The determination of quantitative-temporal characteristics of attracting repair personnel in the event of mass failures in rural distribution electric networks

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Abstract. The paper considers the possibility of using a numerical solution of a system of differential equations describing a delay queuing system. At the same time, to determine the required number of repair personnel, a three-phase queuing system is used, each phase of which represents a certain stage of servicing the requirements for eliminating the failure. Such a system is used in case of mass failures in rural distribution electric networks, for example, in natural emergencies. The criterion for choosing the optimal number of repair personnel for each phase of a multiphase queuing system is not to exceed the specified service waiting time by a request, which is accepted at the level of 30% of the average service time for this phase. An algorithm has been developed that uses the results of a numerical solution of a system of differential equations describing a queuing system and allows determining the point in time when this criterion is violated. For a given point in time, the queuing system changes are an increase in the number of service personnel, and the queuing system is calculated with new parameters, but using the boundary conditions received from the previous queuing system. The developed algorithm has been implemented in software and results are obtained on the required number of repair personnel for the input parameters of the queuing system, obtained from the processing of statistical information on the operation of rural distribution electric networks.

1. Introduction

Currently, the development of agriculture and production in the agricultural sector is impossible without a reliable supply of resources to the industry, including electricity. At the same time, it can be considered that the reliability of the power centers of agricultural consumers is quite high, and the main reasons for the power supply interruptions are failures of the power supply system, which includes distribution networks with a voltage of 10-0.4 kV. The restoration of each of the failures has its own technical features, however, when determining the required number of repair personnel necessary to restore them, it is possible to use queuing systems (QS) [1, 2], in the case of application of which there is an abstraction from specific technical features of the repair of elements of the power supply system. There are various types of QS [3-5], in our case we use one of the most common QS type (M/M/NTEAM):(GD/∞/∞) – Poisson-fed queue, service time distribution is exponential, the number of teams is limited, there is a general queue, the queue size is not limited, an infinite number of requirements can be generated for QS. The use of such a QS is justified for a sufficiently large number of failures that occur in networks, which may be, for example, a consequence of a natural...
emergency (NE).

Input parameters for this system are: the failure flow parameter $\lambda$ (the flow of incoming requests to the QS); average repair time $T_{REP}$; repair rate $\mu = 1/T_{REP}$ (which is true for the applied QS according to [4]); number of repair teams $N_{TEAM}$. The solution for this QS is possible both with the use of expressions for stationary solutions, and with the numerical solution of a system of differential equations (numerical solution) describing this QS [6]. B In this work, a numerical solution have been applied, since the time intervals for considering QS are in the range from 1 to 24 hours [7]. At the same time, the use of expressions for stationary solutions of QS is possible for time more than $5T_{REP}$ [6], which for the longest phase is about 8 hours. According to regulatory documents [8], failures in distribution electric networks are restored in several stages, therefore, when considering QS, a multiphase model was adopted, consisting of three phases: the first phase is servicing of failures by the forces of field service teams (FST), the second is repair work by repair team (RT) and the third is the acceptance of work performed by the RT and the implementation of operational switching by FST. Accordingly, each of the phases is characterized by its input parameters: $\lambda$, $T_{REP}$, $N_{TEAM}$.

2. Materials and methods

A numerical solution of the system of equations describing the QS is performed by the fourth-order Runge-Kutta method. The system with a limited queue size is created $N_Q$, however, it was shown in [6] that under the condition $4N_{TEAM} < N_Q$ the finite value of the queue does not significantly affect the results of numerical solutions of the system of differential equations. Since the result of a numerical solution is an array of probabilities of all states of the system, a methodology for evaluating and using calculation results has been developed, which consists in applying the criterion for the length of time for waiting for service [6, 9]:

$$T_Q \leq 0.3 \cdot T_{REP}.$$  \hspace{1cm} (1)

To calculate this parameter, the Little formula was used:

$$T_Q \leq \lambda^{-1}L_Q,$$  \hspace{1cm} (2)

where $L_Q$ is the average number of requests in the queue, which can be determined by the formula:

$$L_Q(t) = \sum_{k=1}^{N_Q} kP_{N_{TEAM}+k}(t).$$  \hspace{1cm} (3)

It should be noted that formula (2) was derived and proved for average values for stationary solutions, but with some assumptions it can be applied to values obtained by numerical solutions of the system of equations, since it allows establishing a relationship between the probabilistic and temporal characteristics of QS at a constant failure flow rate.

To evaluate the fulfillment of the criterion, an algorithm was developed and programmatically implemented that allows calculations to be made with changing QS parameters. The principle of operation of this algorithm is as follows: calculations begin for QS with one team $N_{TEAM} = 1$, and are executed as long as the criterion is fulfilled (1). If the criterion is violated, the QS changes (the number of teams is increasing $N_{TEAM} = 2$), and the calculations are carried out with the initial conditions obtained in the previous calculation. In case of non-fulfillment of the criterion and with the obtained number of teams, we increase their number by one, the QS is recalculated with the initial conditions from the previous calculation. This algorithm allows determining not only quantitative, but also temporary parameters for attracting repair personnel. In addition, the program executing this algorithm makes it possible to evaluate changes in such parameters as the average number of requests in the
queue $L_Q$ and likelihood of queuing $P_Q$ when changing the failure flow parameter $\lambda$. In this case, the QS is calculated with the initial conditions from previous calculations performed with the previous $\lambda$.

3. Results and discussion

Calculations of QS were carried out on the basis of the initial data obtained from the processing of statistical data on the operation of electrical equipment of power supply systems [7]. When calculating the QS, it was assumed multiphase with the following parameters: $\lambda_1 = 1 \text{ h}^{-1}$, $T_{REP1} = 4 \text{ h}$, $\lambda_2 = 0.75 \text{ h}^{-1}$, $T_{REP2} = 8 \text{ h}$, $\lambda_3 = 0.75 \text{ h}^{-1}$, $T_{REP3} = 1.5 \text{ h}$. While the total review period is 100 hours, step size is $\Delta t = 0.1$ hour, number of equations is $N_{EQ} = 50$. The calculation results are presented in Figure 1. At the same time, the “1 STAGE” curve describes the time dependence of the number of required FSTs when fulfilling the criterion (1) (phase 1 of QS), “2 STAGE” curve shows the dependence of the number of required RTs on time, taking into account the fulfillment of the criterion (1) (phase 2 of QS), “3 STAGE” curve – the dependence of the number of required FSTs for closing repair requests and performing operational switching, taking into account the fulfillment of the criterion (1) (phase 3 of QS).

![Figure 1. Results of calculation of multiphase delay QS: 1 STAGE – dependence of the number of teams on time for the 1st phase of QS, 2 STAGE – dependence of the number of teams on time for the 2nd phase of QS, 3 STAGE – dependence of the number of teams on time for the 3rd phase of QS.](image)

The data in Figure 1 should be interpreted as follows. At time $T = 0$, a sufficiently large flow of incoming requirements (failures) arises with an intensity $\lambda_1 = 1 \text{ h}^{-1}$, which is processed by the first phase of the QS (by forces of the FST) at this point in time there is one and initially there is one field service team. Next, it is necessary to add the second team at time $T = 2.3$ h, the third at time $T = 3.5$ h to meet the specified criterion (1). At time $T = T_{REP1} = 4$ h requests appear at the output of the first phase of the QS and enter the input of the second phase, their intensity $\lambda_2 = 0.75 \text{ h}^{-1}$. For the second phase of QS, a similar dependence is calculated (Figure 1 - 2 STAGE), from Figure 1 it can be seen
that it is shifted along the time axis by the average processing time of requests relative to the first phase. Having passed the second phase of the QS request with intensity $\lambda_3 = 0.75 \text{ h}^{-1}$ appear at the input of the third phase $T = T_{REP} + T_{REP2} = 12 \text{ h}$ later. For the third phase of the QS, a similar dependence is calculated (Figure 1 - 3 STAGE).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{QS calculation results when the failure flow parameter changes, $\lambda=0.01 \text{ h}^{-1}$ (in the range of $T=0...10 \text{ h}$ and $T=34...100 \text{ h}$), $\lambda=1 \text{ h}^{-1}$ (in the range of $T=10-34 \text{ h}$), $T_{REP}=4 \text{ h}$, $N_{EQ}=50$, review period is 100 hours, step is 0.1 h with the number of teams: a – $N_{TEAM}=1$, b – $N_{TEAM}=5$}
\end{figure}
Thus, using Figure 1, you can get the required number of each type of team at a given time. For example, 15 hours after the onset of an emergency, six FSTs for the 1st phase, six RTs for the 2nd phase and three FSTs for 3rd phase are required. At the same time, the average time for eliminating failures will be less than 16 hours. For time $T = 5 \text{ h}$, four FSTs are required for the 1st phase, two RTs for the 2nd phase, and at time $T = 12 \text{ h}$, one FST for the 3rd phase is required.

Of interest is also the behavior of the QS characteristics with a change in the failure flow parameter. To do this, using a specially designed program, the calculations for one phase have been carried out, when the failure flow changes stepwise from the background value corresponding to the normal operation of the power supply system ($\lambda = 0.01 \text{ h}^{-1}$) to the value corresponding to mass failures in an natural emergency ($\lambda = 1.0 \text{ h}^{-1}$), emergency duration is expected 24 hours. The calculation results are presented in Figure 2. So, if there is one FST, a significant increase in the number of requests is observed in 24 hours, and their processing and return to normal operation is quite lengthy for more than 100 hours even with a sharp reduction in new requests at time $T = 34 \text{ hours}$. When the number of FST is five ($N_{\text{TEAM}} = 5$) a significant accumulation of requests does not occur, and after the termination of the intensive receipt of requests, the system returns to its original parameters at time $T=45 \text{ h}$.

It should be noted that for such a statement of the problem, formula (2) is not applicable, since it relates probability and time characteristics through the parameter $\lambda$, and its transition from a value of 1 to a value of 0.01 will increase the parameter $T_Q$ by a hundred times, which is not a valid indicator of QS. In this case, it is necessary to apply another functionality, for example $L_Q$, and recalculate it into time characteristics for a single time interval, for example, for 1 hour.

4. Conclusion
As a result of this work, studies have been carried out on the applicability of the numerical solution of a system of differential equations describing a multiphase delay QS of determining the quantitative and temporal characteristics of the involvement of repair personnel in the elimination of mass failures in rural power supply systems. It has been shown that the application of this technique allows not only to determine the number of teams involved in the elimination of emergency situations, but also the time of their involvement in each elimination phase.

A delay QS has been considered while changing the incoming requirements flow parameter. Based on the numerical solution of the system of equations, transition characteristics have been obtained for such QS functionalities as the probability of queuing $P_Q$ and the number of requests in the queue $L_Q$, with stepwise increase or decrease of the failure flow parameter, which can be used to determine the required number of repair personnel.

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