Результаты. Проведен анализ физической модели процесса, происходящего при отдаче тепловой энергии от потока выхлопного газа в трубопроводе генератора, и определен принцип расчета его основных параметров. Разработана математическая модель теплообмена в трубопроводе блочного термоэлектрического генератора. Создана программа на базе программного обеспечения Wolfram Mathematica и проведен расчет соответствующих параметров для каждого блока при различных нагрузках ДВС. Технически обосновано создание устройства для рекуперации выбрасываемой наружу энергии топлива для ДВС легковых автомобилей. Соответствующим устройством является термоэлектрический генератор блочной структуры, который работает на тепловой энергии выхлопных газов. Предложено использовать воздушное охлаждение для получения оптимального КПД преобразования. Показана возможность получения при его использовании до 1 кВт электрической энергии.

Научная новизна. Разработано инновационное устройство по утилизации энергии выхлопных газов для существующих моделей автомобилей. Впервые предложено и обосновано структурное разделение термоэлектрического генератора на три блока, которые работают как отдельные термоэлектрические генераторы, а также введение внутрь газового потока полого цилиндра с продольными ребрами на поверхности для улучшения теплопередачи за счет излучения.

Практическая значимость. Использование предложенного термоэлектрического генератора позволяет провести замену электромеханического генератора автомобиля с последующим использованием избыточной энергии рекуперации. Энергия, сохранённая в результате рекуперации, в пересчете на потребляемое топливо составляет не менее 2 %, что является важным как в экономическом, так и в экологическом аспектах.

Ключевые слова: *энергосбережение, термоэлектрический генератор, утилизация, выхлопные газы*

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SYMMETRIZATION OF THREE-PHASE SYSTEM WITH NEGATIVE COMPONENT FILTER USING SIMULATION

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СИМЕТРУВАННЯ НА МОДЕЛІ ТРИФАЗНОЇ СИСТЕМИ З ФІЛЬТРОМ ЗВОРОТНОЇ СКЛАДОВОЇ

Purpose. The determination of the optimal mode of asymmetric three-phase electrical system using the symmetrical component filters and computer power system model is considered.

Methodology. The system is represented as a visual model that uses a resistive-capacitive filter to select reverse symmetrical components. Its amplitude is a function of the target value, which in the process of optimization is reduced to zero. The variables used to be optimized are the parameters of the balun. Optimization is performed by a zero-order method.

Findings. In the process of optimizing the balun device parameters are calculated. The power supply system is set to symmetrical mode. Changing the angle of the line currents with respect to the phase voltages by changing the parameters of the balun device, and at the same time symmetric mode in the system is maintained. Thus the optimum mode can be achieved in which the reactive power in the power system is fully compensated.

Originality. A new approach to the problem of balancing the three-phase power supply systems based on the use of the visual system models and optimization techniques is proposed. The principles of formation of the objective function in order to achieve a symmetrical mode are formulated. The possibility of using filters of symmetrical components for this purpose is shown. The method of exclusion of their direct impact on the power system with dependent sources is found.

Practical value. The proposed method does not require special measuring devices and may be easily implemented in practice. The method is characterized by high accuracy and reliability. It can be used in a digital implementation of balancing system based on the use of microcontrollers. It does not require complex processing of signals removed from the voltage sensors.

Keywords: *three-phase system, unbalance, reactive power, symmetrical component filters*

Introduction. The emergence of unsymmetrical modes is representative of a number of consumers in public utilities, agriculture, steelmaking, railway electric transport [1, 2]. In these cases, separate phases of the system are unevenly loaded, which can be treated as equivalent single-phase load connection, distorting the symmetric mode. In addition to the reactive power *Q*, mainly due to inductive load nature, additional reactive power *N* emerges, conditionally called reactive power of asymmetry [3]. When sinusoidal currents occur, in order to optimize the mode it is necessary to compensate both components of reactive power. For this purpose, reactive symmetrical elements are connected to the terminals of unbalanced load. They alter amplitudes and phases of currents in power lines, without any losses. At the same time amplitudes of the currents become equal, and phases of the currents should coincide with the phases of the supply voltages. In this case, transmission losses of electrical energy from the source to the load became minimum, i.e. this mode is optimal.

Calculation of parameters of balancing elements, as it was shown in the fundamental works of A. K. Shydlovskyi, V. Kuznetsov, V. A. Venikov, is a rather complicated nonlinear problem. Its content is reduced to finding the types of reactive elements and the values of their parameters, which depends entirely on the system parameters and loads.

In some cases, the problem is simplified, by neglecting a number of factors, and the approximate analytical and graphical methods are used. The methods are based on calculations of such currents of the balun that could compensate for the symmetric component of the reverse sequence. Further, depending on the magnitude of the inverse vector component and its phase formula for determining the parameters of the balancing device has been selected.

However, the solution of the problem, in full view of its non-linearity is only possible with the use of numerical methods implemented in computer mathematics systems. In [3] the possibility of such solutions with use of search optimization is shown. In these works models of asymmetrical three-phase systems with a balancing device connected to the terminals of load are used. The problem is stated as an optimization one, where the variables of optimization parameters are the values of balancing elements. The optimization criterion is reducing to zero reactive powers consumed from sources of electrical energy. In the model, such measurements do not cause difficulties, because it can be connected to required virtual instruments at the terminals of generators of electrical energy.

This makes it possible to measure the voltage at each source and the current supplied to it. From these data, the total power is calculated using a virtual meter of active and reactive power. The use of indications of the reactive powers of the sources of electrical energy makes it possible to form the objective function for optimization, which is a ball metric composed of the coefficients for imaginary parts of the total power. This optimization criterion is characterized by simplicity and high reliability in solving the problem of optimizing the regime. In practice, not all of the required measurements are available on the side of electricity energy consumers. The only accessible part of the system for them is the one which relates directly to the load. In addition, the guidelines contain only asymmetry coefficient for voltage at the customers' terminals and the limit values (2–4 %) must be provided with electricity consumption by asymmetrical loads.

The objective of the article is development of optimization method of asymmetrical mode of three-phase three-wire power supply system on the visual model by use of search optimization, where the objective function is formed as a result of measurements on the side of the load by means of a filter for symmetrical component of negative sequence.

Presentation of the main research. We will consider a generalized asymmetric three-phase three-wire system. Its visual model simulated in system SimPowerSystem is shown in Fig. 1.

The amplitudes of the supply voltages are 100 V, the frequency is 50 Hz. Complex resistances of electric power lines are taken equal $(0.1 + j\omega 0.001)$ ohms. Load resistances in phases *A*, *B*, *C*, are correspondently $(0.7 + j\omega 0.005)$, $(1.0 + j\omega 0.01)$, $(2.0 + j\omega 0.04)$ ohm, where $\omega = 2\pi f$ – circular frequency of the line voltages, which represent the symmetrical three-phase system.

To measure the symmetrical component of negative sequence of three phase voltage at the load terminals the filter for negative sequence was connected to them. The resistive-capacitive circuit of the filter was selected, which is represented in Fig. 1 by elements *Ca*, *Ra*, *Cc*, *Rc*. Calculation of parameters of filter elements were carried out by the system of computer mathematics MathCAD. For frequency of supply voltages, the following parameters of the selected filter were received, which satisfy conditions of separating negative sequence voltage at complete suppression of positive sequence voltage: Ca = 5.513289 uF; Cc = 3.183099 uF; Ra = 1000 ohms; Rc = 577.350269 ohms. It should be noted that this variant of the parameters is not unique, since the problem of determining the parameters of symmetric component filters has a number of solutions even for one selected filter scheme. Variation of the parameters will lead to a change in the equivalent Q of the designed filter. However, attention is drawn to the fact that the capacitances of the filter capacitors are relatively large. The direct connection of the symmetric component filter to the power supply system has an effect on the mode in the system, and this effect can be quite noticeable.

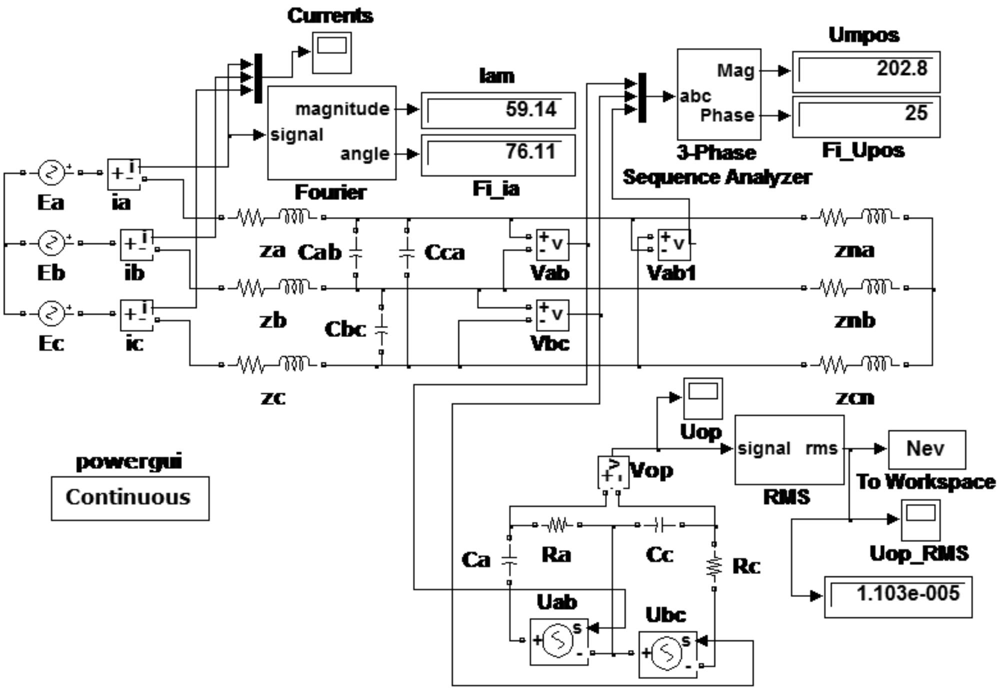

Fig. 1. Visual model of the generalized three-phase system of power supply

In the visual model of the power supply system, this effect can be eliminated. In order to avoid the direct influence of elements of the negative sequence filter on the processes in the power part of the circuit and distortion of the research results in the model the filter was not connected to the load terminals directly. It is rational to connect filter to three terminals, which repeat linear voltages on the load using dependent voltage sources *Uab* and *Ubc* (Fig. 1) controlled by signals from the virtual voltmeter *Vab* and *Vbc*. In the model the output voltage of the filter is measured by virtual voltmeter *Vop* and fed to the effective value measurer *RMS*. The output signal of the last device is used as the value of the objective function of optimization.

The optimization program *fminsearch* is a built-in MATLAB function, which includes, as the required parameters, the name of the file-function which delivers the value of the objective function. The file-function contains a call to the model, which is drawn up in the worksheet using the elements of SimPowerSystem library. In order to bind variables of optimization with the value of the objective function in the model, the file-function and the main program, these variables are declared as global. From the model into the programs the objective function value, announced by the name of Nev, is transferred to the MATLAB workspace by a special block To WorkSpace. The texts of the call program and the file-functions are shown in Fig. 2, *a, b,* respectively. After optimization finishing the obtained values of optimization variables and the objective function can be taken from the workspace with the necessary number of significant digits.

It is necessary to note that in general case balancing of power supply system can be achieved by a variety of combinations of parameters of a balancing device. Reached values of optimization parameters are dependent on the initial values of the optimization variables vector. The course of the optimization process is determined by the optimization algorithm by deformable polyhedron method and has random character.

This method is a method of the so-called direct search. In its work it does not require the calculation of derivatives of the first and second order, but uses calculations of the objective function itself at several adjacent

```
warning off
global Cab Cbc Cca Nst Nev
Nst = 0
Y = fminsearch('func_s3fnesim',[700 1000 200])
Nst
```

a

```
function Nev = func_s3fnesim(x)
global Cab Cbc Cca Nst Nev
Cab = abs(x(1)*1E-6)
Cbc = abs(x(2)*1E-6)
Cca = abs(x(3)*1E-6)
sim s3fnesim3FOP_CSofV
Nev
Nst = Nst + 1
```

b

Fig. 2. Texts of programs:
a – calling function; b – file-function

points. In this case, the so-called simplex is constructed, which is a polyhedron in a multidimensional space. In the process of implementing the optimization algorithm, this polyhedron is subjected to reflection, expansion, outside and inside constrictions and shrink operations. This causes the polyhedron to move along the hyper surface of optimization in the direction of the required minimum. The trajectory of the displacement of the deformed polyhedron is unpredictable in advance and depends on many factors. One of these factors is the vector of initial values of the optimization variables. In the problem under consideration, the solution is further complicated by the fact that only the balancing of the power supply system is required. Symmetric mode can be achieved not by a single method, that is, the problem has an ambiguous solution. On the one hand, this circumstance makes it easier to find the optimal solution, since we are talking about finding not a global optimum, but only one of the set of local optima. This disengages the optimization parameters from the need to bring the solution to a single point of the global optimum further contributes to the random character of the behavior of the trajectory of the deformed polyhedron.

In Table, optimization results for the three cases of initial values of the optimization variables vector are represented.

The simulation was carried out by method ode23 (stiff/Mod. Rosenbrock) at the maximum allowable step of integration 0.0001 s. Diagrams of currents in power lines in the absence of a balancing device are shown in Fig. 3.

The amplitudes of the currents in phases *A*, *B*, *C*, respectively, are 31.5 A, 31 A and 10.34 A. The amplitude of the symmetric negative sequence component for linear voltages on the load is 10.8 V. The amplitude of the direct sequence is 160.1 V. Thus, the ratio of these amplitudes, which is the voltage asymmetry coefficient, is 6.75 %, which is 2–3 times higher than the maximum permissible values.

The model in Fig. 1 shows the state of the instruments after optimization for the third option. It should be noted that balancing with the full reactive power compensation corresponds to the options with parameters *Cab* = 562.1295 μF; *Cbc* = 182.3177 μF; *Cca* = = 34.465 μF. For this case the amplitudes of the currents in the wires of power line are minimal and amount value 7.754 A, and all the line currents completely coincide with its phase voltages of sources of electrical energy, which corresponds to unit power factor. Comparing the results of the optimization, it can be seen that the closest to the symmetrization option with absolute compensation of reactive power was the second option, which is characterized by the least values of the shift angle of current and its amplitude. The other options provide balancing with overcompensation mode on reactive power. For these options advanced angle of the current in the power lines and large quantities of capacitances of the compensation capacitors are characterized in comparison with the option of full reactive power compensation. The amplitudes of the linear voltages on the load increase and exceed the voltages in the beginning of the power line.

To bring the system to optimal mode a method of vectors rotation of currents in power lines is proposed. The rotation is implemented by changing the capacitances values of capacitors batteries to the same value.

Table

The optimization results for different initial values of the variable vector

Research options	Parameters of the research options		
Number of option	1	2	3
Initial values of vector **x** (μF)	[7 10 12]	[70 100 120]	[700 1000 1200]
Capacitances of the balancing capacitors:			
Cab	213.6047	553.6363	1089.6738
Cbc	433.7939	173.8255	709.8629
Cca	285.9409	25.2725	562.0100
Amplitude and phase of current in phase A:			
$I_{Am}(A)$	25.91	7.756	5914
φ_A (electrical degree)	68.93	–5.814	76.11
Amplitude and phase of positive component of line voltage on load:			
U_{LVL} (B)	185.4	171.5	202.8
φ_{LVL} (electrical degree)	27.03	28.64	25.00
Amplitude of negative component of line voltage on load:	8.18E–6	6.943E–6	9.982E–6
Capacitances of capacities for two-capacitors balancing:			
Cab	527.6638	527.6638	527.6638
Cbc	147.8530	147.8530	147.8529

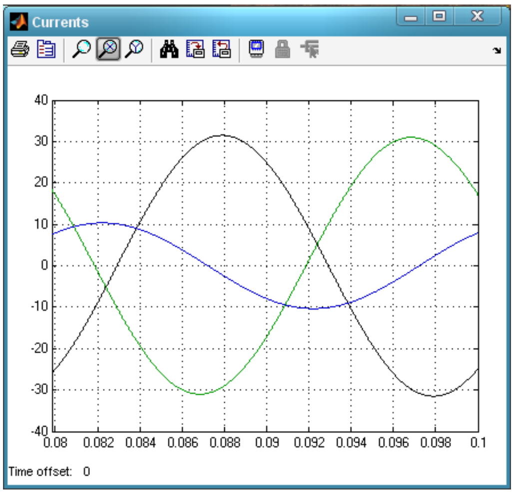

Fig. 3. Line currents in asymmetric mode

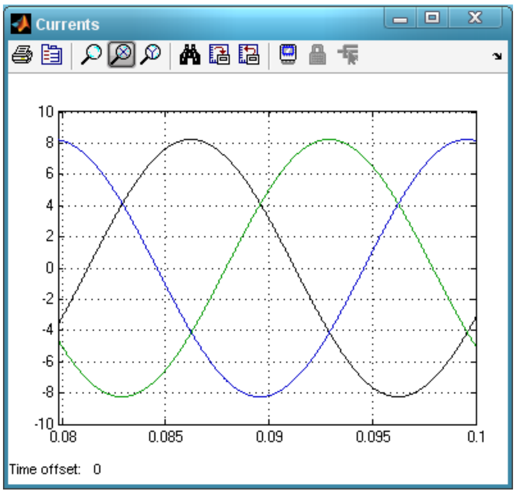

Fig. 4. Current in the line with two-capacitor balancing

Since the reactive power of balancing device is changing to the same value on each phase, the symmetry of currents in power lines is not violated. Identification of the onset of optimal mode with the full reactive power compensation can be carried out in several ways. You can measure the reactive powers delivered by each source of energy – in the optimal mode, they must become equal to zero. You can identify the optimal mode, watching decreasing of the absolute value of the current shift angle in the line against the corresponding phase voltage to zero. Finally, when the mode is optimal, amplitude of each line current becomes the minimum, which indicates the optimum mode input. The last method is the most appropriate from the point of view of practical implementation, because it is limited by the minimum volume measurement.

Boundary case of the rotation of linear currents vectors is reduction of the value of capacity of balancing capacitor with minimal capacity to zero. This capacitor, in such a way is being excluded from the balancing device, and the system operates in a symmetrical mode with a two-capacitor balancing device. Calculating of capacities of the two-capacitor balancing device is implemented by subtracting from the values of capacities of three-capacitors balancing device a minimum capacity. The results of these calculations for all three options are given in the last line of Table 1. Calculation of parameters of the two-capacitor balancing device from the optimal mode gives accurate results: $Cab = 527.6645$ μF; $Cbc = 147.8527$ μF. As it can be seen from the comparison, obtained results coincide with the six significant digits. Checking on the model modes with the two-capacitors balancing device confirmed the high accuracy of the calculation of symmetrical mode in power supply system.

Fig. 4 shows diagrams of linear currents for the case of two-capacitor symmetrization.

The currents in the line have the same amplitudes of 8.24 A, and the amplitudes of the reciprocal and direct symmetrical components for the line voltages are 2.66 E-5 V and 170.2 V, which causes a practically zero coefficient of asymmetry.

Fig. 5 shows the diagrams of linear currents with full compensation of reactive power in the system. The parameters of the compensating capacitors for this case are obtained as a result of the proposed rotation procedure. For this, the capacitances of all three capacitors were simultaneously increased, ultimately, by 34.465 μF in comparison with the two-capacitor balancing variant. The amplitudes of the linear currents decreased to 7.754 A, which provides a reduction in losses in the transmission line by 13 % compared to the two-capacitor symmetrization and by more than 30 times compared with the version where the balun is absent.

Conclusions.

1. The proposed method for calculation of the optimal mode in an asymmetrical three-phase power supply system on the basis of visual models and optimization techniques allows avoiding complex calculations and finding the solution for the optimal mode to high precision.

2. For implementing the method the algorithm is proposed for linking the program MATLAB optimization system with a visual model of electric supply system SimPowerSystem.

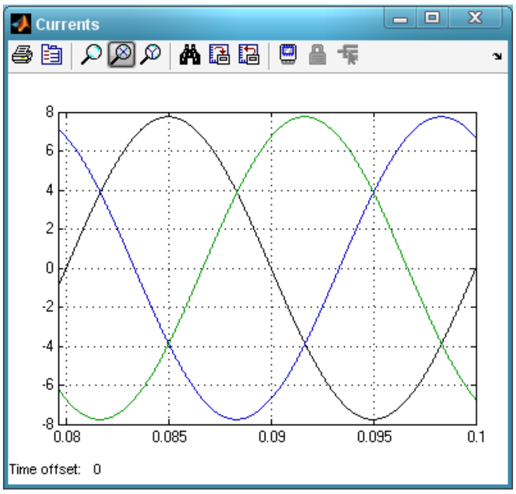

Fig. 5. Line currents when full compensation

3. For the calculation of the objective function in process of optimization it is effective to use the symmetrical component filter of the reverse sequence. Elimination of the direct impact of the filter on the power supply system is achieved by introduction of dependent sources of voltage, whose output signals are brought to the filter.

4. Computer experiments with the model showed that depending on the initial values of the balancing device parameters in the process of optimization, the various parameters of symmetrical mode and of balancing device are achieved.

5. An effective calculation technique of vectors rotation of linear currents with symmetry conservation was proposed and tested. This allows passing to the full reactive power compensation mode in the power supply system, in which the losses become minimal.

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Мета. Визначення оптимального режиму трифазної несиметричної електричної системи за допомогою фільтрів симетричних складових і комп’ютерної моделі системи електропостачання.

Методика. Система представляється у вигляді візуальної моделі, що за допомогою резистивно-ємнісного фільтра виділяє зворотну симетричну складову. Її амплітуда є значенням цільової функції, що у процесі оптимізації зводиться до нульового значення. Змінними оптимізації є параметри симетруючого пристрою. Оптимізація виконується методом нульового порядку.

Результати. У процесі оптимізації обчислюються параметри симетруючого пристрою. У системі електропостачання встановлюється симетричний режим. Зміна кута зсуву лінійних струмів щодо відповідних фазних напруг здійснюється зміною параметрів симетруючого пристрою, і при цьому в системі зберігається симетричний режим. Таким чином, може бути досягнутий оптимальний режим, за якого реактивна потужність у системі електропостачання повністю компенсується.

Наукова новизна. Розроблено новий підхід до проблеми симетрування трифазних систем електропостачання, заснований на застосуванні візуальної моделі системи й методів оптимізації. Сформульовані принципи формування цільової функції для досягнення симетричного режиму. Показана можливість застосування для цієї мети фільтрів симетричних складових і спосіб виключення їх безпосереднього впливу на систему електропостачання за допомогою залежних джерел.

Практична значимість. Запропонований метод не вимагає спеціальних вимірювальних приладів і може бути легко реалізований на практиці. Метод характеризується високою точністю й надійністю. Він може бути використаний за цифрової реалізації системи симетрування на основі застосування мікроконтролерів. При цьому не потрібно складної обробки сигналів, що знімаються з датчиків напруги.

Ключові слова: *трифазна система, несиметрія, реактивна потужність, фільтри симетричних складових*

Цель. Определение оптимального режима трехфазной несимметричной электрической системы с помощью фильтров симметричных составляющих и компьютерной модели системы электроснабжения.

Методика. Система представляется в виде визуальной модели, которая с помощью резистивно-емкостного фильтра выделяет обратную симметричную составляющую. Её амплитуда является значением целевой функции, которая в процессе оптимизации сводится к нулевому значению. Переменными оптимизации служат параметры симметрирующего устройства. Оптимизация выполняется методом нулевого порядка.

Результаты. В процессе оптимизации вычисляются параметры симметрирующего устройства. В системе электроснабжения устанавливается симметричный режим. Изменение угла сдвига линейных токов относительно соответствующих фазных напряжений осуществляется изменением параметров симметрирующего устройства, и при этом в системе сохраняется симметричный режим. Таким образом, может быть достигнут оптимальный режим, при котором реактивная мощность в системе электроснабжения полностью скомпенсирована.

Научная новизна. Разработан новый подход к проблеме симметрирования трехфазных систем электроснабжения, основанный на применении визуальной модели системы и методов оптимизации. Сформулированы принципы формирования целевой функции для достижения симметричного режима. Показана возможность применения для этой цели фильтров симметричных составляющих и способ исключения их непосредственного влияния на систему электроснабжения при помощи зависимых источников.

Практическая значимость. Предложенный метод не требует специальных измерительных приборов и может быть легко реализован на практике. Метод характеризуется высокой точностью и надежностью. Он может быть использован при цифровой реализации системы симметрирования на основе применения микроконтроллеров. При этом не требуется сложной обработки сигналов, снимаемых с датчиков напряжения.

Ключевые слова: *трехфазная система, несимметрия, реактивная мощность, фильтры симметричных составляющих*

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