IOP Conf. Series: Materials Science and Engineering **791** (2020) 012022 doi:10.1088/1757-899X/791/1/012022

Development of an algorithm for searching optimal solutions for compensation of reactive power

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Abstract. The problem of reactive power compensation, which includes many tasks, was substantiated in the work. Taking into account a number of specific problems of reactive power compensation and analysis of various electrical systems, an effective method of the calculation of the steady-state operation of the electrical network, on the basis of which the program "KRM_2021V7" was developed, is proposed. The method of nodal voltage, which was accompanied by the compilation of the system of equations and schematic matrices, among which the matrix of nodal conductivities and nodal loads were distinguished, is considered. An algorithm for finding optimal solutions for reactive power compensation is formulated and developed. Also, the work explains the use of genetic algorithms of mutation and population to find optimal solutions. The result of the calculation of losses in power lines for the considered electrical network is given.

1. Introduction

Reactive power causes additional power and electric energy losses in the elements of the electrical network with active resistance [1]. The var flows decreases the capacity of power lines and transformers, and loads the electrical power supply system of enterprises. The value of var flows can be reduced by means of compensating devices, which are most often used as capacitor banks [2] installed directly in areas of reactive power consumption. The problem of reactive power compensation includes a number of technical and economic tasks.

To consider specific problems of reactive power compensation, it is necessary to conduct an analysis of electrical systems using the concept of the balance of active and reactive power and electrical energy. Increasing of var flow or reactive power factor leads to the increase of total current; it is causes the additional voltage losses and tends to the number of negative events. For the calculation and installation of compensating devices, it is necessary to conduct an analysis of electrical networks of power supply systems. Power supply systems for industrial enterprises, although they can have the same electrical schemes, but at the same time designed to power various consumers of electrical energy and can include elements with different electrical parameters. If part of the electrical network also includes residential buildings as consumers, then for them the voltage can vary significantly with changing operating modes of industrial enterprises.

Based on the above, it is necessary to have energy parameters of the power supply system for more efficient use of compensating devices. Therefore, the methodology and program for conducting research and calculating of the steady-state operating mode of the electrical network is proposed.

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2. Materials and Methods

Analysis of electrical systems, their parameters and characteristics is an integral part of the process of power supply to consumers. At the moment, they are trying to carry it out using various methods and tools, programs oriented to a quick [3] and effective [4-6] state assessment. Moreover, genetic algorithms are often used for predicting situations in complex ramified power systems [7 - 10]. They are based on assigning different values to a data array.

Programs and methods of analysis are aimed either at changing the parameters of the electrical network itself, or at optimizing operating modes, including administrative methods with the introduction of penalties for enterprises for violations [11].

Reactive power generation can be estimated using nonlinear programming [12], often the load is represented as a random matrix [13] and a semblance of load is used on certain days during the considered time period. In this case, the economic component [14] should be taken into account, since the location of capacitor banks at different points and nodes leads to change losses in electrical network. The reliability of power supply to consumers depends on reactive power [15].

In connection with the foregoing, this article uses the method of genetic analysis and computer simulation with the compilation of load matrices and the possibility of their subsequent correction in accordance with real data. The program is designed in such a way that it is possible to calculate the optimal location of the capacitor banks to compensate for reactive power in terms of electrical network losses and the cost of electricity transmission.

3. Results

3.1. Calculation of the steady-state operating mode of the electrical network

Calculations of complex and meshed electrical networks were carried out using the electronic computing system and the nodal voltage method. This allowed building a universal calculation algorithm, which is convenient to apply to any scheme of the electrical networks or enter corrections, when changing networks parameters. Thus, equivalent scheme conversion can be avoided.

For calculation by nodal voltage method, it is necessary to form and find solution a system of equations.

For the searching networks scheme (Figure 1), number the nodes. The node 0 – it is the basic node, the voltage in which is equal to the known value U_b.

Then, compose for this scheme the matrix of complex nodal conductivities.

$$\dot{Y} = \begin{vmatrix} \dot{Y_{11}} & \dot{Y_{11}} & \dot{Y_{11}} & \dot{Y_{11}} & \dot{Y_{11}} \\ \dot{Y_{21}} & \dot{Y_{22}} & \dot{Y_{23}} & \dot{Y_{24}} & \dot{Y_{25}} \\ \dot{Y_{31}} & \dot{Y_{32}} & \dot{Y_{33}} & \dot{Y_{34}} & \dot{Y_{35}} \\ \dot{Y_{41}} & \dot{Y_{42}} & \dot{Y_{43}} & \dot{Y_{44}} & \dot{Y_{45}} \\ \dot{Y_{51}} & \dot{Y_{52}} & \dot{Y_{53}} & \dot{Y_{54}} & \dot{Y_{55}} \end{vmatrix}, \quad (1)$$

where $\dot{Y}_{ij}$ – are the complex conductivities between the node i and the node j, and in the case $i = j$ – it is the sum of the complex conductivities of the given node with all the connected nodes.

In accordance with the expression (1), the matrix of nodal conductivities for the electrical networks scheme with electric parameters, shown in Figure 1, has the form:

$$\dot{Y} = \begin{vmatrix} 0.234 - j0.368 & 0 & -0.062 + j0.108 & -0.12 + j0.16 & 0 \\ 0 & 0.247 - j0.365 & -0.195 + j0.244 & 0 & 0 \\ -0.062 + j0.108 & -0.195 + j0.244 & 0.351 - j0.486 & 0 & -0.094 + j0.134 \\ -0.12 + j0.16 & 0 & 0 & 0.22 + j0.108 & -0.1 + j0.3 \\ 0 & 0 & -0.094 + j0.134 & -0.1 + j0.3 & 0.194 - j0.434 \end{vmatrix}$$

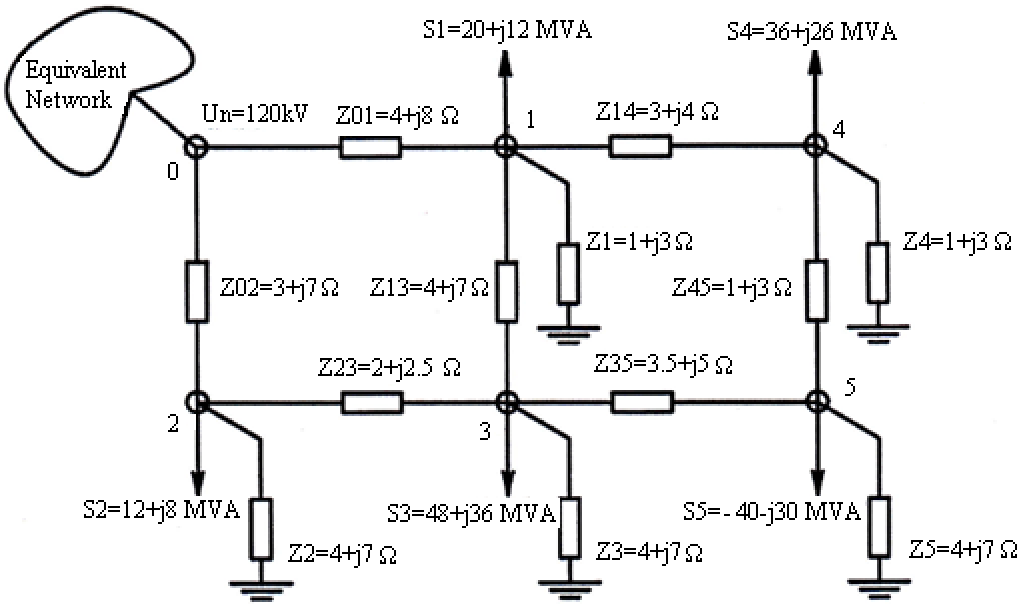

Figure 1. Test electrical network.

The number of columns and rows is determined by the number of nodes in the electrical network, except for the basis node.

Create a matrix of capacities of the consumers, connected to the corresponding nodes of the scheme:

$$\dot{S} = \begin{vmatrix} \dot{s_1} \\ \dot{s_2} \\ \dot{s_3} \\ \dot{s_4} \\ \dot{s_5} \end{vmatrix}, \tag{2}$$

where $\dot{s_i}$ – a capacity of the consumer connected to the i-th node.

In accordance with the expression (2), the matrix of nodal loads for the electrical network scheme showing in Figure 1 has the form:

$$\dot{S} = \begin{vmatrix} 20 + j12 \\ 12 + j8 \\ 48 + j36 \\ 36 + j26 \\ -40 - j30 \end{vmatrix}.$$

The values of the voltage at the nodes can be determined from the matrix formula:

$$\dot{U} = nU_b - \dot{Z}\left(\dot{U}_{\dot{D}}\right)^{-1}\dot{S}, \tag{3}$$

where n – is the matrix column consisting of units, the number of rows of which corresponds to the number of rows of the nodal conductivities matrix;

$\dot{Z}$ – is the matrix of nodal complex resistances equal to $\dot{Y}^{-1}$;

$\left(\dot{U}_{\dot{D}}\right)^{-1}$– is the inverse diagonal matrix of nodal voltages, the elements of which complex interfaced.

In formula (3), the nodes voltages enter both the left and right parts of the equation. Therefore, it is possible to solve this equation only by an iterative method. For this it is necessary to set the initial ap-

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proximation of nodal voltages. Also at each stage of the calculation in the right part of equation should insert the values obtained from the previous iteration.

Calculation using formula (3) is made in the programming language c ++. The input data for the calculation are the files "G_matrix.txt" and "X_matrix_txt", "P_matrix.txt" and "Q_matrix.txt". Files "G_matrix.txt" and "X_matrix_txt" fill with matrices of active nodal resistances and reactive nodal resistances. Files "P_matrix.txt" and "Q_matrix.txt" fill with matrices of active nodal load capacities and reactive nodal load capacities.

As a result of program execution, the results of calculations for the corresponding nodes will be displayed in the system command window.

The losses of active and reactive power for the power lines were calculated using the following formulas:

$$\Delta\dot{P} = \dot{S}_t\left(\dot{U}_{\dot{D}}\right)^{-2}\dot{R}\dot{S},$$
$$\Delta\dot{Q} = \dot{S}_t\left(\dot{U}_{\dot{D}}\right)^{-2}\dot{X}\dot{S}, \qquad (4)$$

where $\dot{S}_t$ – is the matrix row obtained by transporting the matrix $\dot{S}$;
R and X – is the active and reactive resistances of the line.

The calculation results according to the formula (4) are shown in Table 1.

Table 1. Results of power loss calculation.

Node number	Power at the beginning of the line, MVA	Power at the end of the line, MVA	Power losses for the line, MVA	Power compensating device in the node, MVAr
01	37.9+j23.9	37.3+j23.5	0.6+j1.3	0
02	39.5+j27.6	37.0+j27.1	0.5+j1.2	0.05
13	27.0+j19.1	6.1+j6.9	0.02+j0.04	0.1
14	11.2+j5.2	11.2+j5.5	0.03+j0.	0.3
35	15.1+j9.6	15.0+j10.0	0.1+j0.1	0
45	24.9+j20.4	24.8+j20.5	0.1+j0.2	0.06

3.2. Search conditions for optimal solutions of reactive power compensation

To solve the problem of optimization of reactive power compensation, two criteria are adopted:

- minimization of costs for generation and transmission of reactive power;
- regulation of voltage in the set limits from U_{min} to U_{max}.

The objective size of the costs will be determined by the formula:

$$C = C_l + C_g, \qquad (5)$$

where C_l – is the costs for reactive power losses;
C_g – is the costs for generation of reactive power by capacitor banks.

Costs for reactive power losses:

$$C_l = c_0 \Delta P,$$

where c_0 – is the specific costs of active power losses;
ΔP – is the active power losses.

Costs for capacitor banks:

$$C_g = \left(E_n + a_{op}\right)(K_c + K_{tr} + K_m) + c_0 \Delta P_{CB},$$

where E_n – is the norm coefficient of efficiency of the investments, accepted for calculations in the electric energy industry equal to 0.125;
a_{op} – is the norm coefficient of amortization for maintenance and repair equal to 0.05 for electrotechnical installations;

K_c – is the initial costs for the acquisition capacitor banks;
K_{tr} – is the costs for transportation of capacitor banks to the destination;
K_m – is the cost of mounting capacitor banks;
ΔP_{CB} – is the specific power loss in a capacitor bank.

Fixed costs independent from the capacity of capacitor banks are taken equal to:

$$\mathrm{K}_0 = K_{tr} + K_{\mathrm{m}}.$$

The optimal voltage must satisfy the requirement:

$$U_{min} \leq U \leq U_{max}.$$

In this case, the reactive power factor must satisfy the condition:

$$tan\phi > 0.1.$$

The search for optimal solutions is based on genetic algorithms. The multiple values that need to be found in this case will correspond to the multiple power values of the compensating devices. Matrix of the multiple power values of the compensating device Q_{CB} consists from n rows and m columns, where the columns are the schema nodes and the rows are the values sought.

The mutation of the population is a random variation in one of the elements of the Q_{CB} matrix. The value of the mutable element takes a new value, which is randomly selected from desired range. The range of possible values of the Q_{CB} elements is determined based on the maximum value of the reactive power of the load Q_{max} in the researching scheme of the electrical network.

The application of the genetic algorithm makes it possible to account the discreteness of the scale of the produced capacitor devices, which makes it possible to increase the calculation speed by tens of times. For this, it is necessary that the individuals of the population (solutions) are taken the discrete values.

The searching of optimal solution is suggested to determine not by the annual number of hours of the maximum losses, because this indicator does not give an accurate estimate of the power losses for the year, but according to the graphs of the daily loads of consumers. Thus, it is proposed to use an information model that takes into account the network operation mode for each individual period of per day, which will allow obtaining more accurate results.

For the generated population (the range of Q_{CB} values), adaptions is calculated. The adaptions function will estimate the value of the total annual costs for generating and transmitting reactive power and matching the voltage to the standardized values. The most adapted solutions will fall into the new population, with that crossing with other relevant solutions. There may be a large number of possible solutions. Let's show by example one of the possible variants of crossing, which is performed in the decimal system of calculation:

$$Q_{CB\,k} = \frac{Q_{CB\,[k-1][i+1]} - Q_{CB\,[k-1][i]}}{2},$$

where k – is the generation number;
i – is a number of the group of individuals.

When taking into account the discreteness of the scale of capacitor devices, the Q_{CB} values are also discrete, in which case the operation of crossing solutions is simplified or completely eliminated, and the diversity of the population (solutions) will be provided by other types of crossover (random increment of solutions). The optimal for the developed algorithm will be randomly changing one of the individuals or all individuals to a random increment Q_{CB}. When accounting the discreteness, population is replaced by a multiple of integer values, each of which corresponds to the technical and economic parameters of one of the capacitor devices. In this case, a crossover based on the displacement of any random individuals will be $\Delta N = 1$.

When calculating the discrete values Q_{CB}, formula (5) takes the form:

$$C = K_0 + C_K + C_O + c_0\,\Delta P_{CB} + c_0 \Delta P,$$

where C_K – cost of the capacitor bank of the certain nominal;
C_0 – costs for servicing a capacitor bank of a certain brand and nominal for the considered period of time.

A new generation of the solutions or a new population will be a new Q_{CB} matrix, the individuals of which will consist of a certain number of individuals (multiple of solutions) of the previous generation (the previous Q_{CB} matrix), a certain number of individuals that subjected of a little change (crossover) and new individuals consisting of randomly generated (mutated) Q_{CB} values. To prevent premature convergence to the local imaginary cost function, and to ensure acceptable value, it is necessary to keep a certain balance between individuals undergoing mutation and crossover. When writing the developed program "KRM_2021V7", the relationships between individuals, subjected to a crossover (small increment) and a mutation (random change), were determined experimentally. The optimal number of individuals in the population was determined to be 500. That is, the number of rows of the Q_{CB} matrix will be 500, and the number of columns is determined by the number of nodes in the electrical network.

The more generations of solutions will be grown, the more accurate the solution will be. The recommended number of generations (iterations) for the developed methodology varies depending on the complexity of the calculated scheme. But it should be noted that with each increase in the scheme per node, the complexity of the calculations increases according to the parabolic law.

Figure 2 shows a block diagram of the operation of the developed algorithm.

Subprograms (functions) are not presented in the form of a block diagram because of their volume, but their work can be used with the source code of all functions in the language c ++ / 11.

A technique for theoretical analysis of the determination of power and nodes locations has been developed, where it is necessary to introduce compensating devices to compensate reactive power.

4. Discussion

The program is written in the programming language with ++ / 11, she use only the standard language libraries. This program was compiled in the operating system "Windows 10" by the "min GW" compiler. Also compilation of the program by compilers MS VC ++, Intel c ++, Borland c ++ is possible.

The program does not contain its own graphic interface and uses the console host to interact with the user. To set the initial data, it is need to create files with the names: "G_matrix.txt" and "X_matrix_txt", "P_matrix.txt" and "Q_matrix.txt", "G_base_matrix.txt" and "X_base_matrix.txt". The results are displayed in the console window.

Also for each load, it is need to create a matrix of the diagram of daily load, the rows of which will correspond to the nodes, and the time-of-day columns with an interval of one hour. These matrices need to fill in the files "P_T.txt" (for active loads) and "Q_T.txt" (for reactive loads).

Data on the costs of losses and capacitor banks, as well as data on the nominal values of the produced compensating devices, are in the program itself.

5. Conclusion

Thus, from the above, we can conclude:

- Mathematical models of optimization tasks are analyzed and an optimal model is chosen for solving the problem of reactive power compensation. It was revealed, that the optimal for the solving problem is a model based on genetic algorithms, which has an advantage over other methods both in the calculation speed and in the reliability of the results obtained.
- A program has been developed in the programming language c ++, which solves the problem of optimal power and location of compensating devices using genetic algorithms. The calculation is based on the analysis of the diagrams of the daily consumption of active and reactive power by electric loads.
- Investigations have been carried out on a fragment of the urban electrical network, which prove the effectiveness of the reactive power compensation method developed in the work.

- The algorithm developed in the work can be used by both energy-saving enterprises to optimize the transfer of reactive power, and large energy consumers to reduce the electricity costs.

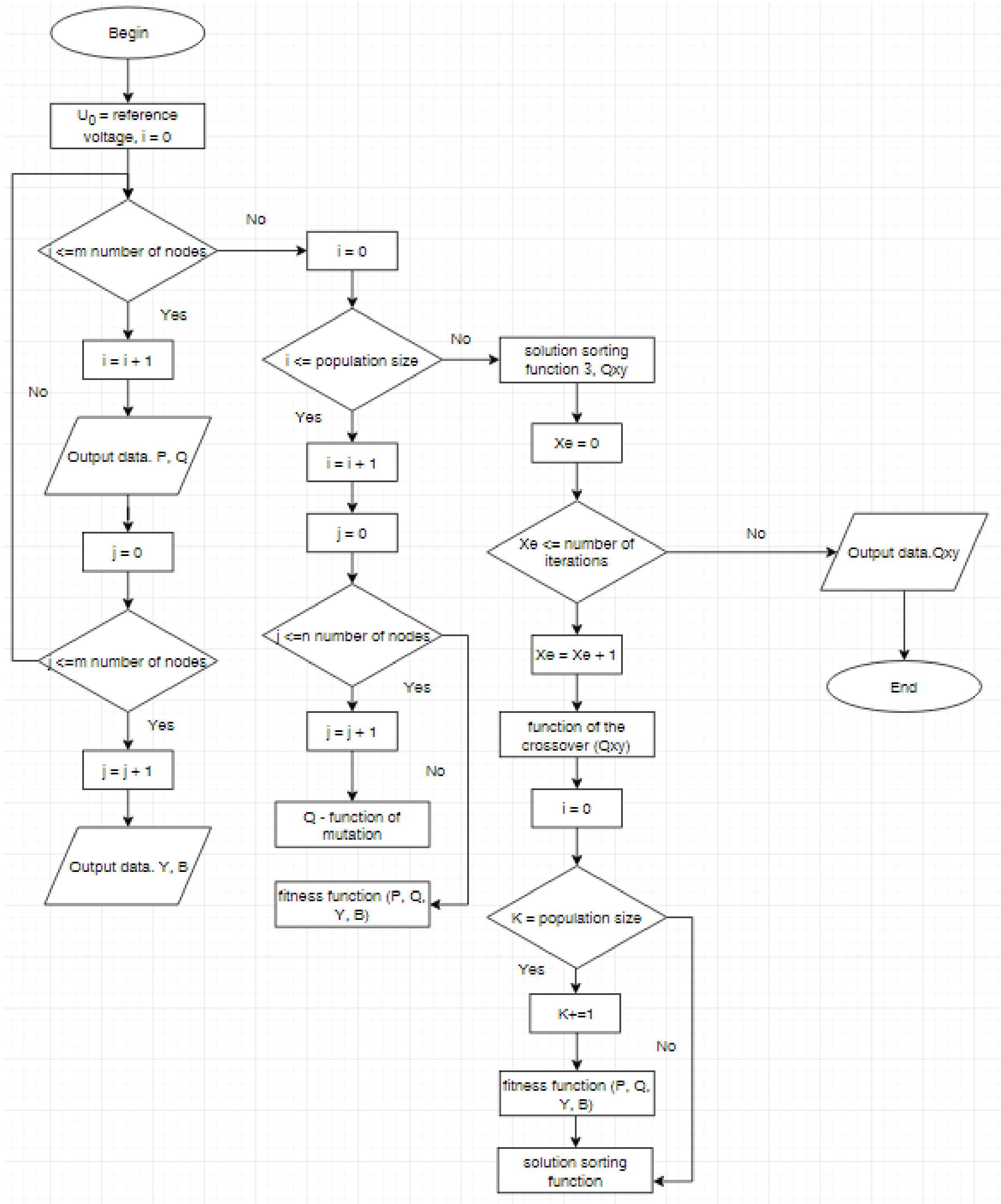

Figure 2. Program "KRM_2021V7" operation algorithm.

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