Application of specialized software systems for determination of normal and emergency operation modes parameters of power distribution networks

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Abstract. The paper analyzes the normal and emergency operation of rural distribution electric networks applying specialized software system - RASTRWIN PC, which is used at many power network enterprises in Russia. This specially designed program uses the RASTRWIN PC calculation core - Astra.dll, which calculates normal and emergency network conditions. It is used to solve the problem of calculating the modes of distribution networks 6-10 kV. To achieve greater accuracy of results, we use the scaling network parameters (currents, voltages, loads). For greater accuracy in calculating emergency conditions, the currents of the previous pre-emergency operation mode are used, as well as the dependence of the load current on the voltage in the network in emergency operation mode. The paper also substantiates the equivalent of the distribution network scheme based on a comparison of the calculation results of the modes for the full network section scheme and a simplified scheme. It is done to reduce labor costs when drawing up a design diagram of a distribution power network with a large number of taps on feeders. Using the developed program for a section of a distribution power network with the voltage 10 kV, normal and emergency operation modes of the network were calculated.

1. Introduction
Currently, modernization of rural distribution power networks is being actively carried out, the purpose of which is to increase the reliability of power supply to agricultural consumers. At the same time, new terminals of relay protection and automation devices with a large set of protection functions are installed in electrical networks. Regulatory documents on the application of these protection functions are often either absent or insufficiently relevant. For this reason, it becomes necessary to model various modes of operation of rural distribution electric networks. At the same time, it becomes necessary to evaluate a large number of network circuits when using such devices, automatic sectioning points or reclosers.

In this paper, we solve the problem of modeling calculations of normal and emergency network operation modes using specialized software systems. Calculations of normal and emergency modes of networks can be carried out by various methods [1-4], for example, analysis of flow distribution [1, 2, 4], or using calculations based on instantaneous values [3]. In such cases, specialized software systems are often used [4, 5], one of which is the RASTRWIN PC [5], which is widely used at power network enterprises in Russia. The interface of this PC is optimized for solving the problems of...
calculating the mode in networks with the voltage of 110 kV and higher. However, in this work, the calculation module Astra.dll is used, which has a COM interface and can be used with different application software.

2. Materials and methods

To solve the problems of modeling the operation of distribution networks, application software was developed in Visual Basic for Applications (VBA) in Excel. Using the developed program, it is possible to create calculation models and perform calculations. The network normal mode template (the “mode.rg2” template) is used to determine the operating currents in the network elements, and the dynamics template (“dynamics.rst”) is used to calculate the short-circuit current (SCC). The initial data in the preparation of the calculation model are the network diagram, information about the lines, information about the nodes of the scheme. The network diagram is used to bring the considered section to one voltage level to simplify the model. According to the information about the lines (length, line type, type of wire, wire cross-section), the line resistance is calculated along the straight line ($r_1$, $x_1$), reverse ($r_2$, $x_2$) and zero sequence ($r_0$, $x_0$), taking into account the number of circuits parallel to the lines, the type of line - cable or overhead [6], also the capacitive conductivity of the lines to the ground. Information about the nodes of the circuit includes the rated voltage, load power, power generation, and type of node. When compiling a network model, the one from the nodes is assigned as the basic. Its voltage is always constant, and the generation power is determined by the calculation results (imbalance in active and reactive power). Usually, when considering distribution networks as generating units, you can take the section busbars of substations supplying this network. When compiling the model for calculating the SCC, the same data are used as for the model for calculating the regime. In this case, the EMF and the angles of the generating units obtained from the results of the calculation of the mode are used in the calculations of SCC. For calculations in memory, a workspace is created containing the necessary set of tables. But the template “mode.rg2” is used for calculations of normal mode, and the “dynamics.rst” template is used for the short-circuit current calculations. The model files are not saved on the disk (all data is stored in developed software).

In general, the Astra.dll calculation module calculates the network operating mode in the form of a system of equations of nodal voltage in the form of a power balance in polar coordinates. The result of the calculation is the voltage in the nodes, and all other mode parameters are calculated according to the well-known equivalent circuits of network elements. The equations are solved numerically, the criterion for the solution correctness is the imbalance value in active and reactive power (the minimum value is 0.1 mW). The mode is calculated correctly when the voltage in the nodes in the range from 2 to $U_{\text{Nom}}$, when the voltage in the nodes beyond these limits, the calculation ceases, a message is displayed about the mode divergence. The power unbalance value in its basic form is not entirely suitable for calculating the distribution network mode (where the power of the consumer TP can have a value of less than 100 kV). Therefore, when building a model for calculating the normal mode the scalability is applied: while maintaining the same equivalent circuit parameters – the load capacities increase 100 times, voltages - 10 times. It will give currents 10 times more than the rated currents. When evaluating the results, they are brought to the initial values.

SCC calculations for phase-to-phase shorts are performed on the asymmetry model, while the SCC is determined taking into account the previous network load mode. This is implemented in the following way. Initially, emergency currents during short circuit (SC) at a given point are calculated without taking into account the load. Then the obtained data on the phase voltages $U_N$ in the nodes are analyzed and compared with the permissible residual voltage in the network $U_{\text{RES}} = 0.7 \cdot U_{\text{Nom}}$: at $U_N > U_{\text{RES}}$ the load in the node does not change, at $U_{\text{RES}} > U_N > 0.2 \cdot U_{\text{Nom}}$ the load power increases by the load self-starting coefficient. For $U_N < 0.2 \cdot U_{\text{Nom}}$ the load in the node is assumed to be zero. These changes are made in the model to calculate the mode, which is used to obtain load currents. Then the load currents are vectorially summed with short-circuit currents obtained without taking into account the load.
3. Results and discussion

To carry out the calculations, the scheme of the network section was set, presented in Figure 1, which is a typical scheme for rural distribution power networks. There are two feeders in the circuit, which are powered from different busbar sections with the voltage 10 kV. For backup purposes, there is a jumper between the feeders (L121), which is off in normal mode (SQ21 open).

![Figure 1. The fragment of the distribution network diagram.](image)

For a given section of the network the equivalent circuit was drawn up, which is shown in Figure 2. The parameters of the transformers in this circuit are reduced to the voltage 10 kV.

![Figure 2. An equivalent circuit for calculating normal and emergency network operation.](image)

Several cases of operation of this network section scheme are considered. In normal mode, during calculations, ZL121 branch is off (SQ21 is off) and two feeders can be considered independently of each other. We calculate the currents in the lines and the voltage in the network nodes when a short circuit occurs at point 81 (Figure 2). The loads are located on the low side of transformer substations and make up 80% of the rated power of transformers at cosφ=0.8.

The resistance of the straight reverse and zero sequence of lines is determined according to [6]. In the calculations, it is assumed that the distribution network is powered by transformers, therefore the assumption is made that the resistance of the power source (when calculating the SCC) in the straight, reverse and zero sequence are equal and determined only by the power of the transformer supplying the network (T1 or T2, Figure 1). The calculation results are presented in Tables 1 and 2.
With the same load parameters, we calculate the SCC for another network configuration, namely, the disconnected switch Q2 and the disconnector Q12 turned on. The calculation results are presented in Tables 3 and 4. As can be seen from the Tables, with the calculated load values the short circuit current, especially if it occurs on the low voltage side of the transformer (node 81), can be comparable with the current of the previous load mode and this fact should be taken into account when choosing the settings of relay protection and automation or when modeling the operation of the distribution power network.

**Table 1.** Calculation result, phase voltages in the nodes, at K (2) 81 (Q1 and Q2 are on, SQ21 is off).

| Node | Ua, kV | Phase Ua, deg | Ub, kV | Phase Ub, deg | Uc, kV | Phase Uc, deg |
|------|--------|---------------|--------|---------------|--------|---------------|
| 1    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -59.75        |
| 2    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -59.71        |
| 3    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -59.74        |
| 4    | 6.35   | 0.07          | -6.03  | 59.31         | -6.22  | -57.23        |
| 5    | 6.35   | 0.07          | -5.73  | 59.31         | -6.24  | -57.42        |
| 6    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 7    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 8    | 6.35   | 0.07          | -5.12  | 61.08         | -5.92  | -49.14        |
| 9    | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 10   | 6.35   | 0.07          | -5.12  | 61.08         | -5.92  | -49.14        |
| 101  | 6.35   | 0.07          | -5.12  | 61.08         | -5.92  | -49.14        |
| 31   | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 51   | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 71   | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 91   | 6.35   | 0.07          | -6.28  | 59.31         | -6.24  | -57.42        |
| 41   | 6.35   | 0.07          | -6.03  | 60.33         | -6.22  | -57.23        |
| 61   | 6.35   | 0.07          | -5.73  | 60.55         | -6.11  | -54.62        |
| 81   | 6.35   | 0.07          | -3.18  | 0.49          | -3.18  | 0.49          |

**Table 2.** The result of the calculation SCC, currents in the lines, at K^{(2)}_{81} (Q1 and Q2 are on, SQ21 is off).

| Node begin | Node end line | Ia, A | Phase Ia, deg | Ib, A | Phase Ib, deg | Ic, A | Phase Ic, deg |
|------------|---------------|-------|---------------|-------|---------------|-------|---------------|
| 1          | 3             | 303.5 | -64.8         | 303.5 | 84.7          | 303.5 | 55.3          |
| 2          | 4             | 126.9 | -64.2         | 556.2 | 21.4          | 505.3 | 32.4          |
| 3          | 5             | 209.4 | -64.2         | 209.4 | 85.3          | 209.4 | 55.9          |
| 4          | 6             | 69.9  | -63.8         | 499.3 | 21.4          | 467.5 | 28.4          |
| 5          | 7             | 117.8 | -64.1         | 117.8 | 85.4          | 117.8 | 56.0          |
| 7          | 9             | 60.0  | -64.3         | 60.0  | 85.1          | 60.0  | 55.8          |
| 6          | 8             | 35.2  | -63.8         | 464.6 | 21.5          | 447.6 | 23.3          |
| 8          | 10            | 35.2  | -63.8         | 35.2  | 86.5          | 35.2  | 61.6          |
| 3          | 31            | 98.1  | -21.3         | 98.1  | -81.3         | 98.1  | 38.7          |
| 5          | 51            | 91.6  | -19.3         | 91.6  | -79.3         | 91.6  | 40.7          |
| 7          | 71            | 57.8  | -18.9         | 57.8  | -78.9         | 57.8  | 41.1          |
| 9          | 91            | 60.0  | -19.3         | 60.0  | -79.3         | 60.0  | 40.7          |
| 4          | 41            | 55.6  | -19.3         | 55.6  | -79.3         | 55.6  | 40.7          |
| 6          | 61            | 34.7  | -18.8         | 34.7  | -78.8         | 34.7  | 41.2          |
| 8          | 81            | 0.0   | 0.0           | 429.4 | 21.5          | 429.4 | 21.5          |
| 10         | 101           | 35.2  | -18.8         | 35.2  | -78.8         | 35.2  | 41.2          |
An important issue is also the possibility of simplifying the design schemes since rural distribution networks are quite long and the lines have a large number of taps to which consumer transformer substations (CS) are connected. The equivalent example is shown in Figures 3 and 4.

Table 3. Calculation result, phase voltages in the nodes, at K(2)81 (Q1 and SQ21 are on, Q2 is off).

| Node | Ua, kV | Phase Ua, deg | Ub, kV | Phase Ub, deg | Uc, kV | Phase Uc, deg |
|------|--------|---------------|--------|---------------|--------|---------------|
| 1    | 6.35   | 0.07          | -6.28  | 59.33         | -6.25  | -59.73        |
| 2    | 6.35   | 0.07          | -6.28  | 59.33         | -6.25  | -59.76        |
| 3    | 6.35   | 0.07          | -6.16  | 59.80         | -6.23  | -58.53        |
| 4    | 6.35   | 0.07          | -5.57  | 60.13         | -6.01  | -53.46        |
| 5    | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 6    | 6.35   | 0.07          | -5.57  | 60.13         | -6.01  | -53.46        |
| 7    | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 8    | 6.35   | 0.07          | -4.99  | 60.53         | -5.83  | -48.04        |
| 9    | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 10   | 6.35   | 0.07          | -4.99  | 60.53         | -5.83  | -48.04        |
| 101  | 6.35   | 0.07          | -4.99  | 60.53         | -5.83  | -48.04        |
| 31   | 6.35   | 0.07          | -6.16  | 59.80         | -6.23  | -58.53        |
| 51   | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 71   | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 91   | 6.35   | 0.07          | -5.87  | 59.96         | -6.11  | -56.04        |
| 41   | 6.35   | 0.07          | -5.57  | 60.13         | -6.01  | -53.46        |
| 61   | 6.35   | 0.07          | -5.57  | 60.13         | -6.01  | -53.46        |
| 81   | 6.35   | 0.07          | -3.18  | 0.07          | -3.18  | 0.07          |

Table 4. The result of the calculation, the currents in the lines, at K(2)81 (Q1 and SQ21 are on, Q2 is off).

| Node begin line | Node end line | Ia, a | Phase Ia, deg | Ib, A | Phase Ib, deg | Ic, A | Phase Ic, deg |
|-----------------|---------------|-------|---------------|-------|---------------|-------|---------------|
| 1               | 3             | 442.8 | -64.5         | 859.1 | 23.3          | 748.4 | 43.3          |
| 5               | 6             | 134.8 | -64.0         | 551.1 | 22.2          | 497.8 | 33.8          |
| 3               | 5             | 349.8 | -64.1         | 766.2 | 22.5          | 665.4 | 41.8          |
| 4               | 6             | 60.3  | -19.3         | 60.3  | -79.3         | 60.3  | 40.7          |
| 5               | 7             | 121.1 | -64.0         | 121.1 | 85.8          | 121.1 | 57.9          |
| 7               | 9             | 61.8  | -64.3         | 61.8  | 85.5          | 61.8  | 57.7          |
| 6               | 8             | 37.5  | -63.8         | 453.9 | 22.1          | 436.2 | 26.2          |
| 8               | 10            | 37.4  | -63.7         | 37.4  | 86.3          | 37.4  | 62.2          |
| 3               | 31            | 98.9  | -21.3         | 98.9  | -81.3         | 98.9  | 38.7          |
| 5               | 51            | 94.0  | -19.3         | 94.0  | -79.3         | 94.0  | 40.7          |
| 7               | 71            | 59.4  | -18.8         | 59.4  | -78.8         | 59.4  | 41.2          |
| 9               | 91            | 61.7  | -19.3         | 61.7  | -79.3         | 61.7  | 40.7          |
| 4               | 41            | 60.3  | -19.3         | 60.3  | -79.3         | 60.3  | 40.7          |
| 6               | 61            | 36.9  | -18.8         | 36.9  | -78.8         | 36.9  | 41.2          |
| 8               | 81            | 0.0   | 0.00          | 416.4 | 22.1          | 416.4 | 22.1          |
| 10              | 101           | 37.5  | -18.7         | 37.5  | -78.7         | 37.5  | 41.3          |
Figure 3. The initial diagram of the network section.

Figure 4. Equivalent circuit of the network section (a) and substitution circuit for calculating the normal mode of the network and short circuit currents (b).

The following sequence of actions is used for equivalence. A group of closely spaced CS (Figure 3 CS1 - CS4) is selected; they are combined into one CSE (Figure 4 a) with the SLE load equal to the sum of the loads of all the combined substations. Moreover, in the equivalent circuit (Figure 4 b) it is represented as three branches, the parameters of which are as follows: ZT12 - equivalent circuit of the CSE substation, the resistance of which is defined as a parallel connection of resistors CS1-CS4, ZT11 - the resistance corresponds to the branch with the highest resistance (CS with the least power), and the branch ZT13 - resistance corresponds to the branches with the lowest resistance (CS with the highest power), the equivalent load is set at the end of the branch Z12 (node 32). It is used to calculate the mode and ZT11 and ZT13 - to calculate SCC, the first, respectively, to test the sensitivity, the second - for the calculation and selection of protection settings.

The calculation results of normal and emergency modes for the full circuit and the equivalent circuit are shown in Tables 5 and 6. As can be seen from the data, the error in calculating the parameters of the normal mode is not more than 3% and not more than 10% for SCC when using the test circuit (Figure 3).

4. Conclusion

In the research a software application is developed that allows you to calculate the normal and emergency mode parameters for rural distribution power networks using the RASTRWIN PC calculation module - Astra.dll. When calculating short-circuit currents, the currents of the previous normal operating mode of the network are taken into account. Calculations can be carried out with any network circuit (radial, ring, with two or more power sources). The paper also substantiates the option of the equivalent in the initial circuits of the distribution network in order to reduce the time spent on preparation of calculation schemes.
Table 5. Calculation data for the normal mode (voltage in nodes and currents in lines).

| Node | U, kV | Phase U, deg | Node begin line | Node end line | IL, a |
|------|-------|--------------|-----------------|--------------|-------|
| 1    | 11.00 | 0.00         | 1               | 3            | 31.5  |
| 3    | 10.77 | 0.08         | -               | -            | -     |
| 4    | 10.77 | 0.08         | -               | -            | -     |
| 5    | 10.76 | 0.08         | -               | -            | -     |
| 6    | 10.76 | 0.08         | -               | -            | -     |

Equivalent scheme

| Node | U, kV | Phase U, deg | Node begin line | Node end line | IL, a |
|------|-------|--------------|-----------------|--------------|-------|
| 1    | 11.00 | 0.00         | 1               | 3            | 32.2  |
| 3    | 10.75 | 0.10         | -               | -            | -     |

Table 6. Data on SCC calculations.

| Node begin line | Node end line | Ia, a | Phase Ia, deg | Ib, A | Phase Ib, deg | Ic, A | Phase Ic, deg |
|-----------------|---------------|-------|---------------|-------|---------------|-------|---------------|
| 1               | 3             | 14.37 | -64.24        | 195.76| 21.77         | 189.07| 25.38         |
| 3               | 4             | 14.00 | -18.63        | 195.41| 21.71         | 188.59| 25.35         |
| 4               | 5             | 5.37  | -18.56        | 186.79| 21.74         | 184.07| 23.21         |
| 5               | 51            | 0.00  | 0.00          | 181.42| 21.77         | 181.42| 21.77         |

Equivalent scheme

| Node begin line | Node end line | Ia, a | Phase Ia, deg | Ib, A | Phase Ib, deg | Ic, A | Phase Ic, deg |
|-----------------|---------------|-------|---------------|-------|---------------|-------|---------------|
| 1               | 3             | 32.26 | -64.43        | 213.30| 21.96         | 199.48| 29.16         |
| 3               | 33            | 0.00  | 0.00          | 181.06| 21.84         | 181.07| 21.84         |

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