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Application of phase portraits for estimation of reactive power of electric circuits

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Abstract. In this paper we consider the principal possibility of using the estimation of the reactive power of electric circuits by phase portraits of electric current oscillations. The shift of the phase angle of current and AC voltage oscillations relative to each other is displayed on the phase portrait of oscillations by bifurcation of the phase trajectory. The region described by the phase trajectory corresponds to the reactive power. Reactive power must be kept to a minimum to produce an energy efficient power supply. As an optimization criterion it is proposed to use the size of the phase portrait area of stationary oscillations of alternating current. Simulation of the optimization process was carried out on the basis of numerical solution of the system of differential equations using dynamic programming methods. Typical functions of numerical solution of systems of differential equations and optimization of the target function, available in mathematical packages, were used.

1. Introduction

The safety and cost-effectiveness of power systems depend to a large extent on the availability of reactive power. Management and optimization of reactive power is currently receiving increased attention.

In [1] attention is drawn to the fact that the nature of voltage stability in the power grid can be analyzed by studying the generation, transmission and consumption of reactive power.

A number of researches are devoted to methods of evolutionary calculations at optimization of reactive power [2], algorithms of control of tension and reactive power [3], [4], adaptive algorithms [5], [6].

The issues of multi-purpose optimization of active power losses, voltage deviations, static voltage reserve and reactive power compensation are considered [7]. Separately, it should be noted the issues related to the dispatching of reactive power [8].

At the hardware level, the issues of reactive power compensation using thyristor compensators [9], SAPF compensators [10], in GRID-systems [11] are considered.

2. Materials and Methods

The peculiarity of AC electric circuits is the shift of current and voltage fluctuations relative to each other, introduced by inertial links-inductances and capacitances. The divergence of oscillations is characterized by a phase shift, the magnitude of which depends on the reactive power.

Of interest is the consideration of changes in current and voltage without taking into account time, that is, obtaining a phase portrait of oscillations-a picture in which the change of parameters relative to each other is represented, and not relative to time [12].

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In the steady-state mode, the oscillations of the parameters of the electric circuits of alternating current are strictly periodic, repetitive, which greatly simplifies the obtaining of a phase portrait. It should be noted that currently existing mathematical packages (MATLAB, MathCAD) allow to obtain acceptable solutions with minimal costs.

It is generally accepted to consider phase portraits of dynamic objects in relation to the stability analysis of their regime [13].

Phase trajectories, as components of the phase portrait, make it possible to simply and visually represent the presence of reactive power in the operation of AC electrical circuits.

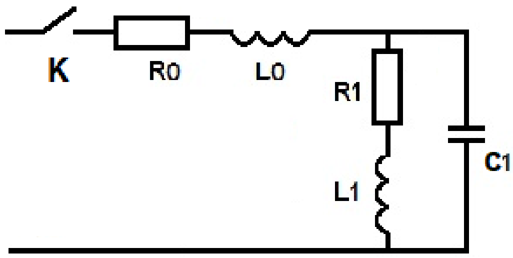

Figure 1. Diagram of a typical electrical circuit.

A typical electrical circuit (Figure 1) contains a power branch with key K, resistance R0 and inductance L0, as well as a load of resistance R1, inductance L1 and capacitance C1. The scheme corresponds to a system of three differential equations, of which two equations describe the dynamics of the current at the input to the circuit and in the load branch with resistance R1 and inductance L1, and the third equation-the voltage change at the capacitance C1. The input of the circuit is supplied with a voltage varying according to the sinusoidal law.

Typical functions of numerical solution of systems of differential equations in the form of Cauchy (Mathcad package) were used for modeling. The system of equations was transformed to the matrix form with the allocation of derivatives of the first order. The result of the numerical solution of the system of differential equations is a table of values describing the graphs of the behavior of the parameters (Figure 2).

The above parameters R0, R1, inductance L0, L1 and capacitance C1 determine the nature of the transition process that occurs in the circuit when switching the key K.

Under zero initial conditions, the change in the parameters of the alternating current acquires the character shown in Figure 2.

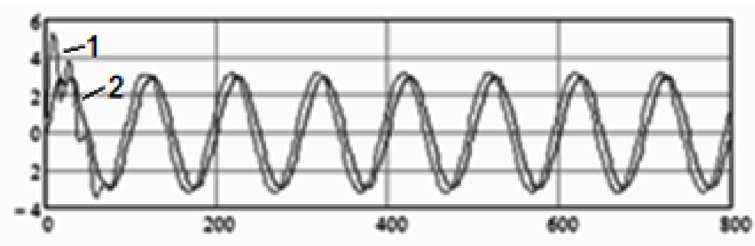

Figure 2. Transient in the presence of reactive power: 1 – the current in the initial branch; 2 – the voltage between nodes.

The discrepancy between the current and voltage fluctuations on the phase shift is clearly traced. During one period, the fluctuations take a steady character.

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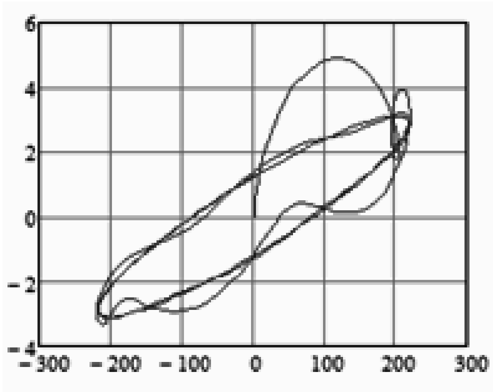

Figure 3. Phase portrait of current fluctuations taking into account the transition process.

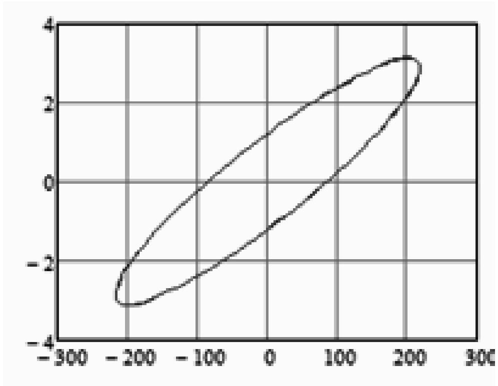

Figure 4. Phase portrait of current fluctuations without taking into account the transition process.

The phase portrait of the oscillations corresponding to the transition process (Figure 2) is shown in Figure 3. The abscissa axis of the phase portrait corresponds to a change in voltage, the ordinate axis-a change in current.

If the transition process corresponding to the switching of the key is excluded from the phase portrait, the phase portrait of steady – state oscillations will be obtained-Figure 4. The reference point in time for steady-state oscillations is the mark «200» on the horizontal axis of the Figure 2 diagram.

The phase portrait for steady-state oscillations is determined by a closed phase trajectory in the form of an ellipse whose axes depend on the phase angle between the current and voltage oscillations.

The Diagram of Figure 5 is a voltage characteristic that displays the dynamics of the behavior of the current and voltage relative to each other. The inclined line «a-b» corresponds to the phase portrait without reactive power, that is, with synchronous oscillation of current and voltage: the ellipse «acbd» does not have a small half-axis OS and degenerates into a segment of the straight line «ab». The area of the «acbd» figure corresponds to the reactive power due to the phase shift of the current and voltage oscillations.

-1×10^4

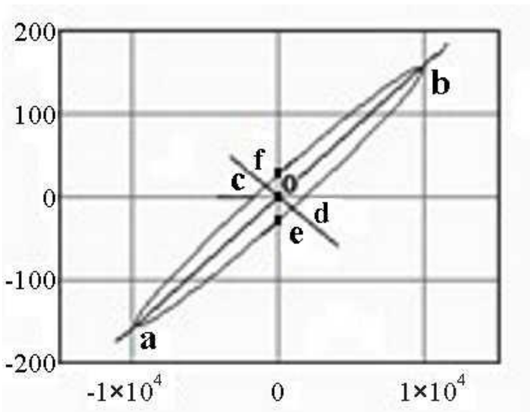

Figure 5. Phase portrait of steady-state oscillations.

For the replacement circuit (Figure 1), you can choose the value of the capacitance C so that the current and voltage fluctuations become common-mode (Figure 6).

This combination of parameters of the electric circuit will correspond to the transition process with the phase portrait in Figure 7, and for steady-state oscillations-the phase portrait in Figure 8.

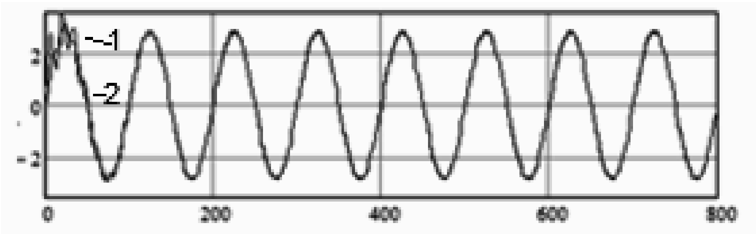

Figure 6. The transition process in reactive power compensation: 1 – the current in the initial branch; 2 – the voltage between nodes.

3. Results

It is of interest to optimize the parameters of the power supply system to achieve a minimum reactive power. The solution of the problem is carried out on the basis of numerical simulation of the system of differential equations using dynamic programming methods [14], [15].

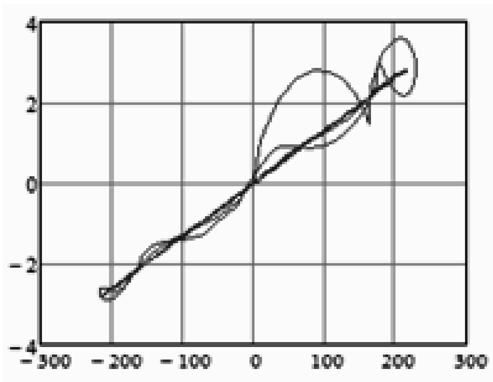

Figure 7. Phase portrait of current fluctuations taking into account the transition process.

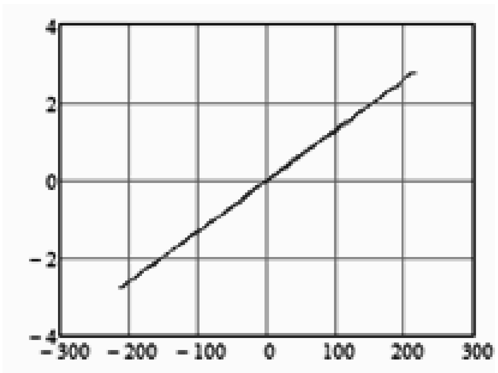

Figure 8. Phase portrait of current fluctuations without taking into account the transition process.

The algorithm for solving the problem consists of several steps:

1. For a fixed combination of parameters a system of differential equations is solved and the reactive power is determined.

2. On the basis of the search algorithm of the optimization function the parameters of the electric circuit are changed.

3. Step 1 for new parameters is executed.

4. The calculated variants are compared according to the selected criterion and the parameters of the optimal variant are fixed. If the compared variants differ from each other by an amount less than the allowable value, the calculation is terminated, otherwise paragraph 1 is performed.

The software implementation of the algorithm is based on combining the matrix equation with the optimization function of minimum search [16].

Typical algorithms and functions of Math Cad package were used. The matrix solution of the system of differential equations was formed as a function that returns the value of the parameters processed by the target function. When calling the optimization function of the Math Cad package, the reference to the function of solving the system of differential equations was passed as the first parameter.

The objective function, as a mathematical record of the optimality criterion, has the form

$$Z(C1, C2, C3) \rightarrow \min \tag{1}$$

where C1, C2, C3 – the desired variables, the values of which are determined in the process of solving the problem, the combination of values of these parameters should ensure the achievement of the minimum reactive power.

The objective function, as a mathematical record of the optimality criterion, has the form.

Taking into account the fact that the search is conducted for the ranges of possible changes in the parameters, the problem is reduced to conditional optimization.

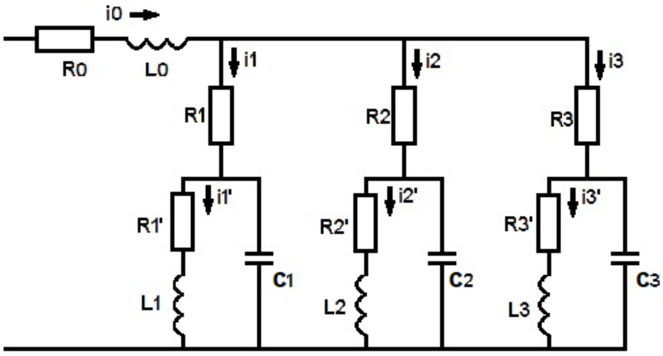

Figure 9. Design scheme for radial power supply scheme.

The radial scheme of power supply was modeled (Figure 9). The behavior of the electric current in the circuit of three load branches is described by a system of differential equations of the seventh order, which includes three equations of current changes in the branches of the load, three equations of voltage changes in the branches of capacitive reactive power compensators, and the equations of current changes at the input to the circuit.

The system of differential equations was reduced to the Cauchy form and solved by the 4th order Runge-Kutta numerical method with automatic step selection. The transient process arising as a result of connection to the circuit of an alternating voltage source was simulated. The initial conditions for the variables of the considered system were assumed to be zero.

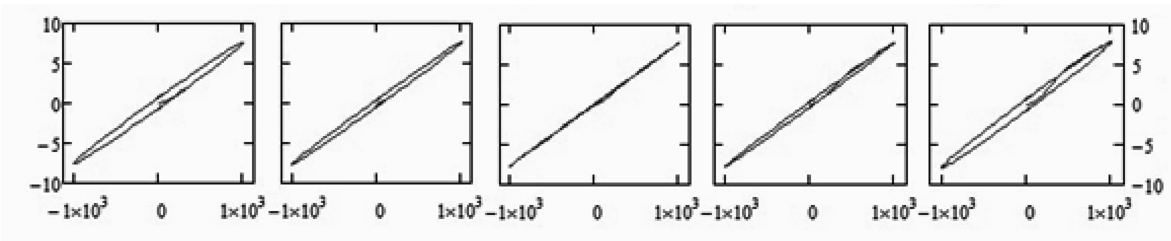

Figure 10. Evolution of the phase portrait of electric current oscillations with successive increase of the capacitance value.

On the basis of the obtained solutions (the change of the current at the input to the circuit and in the branches of the load, as well as the voltage at the terminals of the capacitors in time), the phase portrait "input current – input voltage».

The influence of capacitance of capacitors on reactive power was analyzed. Figure 10 shows the evolution of the phase portrait of the electric current oscillations with a sequential increase in the capacitance of the capacitor. It is obvious that there is a certain capacitance value at which the area of the figure described by the phase trajectory is zero.

The combination of calculation blocks implementing the solution of the system of differential equations and optimization search allowed to compose the program of optimization of the considered scheme on reactive power. As the target function, the value of the characteristic size of the phase portrait (Figure 5) «ef» was taken, as the optimization parameters – the value of the capacitances of reactive power compensators.

4. Discussion

The above approach is justified when taking into account the nonlinearities of electrical circuits, such as relay switching functions, hysteresis of magnetic circuits, mutual inductance of branches, the influence of temperature on the resistance of conductors, etc. It is of particular importance in the analysis of the stability of nonlinear dynamical systems.

In the case of considering the dynamics of nonlinear systems the application of generally accepted methods of the theory of automatic control requires a careful approach to the linearization of nonlinearities. On the other hand, the use of phase portraits as a research tool implies the use of specific mathematical methods that require the researcher to have in-depth knowledge of higher mathematics.

From the point of view of reactive power optimization in power supply systems, it should be noted that the consumer may have specific requirements for the minimum possible level of reactive power, this should be taken into account in the form of additional restrictions in the optimization search.

From the point of view of hardware, it should be noted that at present there are no great difficulties in the manufacture of devices that allow to obtain phase portraits of electric current oscillations.

5. Conclusion

This article considers the possibility of using phase portraits of alternating current oscillations to assess the reactive power and organization of optimization search of electric circuit parameters based on the criterion of minimizing the area of the phase portrait of stationary electric current oscillations. The proposed approach makes it possible to analyze the process of generation, transmission and consumption of reactive power, as well as the possibility of controlling it in order to improve the energy efficiency of power supply systems.

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