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OPEN ACCESS

DOI: 10.15199/48.2025.05.42

Steady state component of the short-circuit current in the electrical grid

Składowa ustalona i składowa przejściowa prądu zwarciowego w sieci elektroenergetycznej

***Abstract**. The paper presents the analysis and evaluation of the short-circuit currents in electrical power systems. The analytical and numerical results are presented. Two current components – steady state and transient component are singled out. The steady state current component is evaluated with the use of signals generated by static compensators.*

***Streszczenie.** Praca zawiera analizę i metody szacowania prądów zwarciowych w systemach elektroenergetycznych. Przedstawiono wyniki analityczne i numeryczne obliczeń dwóch składowych prądu zwarciowego – składowej ustalonej i składowej przejściowej. Opisano metodę oszacowania składowej ustalonej prądu zwarcia za pomocą sygnałów generowanych przez kompensatory statyczne.*

Keywords: short-circuit current, current evaluation, static compensators.
Słowa kluczowe: zwarcia w systemach elektroenergetycznych, estymacja prądu zwarcia, kompensatory statyczne

Introduction

Short-circuit currents are the most often observed faults observed in electrical power systems [1, 2]. The development of the short-circuit currents has a long history. Methods of such currents evaluation have been elaborated from the beginning of electrical grid development. The analysis of the numerical grid models is one of the important approach for short-circuit current evaluation [3]. The numerical models comprise whole electrical systems and should be permanently brought up to date. The short circuit analysis method for real-time distribution protection is presented in [4, 5]. Independently on numerical model analysis, the measurements of real system are performed. One of such methods is based on short time short-circuit execution [6]. It is the disturbance method. The reactive current injection, presented in this paper, also can be treated as the disturbance method.

The considerations presented in the paper concern the single phase models of electrical power systems. It means that the investigations are limited to the balanced three phase circuits and three phase short-circuit.

A particular case of short–circuit current can be observed in the place located between a generator and transformer. In such circumstances the short–circuit current contains non periodic component resulting from the change of magnetic flux while short circuit occurs [1, 2, 3]. Short circuit located close to a synchronous generator also is not considered in this paper.

Assuming that the circuit model representing the power grid is linear the short-circuit current is equal to the sum of two components – steady state component and transient component.

The analysis presented in this paper concerns a sinusoidal steady state component. The presented method consists in applying static compensators. The current generated by static compensator in injected to the grid in the place of the predicted short circuit. A static compensator (STATCOM) is a member of the flexible alternating current transmission system (FACTS) devices [7].

Steady state response

Steady state response is the sinusoidal function depending on voltage sources acting in the system. Each source has its share and this response does not depend on the time instant when short circuiting occurred.

As harmonic contents in the voltage and current is small the analysis can be based on the RMS value. The complex RMS value of the short-circuit current can be expressed as linear algebraic function of the voltage sources. The complex RMS values are denoted by capital letters U and I , vertical bars describe absolute values of these complex values, so $|U|$ and $|I|$ mean absolute values [10].

The multiport approach is chosen for grid analysis. Such multiport is shown in Fig. 1.

The multiport shown in Fig. 1 contains k ports with compensators connected and $l + c$ ports with independent voltage

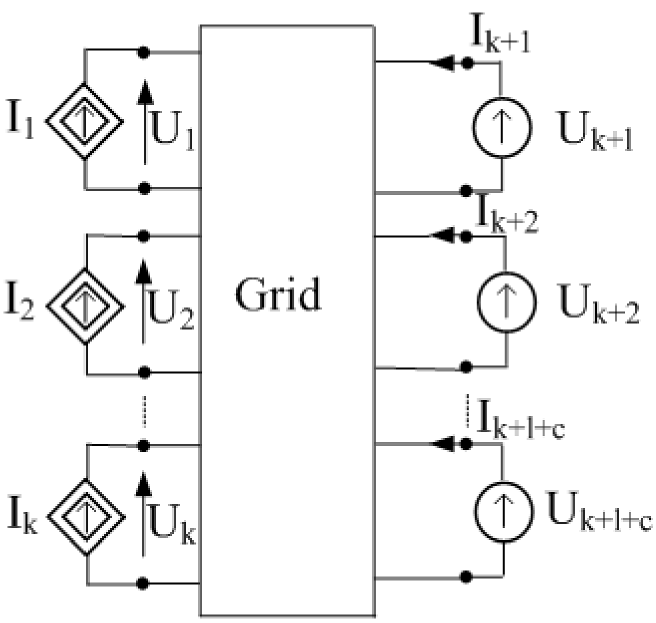

Fig. 1. Multiport grid model

source connected. Compensators are modelled by controlled current sources. Compensator currents $I_1,\ldots I_k$ are controlled by port voltages. The gains of these controlled current sources are the imaginary numbers [8]. The controlled current sources with gains equal to zero are equivalent to open circuit port. It means that only one or a few port from the set ports are connected to compensators the rest of ports are open-circuited.

It is assumed that the grid comprised in the box does not contain sources, all sources are removed outside the box and connected to the port terminals. The circuit is linear and considered in the steady sinusoidal state. For such assumption the ($k + l + c$) – port is reciprocal. It can be described by hybrid equation

$$Y = HX \quad (1)$$

where

$$\mathbf{X} = \left[I_1, I_2, ..., I_k, U_{k+1}, U_{k+2}, ..., U_{k+l+c}\right]^T \quad (2)$$

$$\mathbf{Y} = \left[U_1, U_2, ..., U_k, I_{k+1}, I_{k+2}, ..., I_{k+l+c}\right]^T \quad (3)$$

Elements h_{mj} of square matrix **H** for $m = 1, 2, ..., k + l + c$ and $j = 1, 2, ..., k + l + c$ are complex numbers equal to open--circuit or short-circuit impedances or admittances

$h_{mj} = \dfrac{Y_{mj}}{X_j}$ and $X_r = 0$ for $r \neq j, j = 1, 2, ..., k + l + c$ and $m = 1, 2, ..., k + l + c$.

For the multiport given in Fig. 1 equation (1) can be written as two equations

$$\mathbf{U}_{com} = \mathbf{H}_{cc}\mathbf{I}_{com} + \mathbf{H}_{cg}\mathbf{U}_g \quad (4)$$

$$\mathbf{I}_g = \mathbf{H}_{oc}\mathbf{I}_{com} + \mathbf{H}_{og}\mathbf{U}_g \quad (5)$$

where $\mathbf{U}_{com} = \left[U_1, ..., U_k\right]'$, $\mathbf{I}_{com} = \left[I_1, ..., I_k\right]'$, $\mathbf{U}_g = \left[U_{k+1}, ..., U_{k+l+c}\right]'$, $\mathbf{I}_g = \left[I_{k+1}, ..., I_{k+l+c}\right]'$,

Compensator currents $\mathbf{I}_{com}$ depend on compensator voltages $\mathbf{U}_{com}$

$$\mathbf{I}_{com} = j\mathbf{b}_d\mathbf{U}_{com} \quad (6)$$

where $\mathbf{b}_d$ is diagonal matrix formed of compensator gains

$$\mathbf{b}_d = diag[b_1, b_2, ..., b_k] \quad (7)$$

Putting right side of (6) into (4) gives

$$(\mathbf{d} - j\mathbf{H}_{cc}\mathbf{b}_d)\mathbf{U}_{com} = \mathbf{H}_{cg}\mathbf{U}_g \quad (8)$$

where square unit matrix

$$\mathbf{d} = diag[1, ..., 1] \quad (9)$$

From (8) voltages at the compensator ports

$$\mathbf{U}_{com} = \mathbf{b}_{cc}^{-1}\mathbf{H}_{cg}\mathbf{U}_g \quad (10)$$

where

$$\mathbf{b}_{cc} = \mathbf{d} - j\mathbf{H}_{cc}\mathbf{b}_d \quad (11)$$

Compensator currents can be computed from (6).

Let the attention be focused on the m-th port belonging to the compensator set of ports $(1, 2, ..., k)$. According to the general form (1) the voltage of m-th port for $m = 1, 2, ..., k$ can be written as

$$U_m = h_{m1}I_1 +, ..., h_{mm}I_m +, ..., h_{mk}I_k + G_m \quad (12)$$

where component depending on generator voltages is

$$G_m = h_{m,k+1}U_{k+1} + h_{m,k+2}U_{k+2} + ... + h_{m,k+c}U_{k+c} \quad (13)$$

Compensator currents depend on compensator gains jb, hence (12) can be written as

$$U_m = h_{m1}jb_1U_1 + ... + h_{mm}jb_mU_m + ... + h_{mk}jb_kU_k + G_m \quad (14)$$

Voltage component G_m constitutes the projection of the generator voltages at port m , it is Thevenin substitute voltage. The remaining part of voltage U_m is caused by compensator currents.

Let voltage U_m be measured for two values of the m-th compensator gains $b_m = b_{mo}$ and $b_m = b_{mz}$. The gains of the remained compensators should be equal to zero. For such conditions two equations issue from (14)

$$U_{mo} = h_{mm}jb_{mo}U_{mo} + G_m \quad (15)$$

$$U_{mz} = h_{mm}jb_{mz}U_{mz} + G_m \quad (16)$$

From (15) and (16)

$$h_{mm} = \frac{U_{mo} - U_{mz}}{j(b_{mo}U_{mo} - b_{mz}U_{mz})} \quad \text{for } m = 1, 2, ..., k \quad (17)$$

Parameter h_{mm} is equal to Thevenin substitute impedance.

Voltages of the other ports n , $n = 1, 2, ..., k$ $n \neq m$ also can be obtained from (4) for gain values $b_m = b_{mo}$ and $b_m = b_{mz}$

$$U_{no} = h_{nm}jb_{mo}U_{mo} + G_n \quad (18)$$

$$U_{nz} = h_{nm}jb_{mz}U_{mz} + G_n \quad (19)$$

From (9) and (10)

$$h_{nm} = \frac{U_{no} - U_{nz}}{j(b_{mo}U_{mo} - b_{mz}U_{mz})} \quad (20)$$

Formula (20) gives opportunity to estimate parameter h_{nm} using compensator connected to port *m.*

For reciprocal multiport

$$h_{mn} = h_{nm} \tag{21}$$

Projection of the generator voltages on *m*-th port also can be obtained from (12)

$$G_m = U_m - (h_{m1} jb_1 U_1 + ... + h_{mm} jb_m U_m + ... + h_{mk} jb_k U_k) \tag{22}$$

Particularly, if all compensator gains are equal to zero, then

$$G_m = U_m \tag{23}$$

As parameter h_{mm} is computed according to (17) and voltage G_m computed according to (22) it is possible to compute short-circuit current for port *m*. Let port *m* be short-circuited, then $U_m = 0$ and current of this port I_{ms} can be computed from (14). This equation takes the form $h_{m1} jb_1 U_1 + ... + h_{mm} I_{mz} + ... + h_{mk} jb_k U_k + G_m = 0$ Short circuit current at port *m* is

$$I_{mz} = -\frac{1}{h_{mm}} (jb_1 U_1 + ... + h_{mk} jb_k U_k + G_m) \tag{24}$$

Assuming, that all compensators are switched off and port *m* is short circuited, we obtain

$$I_{mz} = -\frac{1}{h_{mm}} G_m \tag{25}$$

where h_{mm} and G_m are given in (17) and (23), respectively. G_m is Thevenin voltage of port m.

In the next sections the detail investigation are presented for particular case of multiport $k = 2$, $l = 2$, $c = 0$.

Steady state response – numerical example

The 4-port shown in Fig. 2 is considered. The circuit contains 2 ports with compensators connected and 2 ports with connected generators. It means, that for general multiport shown in Fig. 1 we take *k* = 2, *l* = 2 , *c* = 0 .

For the considered circuit the matrix representation proposed in (4) and (5) is as follows

$$\mathbf{U}_{com} = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix}, \ \mathbf{U}_g = \begin{bmatrix} U_3 \\ U_4 \end{bmatrix}, \ \mathbf{I}_{com} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \ \mathbf{I}_g = \begin{bmatrix} I_3 \\ I_4 \end{bmatrix} \tag{26}$$

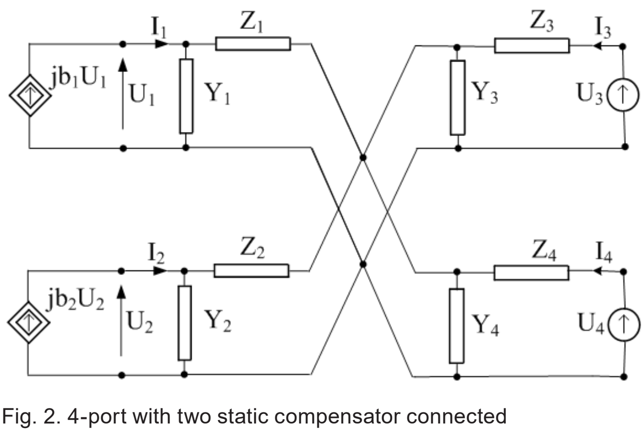

Fig. 2. 4-port with two static compensator connected

As the topology of the circuit constituting the 4-port is given, the elements of the hybrid matrix can be obtained in symbolic form. For example, element h_{11} can be obtained from circuit shown in Fig. 3, obtained from circuit given in Fig. 2 by removing all sources except the first.

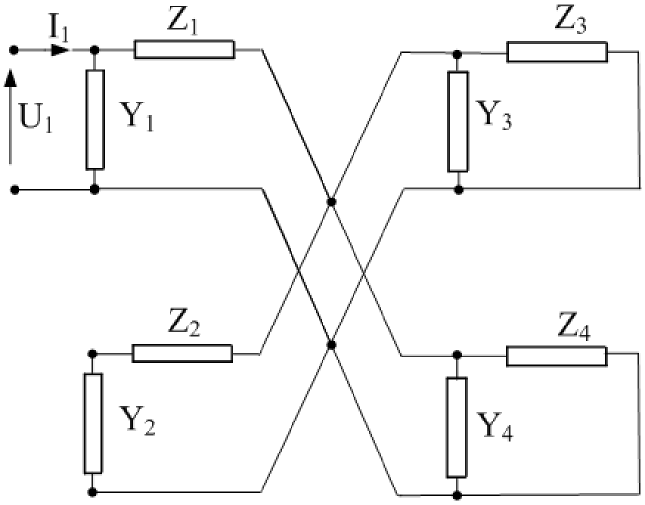

Fig. 3. Circuit for element h_{11} deriving

Let current $I_1 = 1$, voltage U_1 can be derived in symbolic form. As $U_1 = h_{11} I_1$ the obtained voltage is equal to parameter h_{11}

$$h_{11} = \cfrac{1}{Y_1 + \cfrac{1}{Z_1 + \cfrac{1}{Y_{22} + Y_{3344}}}}$$

where

$$Y_{22} = \cfrac{1}{Z_2 + \cfrac{1}{Y_2}}$$

and

$$Y_{3344} = Y_3 + \frac{1}{Z_3} + Y_4 + \frac{1}{Z_4}$$

In similar way the remaining fifteen elements of hybrid matrix $\mathbf{H}$ can be derived.

Let numerical values of the impedances and admittances of the circuit shown in Fig. 2 be given as follows.

$Z_1 = 0.1000 + j0.6280$, $Y_1 = 0.1000 - j0.0003$,

$Z_2 = 0.2000 + j0.6280$, $Y_2 = 0.4000 - j0.0999$,

$Z_3 = 0.0500 + j0.3140$, $Y_3 = 0.0999 - j0.0031$,

$Z_4 = 0.2000 + j1.2560$, $Y_4 = 0.0999 - j0.0031$

Impedances and admittances are nominated in Ω and 1/Ω, respectively.

For such chosen parameters of the 4-port shown in Fig. 2 hybrid matrix has the following numerical representation

$$\mathbf{H} = \begin{bmatrix} 0.2398 + j0.827 & -0.1157 - j0.5938 & 0.7357 - j0.1704 & 0.1839 - j0.0426 \\ -0.1157 - j0.5938 & 0.5011 + j0.6730 & 0.6611 - j0.3001 & 0.1653 - j0.0750 \\ -0.7357 + j0.1704 & -0.6611 + j0.3001 & 0.5131 - j0.7022 & 0.0046 + j0.6010 \\ -0.1839 + j0.0426 & -0.1653 + j0.0750 & 0.0046 + j0.6010 & 0.1248 - j0.6263 \end{bmatrix}$$

The 4-port shown in Fig. 4 is reciprocal, therefore matrix **H** is composed of symmetrical or skew symmetrical blocks. It is assumed, that matrix $\mathbf{H}$ is treated as unknown and its elements h_{11} and h_{22} should be estimated. Independent voltage sources seen in Fig. 2 were taken as follows $U_3 = 230$V, $U_4 = 230e^{-j0.1}$V.

Two compensators are connected to port 1 and 2. Voltages at compensators ports are measured. The complex values of these voltages should be recognized. Equation (17) is used in order to compute elements h_{11} and h_{22}. Numerical experiments are done for three values of compensator gains $\mathbf{b}_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $\mathbf{b}_1 = \begin{bmatrix} 0.05 \\ 0 \end{bmatrix}$, $\mathbf{b}_2 = \begin{bmatrix} 0 \\ 0.05 \end{bmatrix}$.

For $\mathbf{b} = \mathbf{b}_0$ voltages U_{10} and U_{20} are computed

$U_{10} = (210.31 - j53.18)$ V and $U_{20} = (188.14 - j89.98)$ V.

Voltages U_{11} and U_{21} are computed for $\mathbf{b} = \mathbf{b}_1$ and $\mathbf{b} = \mathbf{b}_2$, respectively, $U_{11} = (202.52 - j48.73)$ V, $U_{21} = (184.02 - j82.59)$ V. These voltages are computed from (10). Finely hybrid elements h_{11} and h_{22} computed

according to (17) are $h_{11} = (0.2398 + j0.8270)\Omega$ and $h_{22} = (0.5011 + j0.6730)\Omega$. These recognized impedances are equal to these seen in matrix $\mathbf{H}$.

As impedances h_{11} and h_{22} are recognized the short circuit currents I_{1z} and I_{2z} at port 1 and 2 can be computed from (25). Equivalent Thevenin voltages G_m for $m=1$ and $m=2$ are equal to voltages U_{10} and U_{20} measured for $\mathbf{b} = \mathbf{b}_0$. So, $I_{1z} = \dfrac{U_{10}}{h_{11}}$ and $I_{2z} = \dfrac{U_{20}}{h_{22}}$. Hence, $I_{1z} = (-8.70 + j251,79)$ and $I_{2z} = (-47.89 + j243.88)$.

The short-circuit currents influence on the source currents. Let us consider the equation determining current I_3 of voltage source U_3

$$I_3 = h_{31}I_1 + h_{32}I_2 + h_{33}U_3 + h_{34}U_4 \tag{27}$$

Two states of compensator gains should be analysed $\mathbf{b}_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$ and $\mathbf{b}_1 = \begin{bmatrix} b_{11} \\ 0 \end{bmatrix}$.

For state $\mathbf{b}_0$ we have

$$I_{30} = h_{33}U_3 + h_{34}U_4 \tag{28}$$

Current I_{30} should be measured in the real system. For state $\mathbf{b}_1$, we have

$$I_{31} = h_{31} j b_{11} U_{11} + I_{30} \tag{29}$$

Current I_{31} and voltage U_{11} should be measured in the real system. From (29), we obtain

$$h_{31} = \frac{I_{31} - I_{30}}{j b_{11} U_{11}} \tag{30}$$

If parameter h_{31} is estimated and short-circuit current at port 1' is estimated then the current of source U_3 at port 3' also can be estimated according to (27). Let port 1' be short-circuited with its current I_{1z} equal to (25) and let additionally port 2" be open ($I_2 = 0$), then from (28), we have

$$I_{3z} = h_{31}I_{1z} + I_{30} \tag{31}$$

This formula gives the estimation of the current drawing from voltage source U_3 while port 1' is short circuited.

Two-dimension control signal, simulation results

Phasor measurement plays important role in localizing faults in distribution networks [9]. The simulation of the circuit shown in Fig. 2, presented in this section, is achieved with the use of the PLECS program. This program does not exploit complex numbers. In order to avoid complex numbers the expressions (17), (20) and (26) achieved for phasors should be rearranged. The control signals contain two components – amplitude and phase. The simulations presented below were done for the 4-port shown in Fig. 2. The voltage of the source U_3 is chosen as the reference signal. It is assumed that initial phase of the cosine function describing the voltage of source U_3 is equal to zero. The phases of the remaining sinusoidal voltages and currents refer to the source voltage connected to port 3'. In order to estimate short circuit current at port 1' the hybrid element h_{11} should be computed. Two measurements should be done. Voltage U_{10} should be measured while compensator current $I_{10} = 0$ and voltage U_{11} should be measured while $I_{11} \neq 0$. The first measurement means that compensator gain $b_{10} = 0$; the second measurement should be done for optionally chosen $b_{11} \neq 0$. The second compensator connected to port 2' should have zero current. Element h_{11} as the complex number has real and imaginary parts

$$h_{11} = h_{11r} + jh_{11i} \tag{32}$$

The real and imaginary parts can be expressed by using the formula given in (17)

$$h_{11r} = \frac{U_{10a}}{U_{11a} b_{11}} \sin(U_{10p} - U_{11p}) \tag{33}$$

$$h_{11i} = \frac{1}{b_{11}} \left(1 - \frac{U_{10a}}{U_{11a} b_{11}} \cos(U_{10p} - U_{11p})\right) \tag{34}$$

Subscript a means the amplitude of voltage U, subscript p means the initial phase of voltage U. Subscript 10 means port 1 state 0, subscript 11 means port 1 state 1.The initial phases of all circuit voltages refer to the initial phase of source voltage U_3, for wich the initial phase was put equale to 0. Absolute value and angele of parameter h_{11} are as follows

$$h_{11a} = \sqrt{h_{11r}^2 + h_{11i}^2} \tag{35}$$

$$h_{11p} = \arctan\left(\frac{h_{11i}}{h_{11r}}\right) \tag{36}$$

Using such notations the amplitude and phase of short-circuit current according to (25) can be written as

$$I_{1za} = \frac{U_{10a}}{h_{11a}} \tag{37}$$

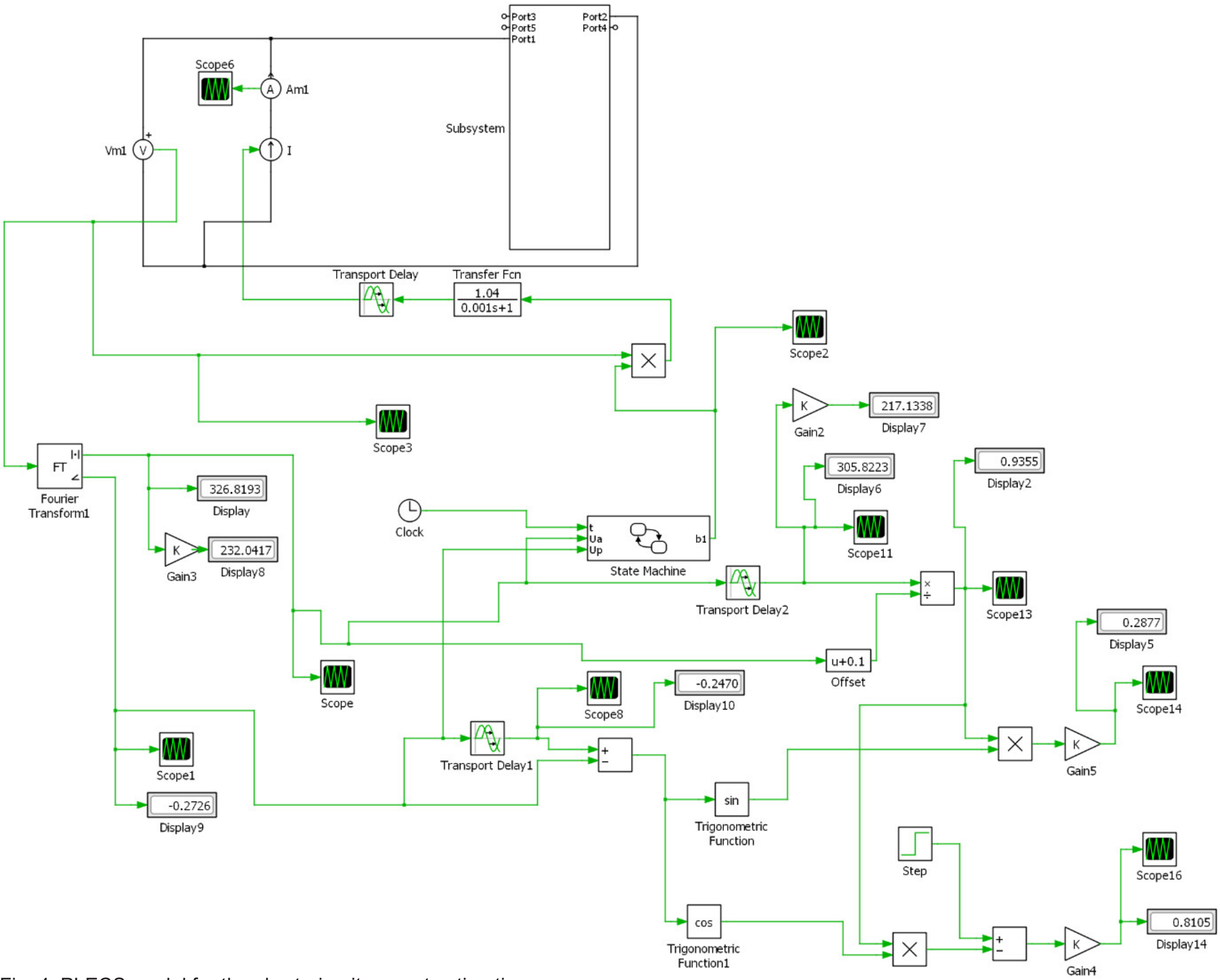

Fig. 4. PLECS model for the short-circuit current estimation

$$I_{1zp} = U_{10p} - h_{11p} \tag{38}$$

The PLECS model elaborated for short-circuit current estimation is shown in Fig. 4.

The circuit shown in Fig. 5 has the structure identical to this shown in Fig. 2. Also resistances, inductances and capacitance have the same values as these used for hybrid matrix $\mathbf{H}$ computation. Two independent voltage sources also have similar waveforms as those considered in Fig. 3,

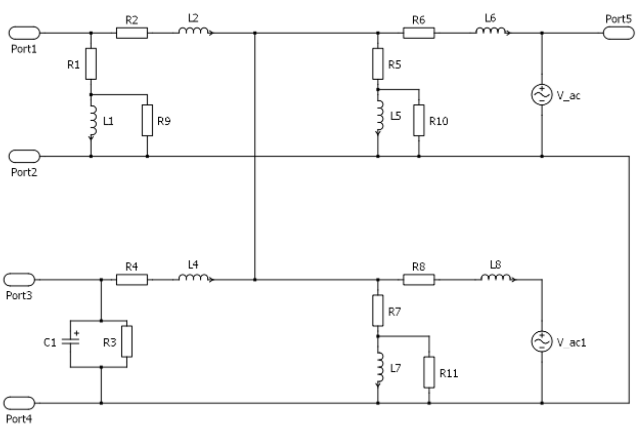

Fig. 5. Electrical circuit comprised in Subsystem of the PLECS model shown in Fig. 4

$$V_{ac} = \sqrt{2}325\sin(314 + \pi/2),$$

$$V_{ac1} = \sqrt{2}325\sin(314 + \pi/2 - 0.1).$$

The initial phases of the *sin* functions are taken $\pi/2$ in order behave the compatibility with Fourier transform used in simulation.

Controlled current source is connected to Port1. This source represents the compensator. Only one compensator is connected to the grid. The second port is open. Port 5 seen in Fig. 5 enables the access to the voltage source, it has not been used in the presented simulation.

State machine is the usephool blocs for the simulation of the switched control systems [8]. State Machine shown in Fig. 6 forces two compensator gains $b_1 = 0$ and $b_1 = 0.08$ as shown in Fig. 7a. The nonzero value i chosen optionaly. The biger gain forces biger compensator current. As the result the bigger voltage changes are obtained and the system parameter identificatiom is more precise.

State machine shown in Fig. 6 forces two values of the compensator gain $b_1 = 0$ and $b_1 = 0.08$, the change happens at $t = 0.3$ s.

Figs. 7 shows the waveforms in the grid while compensator current is injected to the system.

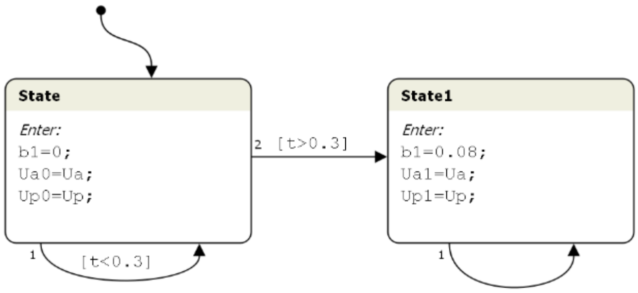

Fig. 6. State machine

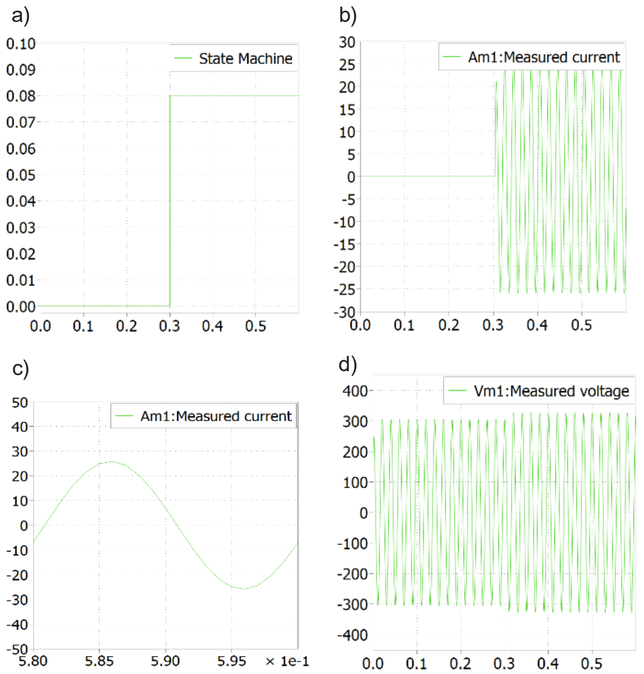

Fig. 7. Grid waveforms a) Compensator gain, b) Compensator current, c) Compensator current within single period, d) Port voltage.

Table 1 contains the estimation results obtained by three approaches. The first table row presents the solution of the available algebraic equations describing the circuit. The second table row presents the estimation results obtained from algebraic model when voltage of one grid port is available. The results placed in the third table row were obtained from the instantaneous values by application of the moving Fourier transformation. The first table column contains the identification results of hybrid matrix element which is equivalent to Thevenin impedance for port 1' The second column contains complex RMS values of the voltage at the open-circuit port 1'. The third column presents predicted short-circuit current at port 1'.

Table 1. Comparison of the estimation methods

	h_{11} [Ω]	[V]	I_{1z} [A]
Algebraic solution	0.2398+j0.8	$216.9334e^{-j0.2477}$	$251.9403e^{j1.6053}$
Algebraic estimation	0.2398+j0.8	$216.9334e^{-j0.2477}$	$251.9403e^{j1.6053}$
Signal estimation	0.2878+j0.8	$217.1338e^{-j0.2470}$	$252.4574e^{j1.6650}$

The results are valid for sinusoidal state. It means that only steady state component of the short-circuit current is considered. The complete solution should contain also transient component. The sum of steady state response and transient response gives the short-circuit current waveform.

Conclusions

Assuming that the circuit model representing the power grid is linear the short-circuit current is equal to the sum of two components – steady state component and transient component. Steady state response is the sinusoidal function depending on voltage sources acting in the system. Each source has its share and this response does not depend on the time instant when short circuiting occurred. The steady state component can be computed using symbolic complex numbers method.

The transient component has different nature. It depends on the time instant when short circuit arises, it depends on the initial phase of this switching.

Steady state component of the short circuit current can be evaluated with the static compensator aid.

Compensator connected to the chosen grid ports can inject desired reactive currents. The current injected to the port causes the voltage variation at this port. The measurement of the voltage at such port brings sufficient data for the evaluation of the input impedance and the steady state component of the short-circuit current. There is no need to measure the compensator current, compensator current is substituted by compensator gain. The voltage if further processed with the use of moving Fourier transformation. Two variables – amplitude and phase of the fundamental harmonic are processed in the real time. The phase is equal the angle shift between the phase of the measured port voltage and the phase of the chosen reference voltage source. Such signals obtained for two values of the compensator gain make possible to identify the grid impedance at considered port and to predict the steady state component of the short-circuit current.

The transient component is not predicted within the presented procedure. Transient component depends on time instant of the short-circuit occurrence. These components are no periodical, they are time decaying.

The analytical and numerical results presented in the paper were obtained for the circuit models of the electrical grid. Generators are modelled by the independent voltage sources. Consumers and lines are substituted by RLC circuit elements. Such approximation is far from real power system. In real systems electrical motors dominate among energy is very rough.

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