

# A Decomposition Four-Component Model for Calculating Power Losses in Low-Voltage Power Supply Systems

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A new model for decomposition of the total power losses, which includes four components is

proposed. Each of the components of the proposed model has a certain physical meaning due to the nature of electromagnetic processes in a three-phase four-wire system. Definitions to

describe each of the proposed components are formulated. It is shown that each of supplemen-

tary components of the total loss power is proportional to the minimum possible loss power

and to the square of the RMS value of the power, which is caused by its occurrence in three-

phase four-wire power supply system, and it is inversely proportional to the mean square of the net power loss. The synthesized Matlab-model for verification of the four-component

structure of power losses showed a high degree of its adequacy. The proposed model allows

us to rethink the description of power losses in three-phase AC circuits and can be used in

specialized measuring instruments for electrical networks monitoring. Using the information

obtained in the monitoring process, it is possible to plan technical measures to reduce losses of

electrical energy in the power supply system, as well as to estimate the capital costs of these

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### INTRODUCTION

The problem of ensuring the required quality of electrical power in low-voltage power supply systems (PSS) which is the most urgent in the power industry has not yet been solved. The transition from traditional power supply to Smart Grid systems contributes to seeking the ways to address this issue [1-4]. One possible option to improve the electromagnetic compatibility of electrical energy consumers or local microelectric systems with a bidirectional energy flow, connected to the central grid, is the use of economically stimulating mechanisms for calculating the electrical power consumed, based on common understandable and physically conditioned principles [5]. That is, it is necessary to perform the transition from the normalized standards of quality indicators to more understandable ones, namely the losses of electrical power due to noncompliance with these indicators [6, 7].

Thus, powerful consumers of electrical power, the modes of operation of which contribute to the occurrence of its losses in the low-voltage PSS, which is part of their energy infrastructure, should understand what the level of power losses in the system is, what share they constitute in the total electrical power consumption, as well as the physical causes of these losses [8, 9]. With this information one can assess the economic damage due to unbalanced operation modes and plan measures to reduce power losses thereby improving the electromagnetic compatibility in the PSS [10, 11].

The accounting of electrical power losses in lowvoltage PSS, based on their quantitative calculation [12, 13], makes it possible to address only the first two questions. However, the lack of information associated with the lack of an answer to the third question, will not make it possible to qualitatively plan measures to reduce electrical power losses in a particular PSS.

In this paper, we propose a method for measuring electrical power losses, based on their decomposition into separate physically determined components, which can form the basis of a specialized measuring device for diagnostics of low-voltage AC

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#### Abstract

measures.

networks. The use of the above device will allow providing competent recommendations on energy saving measures and thereby improving the electromagnetic compatibility of individual consumers (or microgrids) with the industrial power grid.

# EQUIVALENT DIAGRAM OF A LOW-VOLTAGE PSS

Any low-voltage AC power supply system, which is a branch line from the industrial network, can be replaced for analysis with high accuracy by a simple equivalent diagram, shown in Fig. 1, which consists of a three-phase power source, a load, and a threephase four-wire line connecting the power source and the consumer with each other [14]. Despite the fact that low-voltage AC networks are the most branched, the proposed simplified equivalent circuit enables to show where exactly there are losses of electrical energy associated with its transfer from the source to the load (or back), which can be affected by reducing them to the minimum possible (or other established) value.



Figure 1. Simplified equivalent diagram of the low-voltage PSS

The conventionally low-voltage PSS starts from a 10(6) / 0.4 kV step-down transformer, in the low-voltage windings of which considerable currents can flow.

The load of such a system within a traditional power supply can be an industrial, commercial, or residential facility supplied by a transformer substation with a four-wire cable line. The number of individual consumers forming the power supply object can be significant. Their mode and characteristics are usually different, so in the equivalent circuit it is advisable to replace them with a common load, reducing the number of measures required to reduce power losses. In the general case, the load can be both "passive" (i.e. only consume electrical energy from the power supply network) and "active" (i.e. contain other energy sources in its composition). Thus, the parameters of the connecting cable line determine the electrical energy losses for its transmission from the source to the load (or back) and determine the efficiency of the PSS.

Taking into account the experience of designing low-voltage 0.4 kV networks, the cable length of the main feeding section can be from tens to hundreds (and in some cases more) meters [15], and its crosssection is calculated in accordance with the recommendations of EIC (electrical installation code) and will depend on the allowable voltage losses at the line end. The complex resistance of the 0.4 kV cable line mostly depends on the active component  $R_s$ and in many cases the inductive resistance of the line can be neglected (as shown in Fig. 1). Of course, when calculating electrical power losses in the PSS with high-frequency components in the phase current curves, such simplification will result in a certain methodological error, but, as shown by previous studies [14], it will not exceed one percent in the most critical modes.

Using the active resistance of the low-voltage cable line, the power of the three-phase resistive shortcircuit can be calculated

$$P_{sc} = \frac{3 \cdot U_s^2}{R_s},\tag{1}$$

where  $U_s$  is the effective range of the phase voltage of the low-voltage AC network.

In monograph [14], obtained are analytical dependences, which prove that the three-phase PSSs are identified by the greatest energy saving potential in which the parameter  $k_{sc}$ , which determines the ratio of three-phase resistive short-circuit power to the average useful load power  $P_{usf}$ , lies in the range of:

$$k_{sc} = \frac{P_{sc}}{P_{usf}} \le 4...20.$$
 (2)

If we bear in mind that majority of existing lowvoltage PSSs engineered in the 20th century was not designed for the operation of modern electronic equipment with nonlinear characteristics, then the number of power supply facilities where ratio (2) fits into the above range might be considerable.

### FIVE-COMPONENT MODEL OF THE CONSTITUENTS OF THE TOTAL LOSS POWER OF THE THREE-PHASE PSS

As it was specified above, the measurement of electric power losses in the three-phase four-wire PSS will make sense, provided that the reasons causing the measured losses are explained. Therefore, an important scientific task is to create an adequate model of the loss power components, each component of which would be responsible for certain electromagnetic processes causing these losses.

One of the possible ways to build a working model is to apply the approaches and mathematical apparatus of the modern power theory, used to create fast control systems for transistor semiconductor converters with a power factor close to unity and power active filters (PAFs) [16, 17].

In [14, 18] a system of energy components of the loss power for three-phase four-wire PSSs, based on the decomposition of the total loss power into 5 components, was proposed:

$$\Delta P_{\Sigma^*} = \Delta P_{\min^*} + \Delta P_{puls^*} + \Delta P_{Q^*} + \Delta P_{n^*} + \Delta P_{n^*} + \Delta P_{mut^*} \Big|_{P_{usf}} = const,$$
(3)

where  $\Delta P_{\Sigma^*} = \Delta P_{\Sigma} / P_{usf}$  is the relative in the proportion of the mean useful power the total loss power;  $\Delta P_{\min*} = \Delta P_{\min} / P_{usf}$  is the relative in the proportion of the mean useful power the minimum possible loss power;  $\Delta P_{puls*} = \Delta P_{puls} / P_{usf}$  is the relative in the proportion of the mean useful power loss power caused by pulsations of the instantaneous active power;  $\Delta P_{Q^*} = \Delta P_Q / P_{usf}$  is the relative in the proportion of the mean useful power loss power caused by the presence of the calculated reactive power in the PSS;  $\Delta P_{n^*} = \Delta P_n / P_{usf}$  is the relative in the proportion of the average useful power loss power caused by the current flow in the neutral conductor;  $\Delta P_{mut^*} = \Delta P_{mut} / P_{usf}$  is the relative in the promotion of the average useful power loss power caused by the mutual influence of electromagnetic processes occurring in the phase and neutral conductors of the three-phase four-wire PSS.

The five-component power system gave an acceptable result for the calculation of the total loss power in most operating modes of the three-phase four-wire PSS, but in restrained terms, such as the phase asymmetry of the nonlinear load, the use of (3) caused an error exceeding 5%. Another disadvantage of the five-component system proposed in [14] is that it is difficult to use it for the construction of the meter, due to the need to install additional voltage sensors on the transformer low voltage buses (or at the beginning of the cable line), while the device itself is connected at the load terminals (at the end of the cable line). Therefore, the existing model requires refinement, a clearer specification of the causes of electric energy losses in the PSS and full adaptation to the use of loss power components in the meters.

#### NEW FOUR-COMPONENT MODEL OF THE TOTAL LOSS POWER COMPONENTS OF THE THREE-PHASE PSS

For the convenience of using a meter capable of determining the level of the loss power components, its connection should be performed at the load ter-

minals, namely at the end of the cable line (it can be an input-distribution device or the consumer's main switchboard). In the case of further implementation of measures to reduce loss power components in the PSS, filter-compensating and other power equipment, such as PAF, can be installed in the same place. Despite the fact that the mathematical apparatus for calculating the loss power components, based on the use of the provisions of modern power theory, is the same for both the measuring device and PAF, the place of installation of voltage and current sensors (or measuring current transformers) for these two cases must also coincide. In [19] it is proved, that the voltage sensors for measuring the instantaneous values of phase voltages of the threephase system is advisable to install on the load terminals, rather than on the power supply terminals, to enhance the efficiency of compensation and operation of the PAF in general. Fig. 2 shows the diagram of the installation of current measuring transformers for the connection of the loss power components meter. From the diagram we can see that for the operation of the device it is sufficient to possess information about the instantaneous values of phase voltages on the load terminals ( $u_{La}$ ,  $u_{Lb}$ ,  $u_{Lc}$ ) and phase load currents ( $i_a$ ,  $i_b$ ,  $i_c$ ).



Figure 2. Connection of the total loss power components meter

Correct operation of the meter for determining the loss power components is not possible without using the information about the cable line parameters, namely the active resistance of the conductive cores  $R_s$ . Determining the active resistance of the cable line can be performed in several ways. The first simplified method involves calculating the resistance based on the known type, cross-section and the length of the cable section. But this method does not take into account several important factors that affect the resistance of the conductor during operation and gives an approximate result. The most expedient is the use of specialized phase-zero loop resistance (or short-circuit current) meters, which are in sufficient assortment presented in the market of measuring equipment for monitoring the parameters of electrical networks [20]. Determination of the active resistance of three-phase four-wire cable line (taking into account the resistance of the transformer's low-voltage winding and nominal resistance of protection devices) can be performed by the results of four measurements, namely by the resistance of three "phase-zero" loops ( $R_{an}$ ,  $R_{bn}$ ,  $R_{cn}$ ) and the resistance of the "phase-phase" loop (for example  $R_{ab}$ ):

$$\begin{cases}
R_{a} = \frac{1}{2} (R_{an} - R_{bn} + R_{ab}), \\
R_{b} = R_{ab} - R_{a}, \\
R_{n} = R_{bn} - R_{b}, \\
R_{c} = R_{cn} - R_{n}.
\end{cases}$$
(4)

Given that the active resistance of the cable line phases is approximately the same, and the crosssection of the neutral conductor is usually selected to be the same as the intersection of the phase conductors ( $R_n = R_s$ ), to determine the active resistance of the cable phases one can use three measurements and a simplified ratio

$$R_{s} = \frac{R_{an} + R_{bn} + R_{cn}}{6}.$$
 (5)

In the future, when improving the design of the loss power component meter, especially if the device is implemented as a meter, the function of measuring the cable line resistance should be provided in its design, which will greatly facilitate the measurement process and make the device more convenient for use.

From the equivalent circuit in Fig. 2 and [14] it is possible to determine the minimum possible loss power

$$\Delta P_{\min} = \frac{R_s}{U_{Lp}^2} P_{usf}^2, \tag{6}$$

where

$$U_{Lp}^{2} = \frac{1}{T} \int_{t}^{t+T} \left( \left( u_{La}^{2} + u_{Lb}^{2} + u_{Lc}^{2} \right)^{2} - \frac{1}{4} \left( u_{La} + u_{Lb} + u_{Lc} \right)^{2} \right) dt$$
(7)

is the RMS value square of the modulus of the load voltage generalized spatial vector after partial attenuation of the zero-sequence component [21];

$$P_{usf} = \frac{1}{T} \int_{t}^{t+T} \left( u_{La} i_a + u_{Lb} i_b + u_{Lc} i_c \right) dt$$
(8)

is the mean net load power determines the average transmission rate of the electrical energy of the cable line over the time interval T, which in turn determines the repeatability period of the energy processes in the PSS.

It should be noted that determining the period of recurrence T is a separate complex task, the solution of which is associated with a detailed study of the power supply object. For more complete accounting of energy losses in the PSS it is necessary to take into account not only the electromagnetic processes occurring at the frequency of voltage supply, but also the change in the load profile on the second, minute, hourly, and ideally, daily interval. It is a well-known fact that the ideal load profile for any PSS would be one in which the power consumption remains constant throughout the day. The elimination of peaks and dips in the power consumption profile eliminates supplementary energy and economic losses for power transmission. In this paper, the issues of determining the period of recurrence T is not investigated, on the grounds that to create a loss power component meter, it is sufficient to consider the energy processes occurring at the frequency of the power grid. This will provide information about losses during PSS monitoring. To implement the function of measuring loss power components in an appropriate meter, the resolution of this issue is of the utmost importance.

The measurement of the phase voltages at the load terminals, as shown in Fig. 2, makes it possible to go from a five-component total loss power model (3) to a four-component one

$$\Delta P_{\Sigma} = \Delta P_{\min} + \Delta P_{puls} + \Delta P_Q + \Delta P_n \left| P_{usf} = const \right|$$
(9)

ī.

In formula (9), the loss power components are presented in absolute terms.

We will provide comments on each component.

In the ideal case, when the phase voltages of a three-phase source are sinusoidal and shifted in time by an equal angle of 120 electrical degrees, and the load resistances are resistive and have the same values, the total loss power is equal to the minimum possible loss power  $\Delta P_{\Sigma} = \Delta P_{\min}$ . The loss power components  $\Delta P_{puls}$ ,  $\Delta P_Q$ ,  $\Delta P_n$  appear in the threephase four-wire PSS due to unbalanced modes of the power source or load operation. In [14] it was shown that for three-phase four-wire PSS there are 279 variants of its state, where additional electrical power losses occur. The component of the total loss power  $\Delta P_{puls}$  in model (9) is caused by pulsations of the instantaneous active power of the three-phase PSS. The physical cause of its occurrence is the change in the mean power transfer rate in the recurrence interval T. If we ignore the low frequency ripple of the load curve, the frequency of the variable component will be equal to twice the frequency of the low voltage source  $f_{puls} = 2f_s$ . The component  $\Delta P_{puls}$  is proportional to the square of the RMS value of the variable component of the instantaneous active power [14]

$$P_{pulsPMS}^{2} = \frac{1}{T} \int_{t}^{t+T} \left( \left( u_{La} i_{a} + u_{Lb} i_{b} + u_{Lc} i_{c} \right) - P_{usf} \right)^{2} dt, \quad (10)$$

and is determined by the ratio

$$\Delta P_{puls} = \frac{\Delta P_{\min}}{P_{usf}^2} P_{pulsRMS}^2. \tag{11}$$

The component of the total loss power  $\Delta P_Q$  in model (9) is due to the presence of design reactive power in the three-phase PSS. The physical nature of its occurrence in the three-phase four-wire PSS consists in the occurrence of exchange processes between the three-phase source, the load phases and their impact on the energy processes arising during the current flowing in the neutral conductor. These exchange processes are not connected with the conversion of electrical power into another type of energy used to perform the net work output.

The component  $\Delta P_Q$  is proportional to the square of the RMS value of the reactive power [14]

$$Q_{RMS}^{2} = \frac{1}{T} \int_{t}^{t+T} \left( \left( u_{Lb}i_{c} - u_{Lc}i_{b} \right)^{2} + \left( u_{Lc}i_{a} - u_{La}i_{c} \right)^{2} + \left( u_{La}i_{b} + u_{Lb}i_{a} \right)^{2} \right)^{2} dt,$$
(12)

and is determined by the ratio

$$\Delta P_Q = \frac{\Delta P_{\min}}{P_{usf}^2} Q_{RMS}^2. \tag{13}$$

The component of the total loss power  $\Delta P_n$  in model (9) is due to the current flowing  $i_n$  in the neutral conductor of the three-phase PSS:

$$\Delta P_n = \frac{R_n}{T} \int_{t}^{t+T} (i_a + i_b + i_c)^2 dt = \frac{R_n}{T} \int_{t}^{t+T} i_n^2 dt.$$
(14)

The neutral conductor current  $i_n$  can be expressed using the *pqr* power theory coordinate transformation, applied to build a parallel PAF control system of the three-phase four-wire PSS [22, 23]. The axes *q* and *r* of the rotating *pqr* coordinate system determine the corresponding projections of the generalized spatial vector of the  $i_q$ ,  $i_r$  current, which makes it possible to design the projections of the reactive power vector [23]:

$$\begin{bmatrix} q_q \\ q_r \end{bmatrix} = u_p \begin{bmatrix} i_r \\ i_q \end{bmatrix},\tag{15}$$

where  $u_p$  is the projection of the voltage vector on the *p* axis of the rotating spatial *pqr* coordinate system.

The projection of the reactive power vector on the  $q(q_q)$  axis is responsible for the current flow in the neutral conductor, i.e. it indicates the degree of asymmetry of the three-phase system "by amplitude". The projection of the reactive power vector on the  $r(q_r)$  axis is responsible for the presence of the angle of shift between the generalized spatial vectors of voltage and current of the three-phase system, i.e. indicates the degree of asymmetry of the three-phase system "in time".

The sum of squares of RMS values of orthogonal components of reactive power makes it possible to calculate the square of RMS value of the reactive power (12)

$$Q_{RMS}^2 = Q_{qRMS}^2 + Q_{rRMS}^2.$$
 (16)

According to the *pqr* power theory, the instantaneous value of the neutral conductor current can be determined through the projection of the generalized spatial current vector onto the r axis [23]:

$$i_n = \sqrt{3} \cdot i_r \,. \tag{17}$$

Given (15) and (17), relation (14) can be represented as follows:

$$\Delta P_n = \frac{\Delta P_{\min}}{P_{usf}^2} Q_{qRMS}^2, \tag{18}$$

where the RMS value of the reactive power along the q axis is determined by

$$Q_{qRMS}^2 = U_{Lp}^2 \cdot I_r^2 = \frac{U_{Lp}^2}{3 \cdot T} \int_t^{t+T} (i_a + i_b + i_c)^2 dt.$$
(19)

Generalizing relations (6), (11), (13), (18) it is possible to represent a four-component model of loss power components of the three-phase four-wire low-voltage PSS in the form of

$$\begin{bmatrix} \Delta P_{\min} \\ \Delta P_{puls} \\ \Delta P_{Q} \\ \Delta P_{n} \end{bmatrix} = \frac{\Delta P_{\min}}{P_{usf}^{2}} \begin{bmatrix} P_{usf}^{2} \\ P_{pulsRMS}^{2} \\ Q_{RMS}^{2} \\ Q_{RMS}^{2} \end{bmatrix}, \qquad (20)$$

or in fractions of the mean net power load

$$\begin{bmatrix} \Delta P_{\min*} \\ \Delta P_{puls*} \\ \Delta P_{Q*} \\ \Delta P_{n*} \end{bmatrix} = \Delta P_{\min*} \begin{bmatrix} 1 \\ P_{pulsRMS*}^2 \\ Q_{RMS*}^2 \\ Q_{qRMS*}^2 \end{bmatrix}.$$
 (21)

Model (20) makes it possible to draw two generalizable conclusions:

- each of the components of the total loss power is proportional to the square of the RMS value of the power component, which accounts for the nature of the occurrence of this component in the three-phase four-wire PSS;
- 2) each of the components of the total loss power, causing supplementary losses in the threephase four-wire PSS ( $\Delta P_{puls}$ ,  $\Delta P_Q$ ,  $\Delta P_n$ ), is proportional to the minimum possible loss power and in the normal operation mode of the three-phase system cannot be greater than the minimum possible losses.

#### ALTERNATIVE FOUR-COMPONENT MODEL OF THE TOTAL LOSS POWER COMPONENTS OF THE THREE-PHASE PSS

The four-component model (20) is sufficiently exhaustive in explaining the causes of power losses in the low-voltage three-phase four-wire PSS. But it should be noted that the  $\Delta P_O$  component according to relation (16) takes into account both the losses connected with the projection of the reactive power vector on the *r* axis, i.e. the impact of exchange electromagnetic processes in the PSS, and the losses connected with the projection of the reactive power vector on the *q* axis, that is the mutual influence of exchange electromagnetic processes in phases of the three-phase system and the process related to the current flowing in the neutral wire. These individual components can be separated by means of the *pqr* coordinate transformation of the power theory and combined with the fourth component of the

model (20). Thus it is possible to refine the mathematical relationship for calculating the reactive power of the three-phase four-wire PSS and obtain an alternative model for the total loss power components.

Let us use the pqr coordinate transformations of the power theory to calculate the projection of the generalized spatial current vector on the q axis [23]:

$$i_{q} = \begin{bmatrix} -\sqrt{\frac{2}{3}}\sin\theta_{1} \\ -\sqrt{\frac{2}{3}}\sin\left(\theta_{1} - \frac{2\pi}{3}\right) \\ -\sqrt{\frac{2}{3}}\sin\left(\theta_{1} + \frac{2\pi}{3}\right) \end{bmatrix}^{T} \begin{bmatrix} i_{a} \\ i_{b} \\ i_{c} \end{bmatrix},$$
(22)

where

$$\theta_1 = \operatorname{arctg} \frac{u_{sb} - u_{sc}}{\sqrt{3}u_{sa}}.$$
(23)

The square of the RMS value of the reactive power vector projection along the *r* axis of the *pqr* 

coordinate system:

$$Q_{rRMS}^{2} = U_{L}^{2} \cdot I_{q}^{2} = \frac{U_{L}^{2}}{T} \int_{t}^{t+T} i_{q}^{2} dt, \qquad (24)$$

where

$$U_L^2 = \frac{1}{T} \int_{t}^{t+T} \left( u_{La}^2 + u_{Lb}^2 + u_{Lc}^2 \right)^2 dt$$
(25)

is the square of the RMS value of the generalized spatial voltage vector at the load terminals.

From relation (18) the square of the RMS value of the reactive power along the q axis can be determined, after which an alternative four-component model of the loss power components can be presented in the following form:

$$\begin{bmatrix} \Delta P_{\min} \\ \Delta P_{puls} \\ \Delta P_{Qq} \\ \Delta P_{Qr} \end{bmatrix} = \frac{\Delta P_{\min}}{P_{usf}^2} \begin{bmatrix} P_{usf}^2 \\ P_{pulsRMS} \\ Q_{QRMS}^2 \\ Q_{RMS}^2 \end{bmatrix},$$
(26)

where

$$Q_{QRMS}^2 = Q_{RMS}^2 - Q_{rRMS}^2 + Q_{qRMS}^2 = Q_q^{/2} + Q_{qRMS}^2.$$
 (27)

It should be noted that in relation (26), the projections of the reactive power vectors  $q'_q$  and  $q_q$  are calculated with respect to different generalized vectors of phase voltages, as shown in Fig. 3:

$$\begin{bmatrix} \vec{q}_q' \\ \vec{q}_q \end{bmatrix} = \begin{bmatrix} \vec{U}_L \times \vec{i}_r' \\ \vec{U}_{Lp} \times \vec{i}_r \end{bmatrix}.$$
(28)



**Figure 3.** Determination of independent components of reactive power vectors along the *q* axis

#### MEASURES TO REDUCE ADDITIONAL LOSSES IN LOW-VOLTAGE THREE-PHASE FOUR-WIRE PSSS

The four-component model (20) allows by measuring the phase voltages and currents of the threephase four-wire PSS to estimate the influence of "undesirable" electromagnetic processes on the supplementary power losses in the system and to plan measures for their complete or partial elimination. It is reasonable to implement such measures within the development of the Smart Grid concept in the power industry. The Smart Grid concept includes a review of relations and positions between the production, distribution and supply of electrical power and its consumers [24, 25]. Within the framework of the mentioned concept the consumer is provided with an "active" function, which is implemented within the framework of its own distributed generation, i.e. the possibility to both buy and sell electrical power. Despite the fact that the consumer owns low-voltage networks (in some cases, medium-voltage networks up to 35 kV), the quality of electrical power sold to the external market will be of critical importance. The concept of Smart Grid can be defined in various large-scale configurations, for example, to combine groups of consumers on a territorial basis, or production process. Thus, relative to the central grid, Smart Grid facilities form a distributed system that uses the backbone infrastructure and generates the capabilities of the interconnected power system for power exchange.

Having low-voltage networks at their disposal, Smart Grid owners will be interested in reducing electrical power losses (reduction of financial losses for power supply) and improving the electromagnetic compatibility of the Smart Grid with the industrial grid (possibility to sell electrical power to the external market).

Table 1 provides detailed information on the components of the four-component total loss power model (20) with a description of ways to reduce power losses (improved efficiency) of the PSS.

#### SIMULATION OF THE THREE-PHASE PSS OPERATION MODES TO VERIFY THE FOUR-COMPONENT MODEL

For a better understanding of the efficiency of measures to reduce additional losses, we will use the Matlab model of the equivalent circuit of the three-phase four-wire PSS with PAF, which was discussed in detail in [14]. The Matlab model schematic is shown in Fig. 4.

The model layout repeats the equivalent circuit in Fig. 1, except that a parallel PAF based on adjustable current sources is additionally connected to the load clamps. The load unit is implemented by parallel inclusion in each phase of the passive complex resistance and adjustable current source, which makes it possible to investigate any of 279 operation modes of the three-phase four-wire PSS [14].

**Table 1.** Description of a four-component model of the loss power components in low-voltage PSS and ways to reduce them

	Component of the total loss power	Mathad of reduction			
Notations	Description	- Method of reduction			
$\Delta P_{\min}$	<i>Minimum possible loss power</i> is determines the power losses at a constant rate of transmission associated with the characteristics of the medium by which it is transmitted (type of conductor, its geometric, electrochemical, thermal, etc. characteristics)	Improving the characteristics of the conductive medium: using conductors with lower resistivity, increasing the cross section of the cable conductive cores, optimizing the length of the cable line, re- ducing the energy flow density in the line by using its proper generation			
$\Delta P_{puls}$	Loss power due to ripples in the active power curve is related to the change in the average rate of power transmission in the PSS over a certain period of recurrence of $T$	Use of energy storage devices (including energy- intensive ones) separately or in combination with PAF, use of autonomous power sources (including renewable ones)			
$\Delta P_Q$	<i>The loss power due to the presence of reactive pow- er in the PSS</i> is related to the occurrence of ex- change processes between the three-phase source, load phases and their impact on the energy process- es occurring during the current flowing in the neu- tral conductor (both at the utility frequency and at frequencies due to the above harmonics)	Use of passive and active filter-compensating de- vices			
$\Delta P_n$	<i>The loss power due to current flowing in the neutral conductor</i> is related to the asymmetric modes of operation of the three-phase system, causing the neutral conductor loading	Use of symmetrical devices, use of PAF, transition from single-phase to three-phase supply of con- sumers, use of consumers' DC power supply sys- tems			



**Figure 4.** Matlab model of the equivalent circuit of the three-phase PSS with PAF

Separate Matlab model units are required to select the PSS operating mode, control the PAF, measure and display the measured signals.

The difference of the Matlab-model, shown in Fig. 4, from the one described in [14], is the presence of a subsystem for measuring the Calculation2 loss power components, built based on the four-component models (20) and (26). Fig. 5 shows an expanded view of this subsystem.

The Calculation2 subsystem consists of five subsystems built to calculate the total loss power components of four-component models (20) and (26) in which the mathematical relations (6) and (27) given in the paper are used. Switches *K*1 and *K*2 allow selecting one of the two calculation models, giving identical results for the total loss power. Additionally, the Calculation2 subsystem calculates the relative error of the total loss power calculation according to the direct measurement of this power (delta %).



Figure 5. Layout of the Calculation2 subsystem

The Power Active Filter Control System is configured using the *pqr* power theory. The active resistance of the cable line phases and the neutral wire are the same  $R_s = R_n = 0.01815\Omega$ .

To verify the model correctness (20), we assume the option of parallel connection as loads of the asymmetric linear load ( $R_a = R_l$ ,  $R_b = 1.3R_l$ ,  $R_c = ((2 - 1)R_l)$ )

 $(-1.3^2)^{0.5}$   $R_l$ , where  $R_l = 0.3256\Omega$ ,  $L_a = L_c = 0.2777$  mH,  $L_b = 0$ ) and the symmetric nonlinear load with harmonic composition of mains currents of the six-pulse uncontrolled rectifier (mode 1):

$$\begin{bmatrix} i_{aD} \\ i_{bD} \\ i_{cD} \end{bmatrix} = \begin{bmatrix} \frac{0.5U_{ms}}{(R_s + R_l)} \sum_{n=6k\mp 1, k=1}^{k=6} \frac{1}{n} \sin(n\omega) \\ \frac{0.5U_{ms}}{(R_s + R_l)} \sum_{n=6k\mp 1, k=1}^{k=6} \frac{1}{n} \sin\left(n\omega - \frac{2\pi}{3}\right) \\ \frac{0.5U_{ms}}{(R_s + R_l)} \sum_{n=6k\mp 1, k=1}^{k=6} \frac{1}{n} \sin\left(n\omega + \frac{2\pi}{3}\right) \end{bmatrix}.$$
 (29)

The total net power of the load is  $P_{usf} = 585$  kW.

Fig. 6 shows an oscillogram of the network phase currents  $(i_a, i_b, i_c)$ , an oscillogram of the current flowing in the neutral conductor  $(i_n)$ , and an oscillogram of the instantaneous active power  $(p_s)$  of the disconnected PAF. Fig. 6 shows that the phase currents are non-sinusoidal in shape and unequal in amplitude, the load asymmetry causes the significant current to flow in the neutral conductor, the active network graph pulsates with the amplitude of the variable component, which is about 15% of the mean net power load. Fig. 6 also shows the percentage contribution of the mean net power  $P_{usf}$  of each component of the four-component model to the total losses of the three-phase four-wire system.



**Figure 6.** Oscillograms of energy processes when the PAF is not in operation

Fig. 7–9 shows identic oscillograms as in Fig. 6 with sequential input of compensation signals in the PAF control system: compensation of the AC current component on p  $i_{p\sim}$  axis (decay of ripples in the graph of instantaneous active power) (Fig. 7); compensation of the AC current component on p  $i_{p\sim}$  axis and the current component along the q  $i_q$  axis (the higher harmonics in the curves of the

phase currents decay) (Fig. 8); compensation of  $i_{p\sim}$ ,  $i_q$  and the current component along the  $r_i_r$  axis (the phase asymmetry of currents decays (and thus the current in the neutral conductor), as well as the displacement of their basic harmonics relative to the corresponding phase voltages) (Fig. 9). Each of the figures shows the percentage content of the components of the total loss power of the four-component model as a fraction of the mean net power.



**Figure 7.** Oscillograms of energy processes in case of compensation of the AC current component along the p  $i_{p\sim}$  axis



**Figure 8.** Oscillograms of energy processes in case of compensation of the AC current component along the p  $i_{p\sim}$  axis and the current component along the q  $i_q$  axis

Table 2 shows the results of the experiments on the Matlab model for the three-phase four-wire PSS operating mode considered when changing the active resistance of the load phases by producing its value in each phase by the coefficient  $k_l$ , and changes in the amplitude of phase currents of the non-linear load by their product to the factor of  $1/k_l$ , which determined the exact power ratio of the

three-phase *K*3 to the net power load  $k_{sc} = P_{sc}/P_{usf}$  from 10 to 40. Table 2 shows that in the considered operation mode of the three-phase four-wire PSS in the case of changing the ratio of the three-phase short-circuit power to the mean net power load in the range from 10 to 40 additional losses, in the fractions of the mean net power, vary from about 3 to 0.5%. Calculation of the total loss power of the four-component model (20) gives an insignificant error, which on average does not exceed 0.3%.



**Figure 9.** Oscillograms of energy processes in the case of compensation  $i_{p\sim}$ ,  $i_q$  and the current component along the *r*  $i_r$  axis

Let's consider another mode of operation of the three-phase four-wire PSS, which is typical for consumers with single-phase power supply (mode 2). In the balanced symmetric mode of operation of the three-phase system we select the loads of the three phases to be active-inductive ( $R_a = R_b = R_c = R_l = 0.3256\Omega$ ,  $L_a = L_b = L_c = 0.2777$  mH). Let us multiply the resistance and inductance of phase *b* by the coefficient  $k_l$ , which will vary from 0 to  $\infty$  (from a mode close to a single-phase short circuit to a mode where the consumers of phase *b* are disconnected). The results of the study of the four-component models for calculating the loss power components are shown in Table 3.

Table shows that in mode 2, which corresponds to the asymmetry of the linear load, the opportunities to reduce power losses are much broader. Fig. 10 shows the dependences of the additional loss power on the  $k_{sc}$  coefficient for the two considered modes of operation. Similar dependencies can be plotted for other characteristic modes of operation of the three-phase four-wire PSS. In practice, it is better to measure the total loss power components while monitoring the power supply object, taking into account the daily load profile.

		0	1	1 (	/		
k <sub>sc</sub>	10	15	20	25	30	35	40
k <sub>l</sub>	0.63	1.129	1.61	2.083	2.553	3.021	3.488
P <sub>usf</sub> , kW	801.1	532.2	399.8	320	266.7	228.6	200
$\Delta P_{\min}$ , kW	102.3	41.29	22.28	13.94	9.537	6.934	5.267
$\Delta P_{puls}$ , kW	1.602	0.626	0.342	0.217	0.151	0.111	0.09
$\Delta P_Q$ , kW	15.79	4.07	1.814	1.029	0.665	0.467	0.346
$\Delta P_n$ , kW	4.93	2.55 2	1.581	1.074	0.776	0.586	0.458
$\Delta P_{Qq}$ , kW	8.591	4.02	2.377	1.573	1.117	0.834	0.646
$\Delta P_{Qr}$ , kW	12.13	2.602	1.017	0.53	0.324	0.219	0.158
$\Delta P_{\Sigma}$ , ${ m kW}$	124.6	48.54	26.02	16.26	11.13	8.097	6.156
$\Delta P_{add}$ , kW	22.32	7.248	3.736	2.32	1.591	1.136	0.889
$\Delta P_{\min^*}$ , %	12.76	7.743	5.572	4.357	3.577	3.034	2.634
$\Delta P_{puls^*}$ , %	0.2	0.117	0.085	0.068	0.056	0.048	0.042
$\Delta P_{Q^*}$ , %	1.971	0.763	0.454	0.322	0.249	0.204	0.173
$\Delta P_{n^*}$ , %	0.615	0.478	0.395	0.336	0.291	0.256	0.229
$\Delta P_{Qq^*}$ , %	1.072	0.754	0.595	0.492	0.419	0.365	0.323
$\Delta P_{Qr^*}$ , %	1.514	0.488	0.254	0.166	0.121	0.096	0.079
$\Delta P_{\Sigma^*}$ , %	15.55	9.103	6.507	5.082	4.173	3.542	3.087
$\Delta P_{add}*$ , %	2.786	1.359	0.935	0.725	0.597	0.509	0.445
$\Delta P_{\Sigma'}$ , kW	125.3	48.71	26.08	16.3	11.15	8.11	6.165
δ,%	-0.57	-0.344	-0.26	-0.21	-0.18	-0.158	-0.14
$\Delta U$ , %	11.31	7.163	5.26	4.161	3.443	2.936	2.56
η	0.865	0.916	0.939	0.952	0.959	0.965	0.97

Table 2. Simulation results for measuring the total loss power components (mode 1)

Table 3. Simulation results for measuring the total loss power components (mode 2)

k <sub>l</sub>	0.1	0.25	0.5	1	2	10	$\infty$
k <sub>sc</sub>	11.63	13.65	16.99	21.28	25.47	31.28	33.37
P <sub>usf</sub> , kW	687.5	586.2	471	375.9	314	255.8	239.8
$\Delta P_{\min}$ , kW	74.85	51.08	31.61	19.55	13.41	8.753	7.661
$\Delta P_{puls}$ , kW	8.232	3.522	0.691	0	0.289	1.036	1.325
$\Delta P_Q$ , kW	150.5	28.96	5.529	1.404	1.864	3.621	4.266
$\Delta P_n$ , kW	115.6	26.45	4.01	0	1.31	4.588	5.778
$\Delta P_{Qq}$ , kW	224.4	44.57	6.253	0	1.897	6.494	8.13
$\Delta P_{Qr}$ , kW	41.73	10.84	3.287	1.404	1.278	1.715	1.913
$\Delta P_{\Sigma}$ , kW	349.2	110	41.84	20.95	16.86	18	19.03
$\Delta P_{add}$ , kW	274.3	58.93	10.23	1.404	3.453	9.245	11.37
$\Delta P_{ m min^*}$ , %	10.88	8.713	6.711	5.201	4.269	3.422	3.195
$\Delta P_{puls^*}$ , %	1.197	0.6	0.147	0	0.089	0.405	0.553
$\Delta P_{Q^*}$ , %	21.89	4.941	1.174	0.373	0.594	1.416	1.779
$\Delta P_{n^*}$ , %	16.81	4.512	0.852	0	0.417	1.794	2.41
$\Delta P_{Qq^*}$ , %	32.63	7.603	1.328	0	0.604	2.539	3.391
$\Delta P_{Qr^*}$ , %	6.067	1.85	0.698	0.373	0.407	0.671	0.798
$\Delta P_{\Sigma^*}$ , %	50.77	18.77	8.883	5.574	5.369	7.037	7.936
$\Delta P_{add^*}$ , %	39.89	10.05	2.127	0.373	1.1	3.615	4.741
$\Delta P_{\Sigma'}$ , kW	341.7	110.7	41.99	20.95	16.9	18.1	19.14
δ,%	2.17	-0.628	-0.376	0	-0.228	-0.557	-0.595
$\Delta U$ , %	8.177	7.65	6.244	4.952	4.082	3.248	3.018
η	0.668	0.841	0.918	0.947	0.949	0.933	0.926



**Figure 10.** Dependence of the supplementary power losses on the  $k_{sc}$  coefficient

#### CONCLUSIONS

It is proved that to measure the components of total loss power in three-phase four-wire PSS it is enough to have information about instantaneous values of cable line phase currents and voltages at load terminals. Thus, a meter can be created for determining the loss power components in the low-voltage PSS, which should be connected at the end of the cable line at the place of electrical input to the power supply object.

A new four-component model of the total loss power components has been developed that makes it possible to take into account the main causes of electric power losses during its transmission from the power source to the load in low-voltage three-phase four-wire PSSs. The model allows describing the physical causes of electric power losses in low-voltage PSSs and to plan measures for their elimination.

Using the mathematical apparatus of the modern power theory, analytical relations for the four components of the total loss power have been obtained: the minimum possible loss power; the loss power caused by pulsations of instantaneous active power; the loss power caused by the presence of calculated reactive power in the PSS; the loss power caused by current flowing in the neutral conductor of the three-phase PSS, the last three of which are additional and subject to compensation.

Each of supplementary components of the total loss power is proportional to the minimum possible loss power and to the square of the RMS value of the power, which is caused by its occurrence in three-phase four-wire PSS, and it is inversely proportional to the mean square of the net power loss, calculated in the period of repeatability of energy processes T.

For more accurate calculation of supplementary power losses in the low-voltage three-phase PSS, it is advisable to use a detailed daily power supply profile for each object under study, which will make it possible to take into account the instantaneous power pulsations at lower frequencies of the industrial network frequency.

Also proposed is an alternative four-component model of the total loss power components built on the basis of the *pqr* power theory and presents an interpretation of the new four-component model. The model shows that the projections of reactive power vectors on the *q* axis, one of which is associated with asymmetry of the three-phase system and the current flowing in the neutral conductor, and the other with the phase shift of the fundamental harmonic of the phase currents relative to the corresponding phase voltages that are non-collinear, but simultaneously eliminated in compensation for the projection of the space current vector on the *r* axis.

Correctness of the proposed four-component models is tested on the created Matlab model of the three-phase four-wire PSS model with a parallel power active filter. The results of simulation of various operation modes of the three-phase PSS confirmed the high accuracy of calculation of the total loss power by the components of the fourcomponent model. For the majority of cases, the calculation error of the total loss power does not exceed 0.5%.

#### DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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## Декомпозиційна чотирикомпонентна модель для розрахунку втрат електроенергії в низьковольтних системах електропостачання

Дмитро Тугай, Олександр Шкурпела, Валентин Акимов, Іван Костенко, Олександр Плахтій

Анотація. Запропоновано нову модель декомпозиції загальної потужності втрат на чотири компоненти. Кожен із компонентів запропонованої моделі має певний фізичний зміст, обумовлений природою електромагнітних процесів, що відбуваються у трифазній чотирипроводовій системі електропостачання. Сформульовано визначення для опису кожного із запропонованих компонентів. Показано, що кожна з додаткових складових загальної потужності втрат пропорційна мінімально можливій потужності втрат і квадрату середньоквадратичного значення потужності, що викликано її виникненням у трифазній чотирипроводовій системі живлення, а також обернено пропорційна квадрату середнього значення корисної потужності. Синтезована модель Matlab для перевірки чотирикомпонентної структури потужності втрат показала високий ступінь її адекватності. Запропонована модель дозволяє переглянути опис потужності втрат в трифазних колах змінного струму і може бути використана в спеціалізованих вимірювальних приладах для моніторингу електричних мереж. Використовуючи інформацію, отриману в процесі моніторингу, можна планувати технічні заходи щодо зменшення втрат електричної енергії в системі електропостачання, а також оцінювати капітальні витрати на реалізацію цих заходів.

Ключові слова: декомпозиція, чотирикомпонентна модель, система електропостачання, потужність втрат, електрична енергія, Matlab-модель.

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