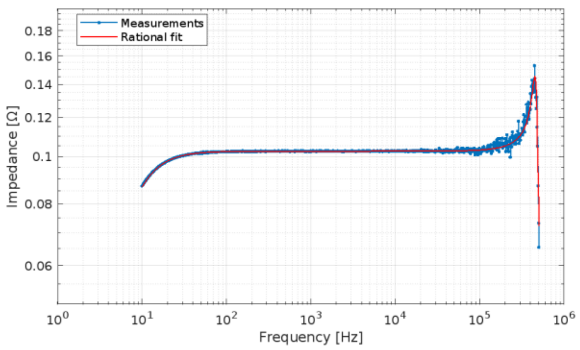

Fig. 10. Approximation of the SCT013 current transformer frequency characteristic for NPoles = 4 in a limited frequency range.

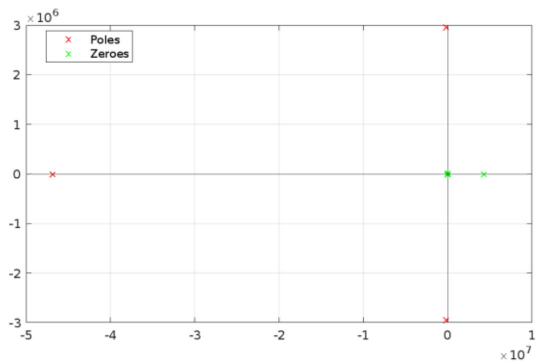

Fig. 11. Zeros and poles of the impedance of the SCT013 transformer shown on the complex plane.

The new zeros and poles calculated with the VF method are shown in the Table 4.

Table 4. Calculated new zeros and poles of the SCT013 CT for NPoles = 4

No.	New POLE	New ZERO
1	$-4{,}6854 \cdot 10^{7}$	$4{,}2492 \cdot 10^{6}$
2	$(-0{,}0216 + 0{,}2942i) \cdot 10^{7}$	$(0{,}0005 - 0{,}0175i) \cdot 10^{6}$
3	$(-0{,}0216 - 0{,}2942i) \cdot 10^{7}$	$(0{,}0005 + 0{,}0175i) \cdot 10^{6}$
4	-39,506	-3,9895

Even for a small frequency range, for which the characteristics can be approximated by two poles, the feasibility conditions do not meet the desired conditions. The results of the approximation are shown in the Fig. 12 and 13.

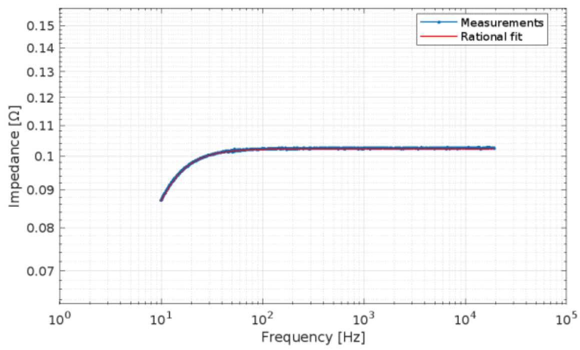

Fig. 12. Approximation of the SCT013 current transformer frequency characteristic for NPoles = 2 in a limited frequency range.

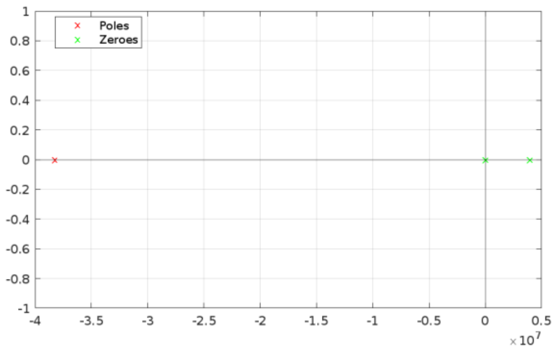

Fig. 13. Zeros and poles of the impedance of the SCT013 transformer shown on the complex plane.

Conclusions

As part of the work, an attempt was made to determine the equivalent model of the current transformer on the basis of measurements of its frequency characteristics. The characteristic was approximated by the vector fitting method, which resulted in an operator function with a comparable frequency response. Despite good approximation results, it was not possible to present the transfer function in the form of an equivalent circuit, because the obtained transfer functions did not meet the conditions of realizability in any of the classes of RLC elements. Subsequent approximation attempts with changed parameters of the vector fitting method did not significantly affect the results. The conducted research shows that the thesis put forward in the work, which reads as follows – "*Based on the measurements of frequency characteristics and approximation of the obtained waveforms using the pole relocation method, it is possible to build a circuit model of the current transformer for the purpose of simulating its operation in eg short-circuit states*", has not been achieved.

The research and considerations undertaken in the work do not exhaust the whole range of issues related to the modeling of equivalent circuits. Further development on the topic of creating models based on the approximation of frequency characteristics is possible, both in terms of modifying the vector fitting method, using another linear regression method or trying to adapt the results obtained in order to enable them to be presented using equivalent circuit.

***Authors**: mgr inż. Paweł Leszczyński, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: pawel.leszczynski.stud@pw.edu.pl; dr inż. Tadeusz Daszczyński, Instytut Elektroenergetyki, Zakład Aparatów i Automatyki Elektroenergetycznej, ul. Pożaryskiego 28, 00-662 Warszawa, E-mail:* tadeusz.daszczynski@pw.edu.pl; *dr hab. inż. Marcin Szewczyk, Instytut Elektroenergetyki, Zakład Aparatów i Automatyki Elektroenergetycznej, ul. Pożaryskiego 28, 00-662 Warszawa, E-mail:* marcin.szewczyk@pw.edu.pl

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