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Novel dependencies of currents and voltages in power system steady state mode on regulable parameters of three-phase systems symmetrization

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ABSTRACT

The unbalanced mode, negative/zero sequence, variation of real power are caused by the nonlinear or unbalanced loads increase the power transmission losses in distributing power systems and also harmful to the electric devices. Reactive power compensation is considered as the common methods for overcoming asymmetry. The critical issue in reactive power compensation is the optimal calculation of compensation values that is extremely difficult in complex circuits. We proposed a novel approach to overcome these difficulties by providing the creation of new analytical connections of the steady-state mode parameters (voltages, currents) depends on the controlled parameter for the arbitrary circuits. The base of our approach to reactive power compensation is the fractional-polynomial functions. We present a new description of the behavior of voltages and currents depending on the controlled parameters of the reactive power compensation devices, and we prove its effectiveness.

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1. INTRODUCTION

The increase in the use of nonlinear devices and the unbalance of consumption, in general, are the causes of asymmetric operating modes in the power supply system. These devices cause damage to the system, electrical equipment, and energy losse. Consequently, overcoming asymmetry, which can be accomplished with many methods, always occupies an important place in the study of it. There are several general and popular methods such as redistribution of loads at phases, the use of reactive power generators or special transformers, the use of equipment static reactive power (FACTS [1-10]. One of the most important issues of these methods is the optimal calculation of compensating values. And in general, this calculation is infinitely complex. It can be lead to the limitation of describing the relationship between steady-state mode parameters and the regulable parameters of the compensators. In this paper, we propose a novel approach to overcome that difficulty for methods using static compensation devices and it could also be extended to the methods by which it uses the Synchronous generators. Because, in principle, synchronous compensation generators can generate or absorb reactive power and within a certain limit, it can be converted to the equivalent of static-compensating devices [11].

This problem can be solve by providing a link between the parameters of the steady-state mode and the control parameters of the compensator. The relationship is described by the fractional-polynomial function, which describes the variation of voltages and currents according to regulable parameters [12-21]. In Section II, we will present the problem that is the answer to how to get the function, as mentioned earlier, along with the comparison of its precision through an example. In Section III, we will present some results that have been made for optimizing the electrical system of a glass factory that operates in the asymmetric mode.

2. FRACTIONAL-POLYNOMIAL FUNCTIONS

2.1. Node voltages method

We consider a three-phase circuit consisting of *(n+1)* nodes and *m (n+1 < m)* so we have the matrix

$\mathbf{A} =$

	1	2		m
1	a_{11}	a_{12}	…	a_{1m}
2	a_{21}	a_{22}	…	a_{2m}
…	…	…	…	…
n	a_{n1}	a_{n2}	…	a_{nm}

where $a_{ij} = 1; i = 1 \div n; j = 1 \div m;$

node; $a_{ij} = -1$ – enters; $a_{ij} = 0$

Vector of the conductance of the branches is

$\mathbf{Y} = \mathrm{diag}(Y_1, Y_2, \ldots Y_m)$

Vectors current and electromotive force sources are give as

$\mathbf{J} = (J_1, J_2, \ldots J_m)^t$.

$\mathbf{E} = (E_1, E_2, \ldots E_m)^t$.

The node voltage equations are formulated as in [4, 5]

$$\mathbf{AYA}^t\mathbf{U}_0 = -(\mathbf{J} + \mathbf{YE}) \tag{1}$$

where $\mathbf{U}_0 = (U_1, U_2, \ldots U_n)^t$ – vector of the node voltages.

Here $\mathbf{AYA}^t = \mathbf{B}$ is the matrix of the aggregate conductance, then the vector equivalent current sources $\mathbf{J} + \mathbf{YE} = \mathbf{C}$ can be rewritten as the following

$B =$

	1	…	i	…	n
1	$B_{1,1}$	…	$B_{1,i}$	…	$B_{1,n}$
…	…	…	…	…	…
i	$B_{i,1}$	…	$B_{i,i}$	…	$B_{i,n}$
…	…	…	…	…	…
n	$B_{n,1}$	…	$B_{n,i}$	…	$B_{n,n}$

and $\mathbf{C} = (C_1, \ldots, C_i, \ldots, C_n)^t$

where $i, j, k = 1 \div n$

(1) becomes $\mathbf{BU}_0 = \mathbf{C}$

The node voltages can be formulated as

$$U_i = \frac{\det \mathbf{B}_i}{\det \mathbf{B}}$$

The matrix determinants of $\mathbf{B}$ and $\mathbf{B}_i$ are defined as follows $\det\mathbf{B} = a_0 + a_1x + a_2y + a_3z + a_4xy + a_5xz + a_6yz + a_7xyz$ $\det\mathbf{B}_i = b_{0i} + b_{1i}x + b_{2i}y + b_{3i}z + b_{4i}xy + b_{5i}xz + b_{6i}yz + b_{7i}xyz$. Take these two equations divided by a_0 and denoted by $a_p / a_0 = \alpha_p;\ p = 1 \div 7$ and $b_{q,i} / a_0 = c_{q,i};\ q = 0 \div 7$, we got:

$$U_i = \frac{\det\mathbf{B}_i}{\det\mathbf{B}} == \frac{c_{0i} + c_{1i}x + c_{2i}y + c_{3i}z + c_{4i}xy + c_{5i}xz + c_{6i}yz + c_{7i}xyz}{1 + \alpha_1x + \alpha_2y + \alpha_3z + \alpha_4xy + \alpha_5xz + \alpha_6yz + \alpha_7xyz} \quad (2)$$

where, coefficients $c_0 \ldots c_7$ và $\alpha_1 \ldots \alpha_7$ are complex numbers; *x*, *y*, and *z* are real numbers; $i = 1 \div n$.

The current flow in that branch from k to j is equal to:

$$I_i = \left(U_k - U_j + E_i\right)Y_i. \quad (3)$$

the currents in the general for all branches are as follows:

$$I_i = \frac{d_{0i} + d_{1i}x + d_{2i}y + d_{3i}z + d_{4i}xy + d_{5i}xz + d_{6i}yz + d_{7i}xyz}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz} \quad (4)$$

it can be seen that in (3), the component in parentheses is in the form of (2), which is the voltage on the consumption load of the *i*-th branch. We label $U_k - U_j + E_i = U_{br,i}$.

In the calculation of all the currents in the branches of the circuit in (3)we obtained the properties that will be used later for finding the coefficients of the functions (2) and (4), as follows: If *x* (Ohm) is connected in parallel with *i*-th branch, and we label $Y_i = Y_i + 1/\,jx = \left(jY_ix + 1\right)/\,jx$, where $j^2 = -1$; Y_i – complex conductance of i-th branch. then, $U_{br,i}$ as follows:

$$U_{br,i} = \frac{\left(e_{0i} + e_{1i}y + e_{2i}z + e_{3i}yz\right)\dfrac{jx}{1 + jY_ix}}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz},$$

and therefore:

$$I_i = \frac{\left(e_{0i} + e_{1i}x + e_{2i}z + e_{3i}xz\right)}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz} \quad (5)$$

similarly, if y (or z) (Ohm) is connected in parallel with i-th branch.

$$I_i = \frac{\left(e_{0i} + e_{1i}x + e_{2i}y + e_{3i}xy\right)}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz} \quad (6)$$

or

$$I_i = \frac{\left(e_{0i} + e_{1i}y + e_{2i}z + e_{3i}yz\right)}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz} \quad (7)$$

If *x* (*y* or z) (Ohm) is connected in serial with i-th branch, and we label $Y_i = 1/Y_i + jx = \left(1 + jx\right)/Y_i$, then, $U_{br,i}$ as follows:

$$U_{br,i} = \frac{\left(f_{0i} + f_{2i}y + f_{3i}z + f_{6i}yz\right)\dfrac{jx}{1 + jx}}{1 + \beta_1x + \beta_2y + \beta_3z + \beta_4xy + \beta_5xz + \beta_6yz + \beta_7xyz},$$

and

$$I_i = \frac{\left(f_{0i} + f_{2i}y + f_{3i}z + f_{6i}yz\right)}{1+\beta_1 x+\beta_2 y+\beta_3 z+\beta_4 xy+\beta_5 xz+\beta_6 yz+\beta_7 xyz} \quad (8)$$

$$I_i = \frac{\left(f_{0i} + f_{2i}x + f_{3i}z + f_{6i}xz\right)}{1+\beta_1 x+\beta_2 y+\beta_3 z+\beta_4 xy+\beta_5 xz+\beta_6 yz+\beta_7 xyz} \quad (9)$$

$$I_i = \frac{\left(f_{0i} + f_{2i}x + f_{3i}y + f_{6i}xy\right)}{1+\beta_1 x+\beta_2 y+\beta_3 z+\beta_4 xy+\beta_5 xz+\beta_6 yz+\beta_7 xyz} \quad (10)$$

to find all the coefficients of functions (2) and (4), first, we need to solve a linear algebraic system of 15 equations and then solve the equation systems of 8 equations. However, by analyzing the current flow in the branch with the compensating devices, the number of equations of the systems decreasing, respectively, is 11 and 8.

2.2. Mesh current method

When we analyzed a similar circuit by the mesh currents method [11-15]:

$$\mathbf{A}_l \mathbf{Z} \mathbf{A}_l^t \mathbf{I}_s = \left(\mathbf{ZJ} + \mathbf{E}\right)$$

or

$$\mathbf{B}_l \mathbf{I}_s = \mathbf{C}_l$$

where, $\mathbf{A}_l$ – matrix of mesh currents method, its size ($\left(m-n+1\right)m$); $\mathbf{Z}$ – diagonal matrix of the resistors of the branches; $\mathbf{I}_s = \mathbf{I} + \mathbf{J}$ – vector total electric currents of the branches; $\mathbf{A}_l \mathbf{Z} \mathbf{A}_l^t = \mathbf{B}_l$; $\mathbf{ZJ} + \mathbf{E} = \mathbf{C}_l$.

The current of the i-th mesh $\left(i = 1 \div \left(m-n+1\right)\right)$ is as follows:

$$I_{si} = \frac{\det \mathbf{B}_{l\ i}}{\det \mathbf{B}_l} = \frac{g_{0i} + g_{1i}x + g_{2i}y + g_{3i}z + g_{4i}xy + g_{5i}xz + g_{6i}yz + g_{7i}xyz}{1+\beta_1 x+\beta_2 y+\beta_3 z+\beta_4 xy+\beta_5 xz+\beta_6 yz+\beta_7 xyz} \quad (11)$$

where coefficients $g \ldots g_7$ are complex numbers. $\beta_1 \ldots \beta_7$ in this case, has the same value as the coefficients $\alpha_1 \ldots \alpha_7$, it means: $I_{si} == \frac{d_{0i} + d_{1i}x + d_{2i}y + d_{3i}z + d_{4i}xy + d_{5i}xz + d_{6i}yz + d_{7i}xyz}{1+\beta_1 x+\beta_2 y+\beta_3 z+\beta_4 xy+\beta_5 xz+\beta_6 yz+\beta_7 xyz}$. The current flows in j-th branch $\left(j = 1 \div m\right)$ can be found by some simple calculations and transformations from vector $\mathbf{I}_s$:

$$I_j = \frac{e_{0j} + e_{1j}x + e_{2j}y + e_{3j}z + e_{4j}xy + e_{5j}xz + e_{6j}yz + e_{7i}xyz}{1+\alpha_1 x+\alpha_2 y+\alpha_3 z+\alpha_4 xy+\alpha_5 xz+\alpha_6 yz+\alpha_7 xyz} \quad (12)$$

by analyzing similar in the previous section, we also get the same results as (5-10).

2.3. Other circuit analysis methods

Similar results were also obtained using the method of loop currents, equivalent transformations of the circuit [11-15].

2.4. Other cases of fractional-polynomial functions

By analyzing the circuit as in section, A, when only one and two compensation devices were used, we got:

$$\begin{cases} U_i = \dfrac{a_{0i} + a_{1i}x}{1+\alpha_1 x} \\ I_i = \dfrac{b_{0i} + b_{1i}x}{1+\alpha_1 x} \end{cases} \tag{13}$$

and

$$\begin{cases} U_i = \dfrac{a_{0i} + a_{1i}x + a_{2i}y + a_{3i}xy}{1+\alpha_1 x + \alpha_2 y + \alpha_3 xy} \\ I_i = \dfrac{b_{0i} + b_{1i}x + b_{2i}y + b_{3i}xy}{1+\alpha_1 x + \alpha_2 y + \alpha_3 xy} \end{cases} \tag{14}$$

coefficients $a_0 \ldots a_3$; $\alpha_1 \ldots \alpha_3$ are complex numbers.

These results can also be derived from (2) and (4). Assuming that, we disconnect the compensator (z-Ohm) out of the circuit, which was in parallel, it means $z \to \infty$, then,

$$U_i = \frac{\dfrac{c_{0i} + c_{1i}x + c_{2i}y + c_{3i}z + c_{4i}xy + c_{5i}xz + c_{6i}yz + c_{7i}xyz}{jz}}{\dfrac{1+\alpha_1 x + \alpha_2 y + \alpha_3 z + \alpha_4 xy + \alpha_5 xz + \alpha_6 yz + \alpha_7 xyz}{jz}}$$

$$= \frac{\dfrac{c_{0i} + c_{1i}x + c_{2i}y + c_{4i}xy}{jz} - j\left(c_{3i} + c_{5i}x + c_{6i}y + c_{7i}xy\right)}{\dfrac{1+\alpha_1 x + \alpha_2 y + \alpha_4 xy}{jz} - j\left(\alpha_3 + \alpha_5 x + \alpha_6 y + \alpha_7 xy\right)}$$

$$U_i = \frac{c_{3i} + c_{5i}x + c_{6i}y + c_{7i}xy}{\alpha_3 + \alpha_5 x + \alpha_6 y + \alpha_7 xy}$$

because

$$\frac{c_{0i} + c_{1i}x + c_{2i}y + c_{4i}xy}{jz} = 0; \quad \frac{1+\alpha_1 x + \alpha_2 y + \alpha_4 xy}{jz} = 0$$

if we continue to disconnect the compensator out of the circuit (y-Ohm), which connected in parallel, it means $y \to \infty$, then,

$$U_i = \frac{\dfrac{c_{3i} + c_{5i}x + c_{6i}y + c_{7i}xy}{jy}}{\dfrac{\alpha_3 + \alpha_5 x + \alpha_6 y + \alpha_7 xy}{jy}} = \frac{\dfrac{c_{3i} + c_{5i}x}{jy} - j\left(c_{6i} + c_{7i}x\right)}{\dfrac{\alpha_3 + \alpha_5 x}{jy} - j\left(\alpha_6 + \alpha_7 x\right)} = \frac{c_{6i} + c_{7i}x}{\alpha_6 + \alpha_7 x}$$

the same for the currents and in the case of compensators are connected in series. Thus, in this section, we show how we got the fractional-polynomial functions [22-27].

3. NUMERICAL RESULTS AND DISCUSSION

3.1. Testing

Next, we compare the difference between the results of the calculation of the current and voltage by the proposed function and by the usual solution. For the circuit described in Figure 1 (in the case of two compensation devices are connected in series). Note that Values x 1 and x 2 can be negative (capacitive) or positive (inductive). Load 1 and load 2 in the general case can be in a triangular connection or star (with/without neutral wire). To find all the coefficients of functions (14), first, we need to solve a linear algebraic system of 7 equations and then solve the equation systems of 4 equations. However, if the argument is the same as to get the (5-10), the number of equations of the systems decreasing, respectively, is 5 and 4. From there we get the functions that describe the dependencies of voltages and currents on the regulable parameters, we labeled $U_{i,\,propose}\left(x_1,x_2\right)$ and $I_{i,\,propose}\left(x_1,x_2\right)$. To find the current and voltage of the *i*-th branch at the $\left(x_1,x_2\right)$, just put x_1 and x_2 in the functions $U_{i,\,propose}\left(x_1,x_2\right)$ and $I_{i,\,propose}\left(x_1,x_2\right)$.

The correct currents and voltages can be found solving the circuit when given $\left(x_1,x_2\right)$, we labeled $U_{i,correct}\left(x_1,x_2\right)$ and $I_{i,correct}\left(x_1,x_2\right)$. The difference between the two results that were mentioned above as shown in Figures 2 and 3. The difference between the two results of the case of one compensation device is connected in the serial was shown in Figure 4. In the cases of three compensators are connected in serial or of one/two/three or more compensation device(s) is (are) connected in parallel are also tested and generally, the difference is tiny, approximately 10^{-7}%.

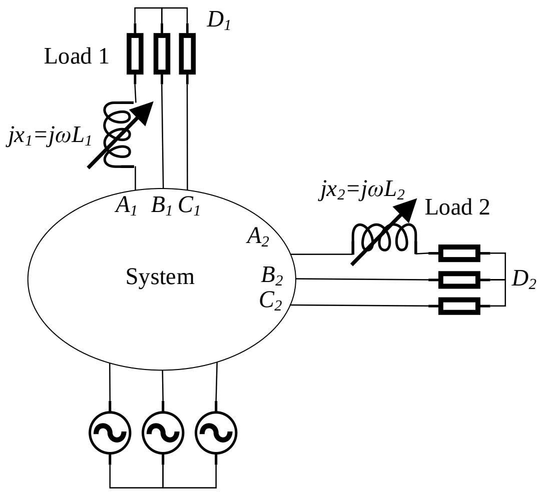

Figure 1. Modeling of electrical systems

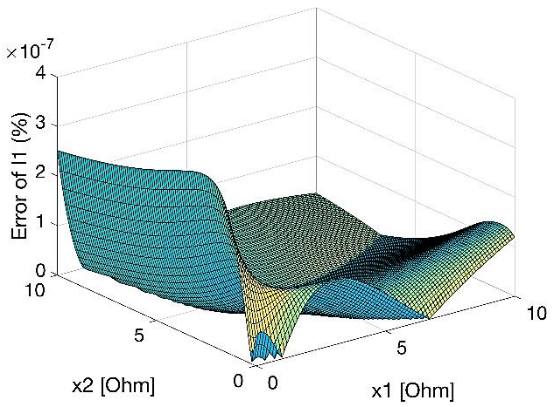

Figure 2. The difference between the currents

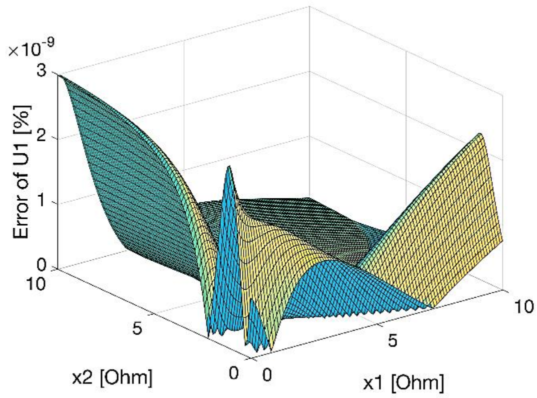

Figure 3. The difference between the voltages

3.2. Application

The proposed fractional-polynomial function has been applied to optimizing the electrical system of the glass factory operating in asymmetric mode, which was mentioned in the previous article [15]. In Figure 5 is one of the results using the proposed function for optimal calculation, in which case we use only two compensators. It can be seen that the currents and voltages have been significantly improved compared to

Figure 6. Together with the result shown in Figure 7 and the results mentioned in the previous articles, all use the proposed function in the optimization has proved its effectiveness.

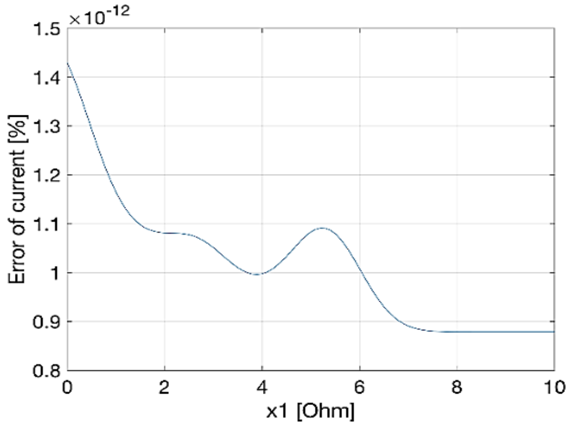

Figure 4. The difference between the currents

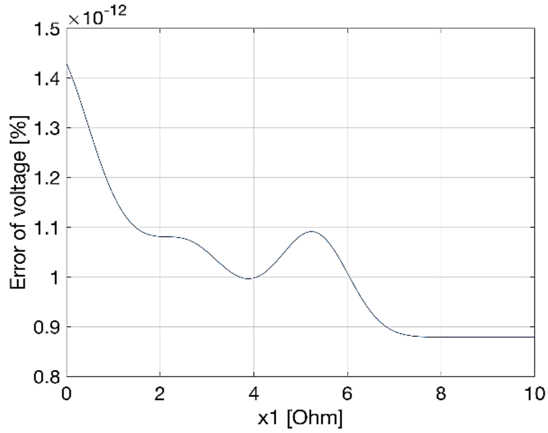

Figure 5. The difference between the voltages

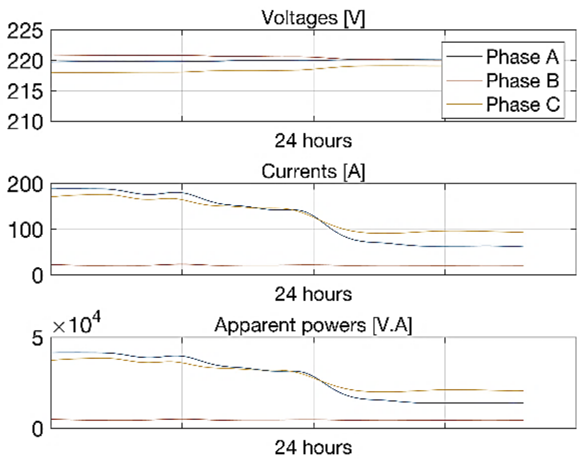

Figure 6. Before compensation

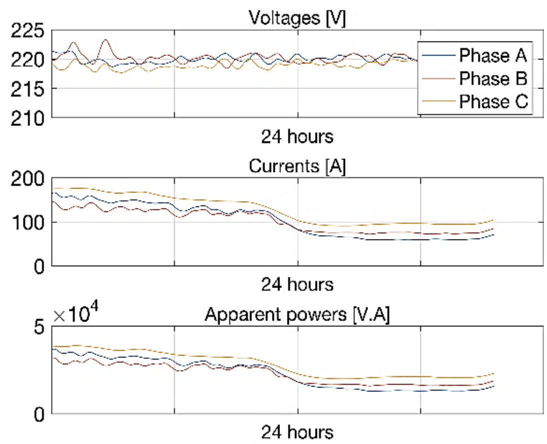

Figure 7. After compensation

4. CONCLUSION

The main issue of this paper that we would like to emphasize is the finding of the fractional-polynomial function that describes the variation of voltage and current according to the regulable parameters of the compensators. This proposal can be applied to the optimal computation of reactive power compensation systems that use static VAR compensators and the ability of extension for a few other exceptional cases. The introduction of a function describing the fundamental quantities of the electrical systems (voltage and current) in the dependencies on the value of the compensator in the general case is of considerable significance, which makes the calculation more convenient and quicker.

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