Application of priority and delay queuing system in non-stationary modes to determine the required number of repair personnel in rural distribution electric networks

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Abstract. The paper considers the possibility of using a queuing system to determine the required number of repair and maintenance personnel in the event of mass failures in rural distribution electric networks. In this case, the separation of requirements for restoring failures (requests) into priority and secondary is used. The multi-channel queuing system is used with two priority levels, with the delay of both priority requests and secondary requests. The algorithm has been developed for composing a system of differential equations describing a given queuing system. The system of differential equations is solved by numerical methods, and, using a specially developed algorithm, based on the results of the solution for a given point in time, the required number of repair personnel is estimated based on such parameters as the probability of queuing and the average waiting time of requests in the queue. The developed algorithms have been implemented in software; the necessary number of repair personnel has been calculated with their use, as well as on the basis of statistical data on failures in rural distribution electric networks. Assessment of the intensity of the flow of priority and secondary requests has been carried out by two methods. In the first method the data from the dispatcher’s record book or acts of investigation of technological disturbances have been used. Failures were divided by such parameters as reliability categories of power supply for cut-off consumers, volume of cut-off load and social significance of cut-off objects. In the second method, those requests that could be fixed by the forces of the field service teams were priority, the remaining requests were considered secondary.

1. Introduction

Currently, more and more significant demands are made on the quality of power supply to rural consumers [1]. One of the ways to improve the quality of power supply is a possible reduction in interruptions of power supply to consumers due to technological disturbances in distribution electric networks. Moreover, to fix technological disturbances [2], repair teams (RT) and field service teams (FST) are used as a rule. Technological disturbances can lead to interruptions in consumers’ power supply or failures. Therefore, there are requirements for their restoration. All requirements can be conditionally divided into priority ones, caused by failures with a large volume of consumers’ cut-off load, socially significant objects cut-off, consumers of I and II reliability categories cut-off, and secondary ones. That leads to limitation of power supply to consumers of the III reliability category, small volumes of cut-off load. Or in other words, there are failures with great economic and
environmental damage and failures that do not significantly affect the economic and environmental performance of the distribution network enterprise.

In the current operation of distribution electric networks, the flow of requirements is quite low, and the number of required personnel is determined by the safety requirements and the requirements of the current work schedule. However, in the event of mass failures, for example, during natural emergencies, a large number of FSTs and RTs must be involved to restore failures. Thus, to determine the time and number of required personnel, the theory of queuing systems is used (QS).

2. Materials and methods

When applying QS, the technical details of failure restoration in electrical networks are not considered, all features are taken into account through such a parameter as the average failure restoration time, that is, the recovery time. At this, the whole process of technological disturbances fixing, according to [2], is divided into three phases: the first is primary processing of the requests by FST, the second is the implementation of work to restore failures by RT, the third is the closure of the work to restore the failure by the forces of FST. However, not all applications go through the second and third phases. In this case, the type of delay QS is used. (M/M/NBRIG):(GD/∞/∞) [3]. In this study, by analogy with [4], a numerical solution of the system of differential equations describing QS has been applied.

The priority and delay QS has been applied here [5], in which there are two types of requests: priority and secondary. Each type is characterized by its failure flow parameters $\lambda_1$ and $\lambda_2$ and service time $T_{REP1}$ and $T_{REP2}$. In the case of the priority request and when all teams are busy, the secondary service is terminated, and the unserved secondary request is lost. The implementation of this approach when restoring failures in electric networks is unlikely, in view of the fact that the maintenance of the priority request begins after the completion of the maintenance of the previous (non-priority request). To account for this factor, the time for servicing a priority request increases depending on the likelihood of queuing from secondary requests. For example, as a first approximation, we can estimate the increase in service time as follows:

$$\Delta T_{REP1} = 0.5T_{REP1} \cdot P_{Q2}$$

where $P_{Q2}$ is the probability of the queue for secondary requests.

Since $P_{Q2}$ depends on the parameter $T_{REP1}$, therefore, accurate calculations are recursive in nature. Naturally, an increase in service time can only be estimated approximately. So, for example, with an acceptable service time delay for requests ($T_{Q2} = 0.3 \cdot T_{REP1}$), adopted as a criterion for assessing the optimal number of personnel [4], the parameter $P_{Q2}$ ≈ 0.5, which ultimately gives $T_{REP1} = 1.25 \cdot T_{REP1ST}$. Where $T_{REP1ST}$ is the recovery time for priority requests based on statistics [6].

3. Results and discussion

The authors have developed a mathematical model of priority and delay QS, the state graph of which is presented in the Figure 1.

As an example, a multichannel QS that has 2 teams ($N_{TEAM} = 2$) for service and 2 places in the queue ($N_Q = 2$) is considered. Priority requirements are characterized by parameters $\lambda_1$ and repair rate $\mu_1 = 1/T_{REP1}$, and secondary requirements - by parameters $\lambda_2$, $\mu_2 = 1/T_{REP2}$. Area A is the queue state for priority requests, and Areas A and B are the queue state for secondary requests.

The differential equation describing one state in this QS has the following general form:
\[
\frac{dp_{ij}(t)}{dt} = -\left( \lambda_i + \lambda_j + \mu_i \cdot i + \mu_j \cdot j \right) p_{ij}(t) + \lambda_j \cdot p_{i,j-1}(t) + \mu_j \cdot (j+1) \cdot p_{i,j+1}(t) + \\
+ \mu_i \cdot (i+1) \cdot p_{i+1,j}(t),
\]

where the index \( i \) shows the state change according to priority requests, and the index \( j \) shows the state change according to secondary requests.

**Figure 1.** Priority and delay queuing system graph (25 states are shown for clarity).

The total number of equations describing the system is defined as:

\[
N_{EQ} = (N_{ST} + 1)^2,
\]

where \( N_{ST} \) is the number of states defined as \( N_{ST} = N_{TEAM} + N_Q \).

In the graph in question, \( N_{ST} = N_{TEAM} + N_Q = 4 \), accordingly, the number of equations is 25. In this case, the number of positions in the queue must be unlimited (subject to the elimination of all failures), however, it is difficult to solve such systems of differential equations by numerical methods. Therefore, based on the results of estimates made in \[4\], it could be considered that the finite queue length does not affect the calculation results on condition \( N_Q \geq 4 \cdot N_{TEAM} \).

To compose the system of differential equations, the algorithm has been developed and the software has been implemented, which allowed considering priority and delay QS for arbitrary number of states. For practical purposes, to obtain an acceptable calculation time, the maximum size of the system was 2500 equations, i.e no more than 49 conditions for priority and secondary requests have been used. As the boundary conditions, the normalizing condition at the initial time \( t = 0 \) has been used:

\[
\sum_{i=0}^{i=N_{ST}} \sum_{j=0}^{j=N_{ST}} P_{ij}(0) = 1,
\]

where \( P_{00}(0) = 1 \), all other state probabilities are 0.

The system of differential equations composed in this way has been solved by numerical methods.
(4th-order Runge-Kutta method). The numerical solution of the system of equations converges for given values of the flow of failure (0.01 < λ < 10) and time step size Δt = 0.1 h.

An important factor is understanding of the solution result. In general, this is an array of probabilities of each system state at each moment of time. However, such presentation of the results is not convenient for evaluation, therefore, the calculation results have been repeatedly processed and calculated programatically. These are such parameters as the probability of queuing for priority requests \( P_{Q1} \) and for secondary requests \( P_{Q2} \):

\[
\begin{align*}
P_{Q1} &= \sum_{i=0}^{N_{Q1}} \sum_{j=0}^{N_{Q1}} P_{i,j}(t), \\
P_{Q2} &= \sum_{i=0}^{N_{Q1}} \sum_{j=0}^{N_{Q1}} P_{i,j}(t) - \sum_{i=0}^{N_{Q1}} \sum_{j=0}^{N_{Q1}} P_{i,j}(i + j \leq N_{TEAM}).
\end{align*}
\]

These parameters (\( P_{Q1} \) and \( P_{Q2} \)) characterize the operation of the QS only indirectly, therefore, such parameter as the average time in the queue \( T_{Q1} \) is more understandable and applicable to practical assessment:

\[
T_{Q1} = \frac{1}{\lambda_1} L_{Q1}, \quad T_{Q2} = \frac{1}{\lambda_2} L_{Q2},
\]

where \( \lambda_1, \lambda_2 \) are the failure flow parameters of priority and secondary requests, \( L_{Q1}, L_{Q2} \) - the average number of requests in the queue, which can be determined by the formula:

\[
\begin{align*}
L_{Q1}(t) &= \sum_{k=1}^{N_{Q1}} \sum_{j=0}^{N_{Q1}} kP_{k,j}(t), \\
L_{Q2}(t) &= \sum_{i=0}^{N_{Q1}} \sum_{j=0}^{N_{Q1}} (i + j - N_{TEAM})P_{i,j}(t)(i + j > N_{TEAM}),
\end{align*}
\]

where \( k \) is the weight coefficient taking into account the position of the state in the queue for priority requests, and \( i + j - N_{TEAM} \) is the weight coefficient for secondary requests.

Calculations using priority and delay QS have been carried out with the information obtained as a result of processing statistical data on the operation of distribution electric networks [6]. In this study, it has been found that the average time to fix technological disturbances is in the range from 2 to 4 hours under normal operating conditions, while the failure flow parameter is quite small (\( \lambda < 0.01 \)). In that situation, it makes no sense to separate failures into priority and secondary. However, in the event of mass failures, for example, in case of an emergency of a natural disaster, the parameter of the flow of failures increases quite sharply to values (0.5 <\( \lambda < 10 \)), while recovery time also increases (average recovery time is \( T_{REPST} \approx 9.4 \) h). At the same time, according to the results of processing information about the nature of the technological disturbance (disconnected equipment, volume of cut-off load, reliability categories of cut-off consumers), one part of requests for restoring failures is recognized as priority, the second as secondary. Moreover, as a first approximation, to estimate the number of required repair personnel, it is possible to use such a parameter as the recovery time \( T_{REP1} = T_{REPST} \approx 9 \) h. At the same time \( T_{REP1} = 1.25T_{REPST} \approx 12 \) h.

The calculation results are presented in Figure 2. As can be seen from the Figure 2a, for priority requests, the criterion \( T_{Q1} = 0.3T_{REP1} \) is fullfilled, which indicates a sufficient number of involved repair teams. If one looks at the results of the calculations for secondary requests (Figure 2b), from the
moment of time $T = 15$ h the delay in servicing exceeds the specified criterion $T_{Q_2} = 0.3T_{REP_2}$, therefore, for secondary requests, this criterion may have a different, including greater, value.

**Figure 2.** Priority and delay queuing system calculation results, for: a – priority and b – secondary requests, received under the following conditions: $T_{REP_2} = 9$ h, $T_{REP_1} = 12$ h, $\lambda_1 = \lambda_2 = 0.5$, $N_{ST} = 35$, $N_{TEAM} = 7$, number of equations is 1296, review period is 100 h, step size is 0.2 h.

The main task with this approach is to prioritize the request. At electric grid enterprises, the priority of requests is determined by the dispatcher, who receives information on emerging technological disturbances in distribution networks from consumers or through automated control systems. In the above calculation example, it has been assumed that half of all requests are priority (the general request flow parameter is characterized by the parameter $\lambda = \lambda_1 + \lambda_2$). Comparison of the calculation results with the data obtained when solving the delay QS with (without priorities) has been shown that the fulfillment of the criterion $T_Q = 0.3T_{REP}$ is possible with the following parameters: $T_{REP} = 9$ h, $\lambda = 1$, $N_{TEAM} = 10$, $N_Q = 40$.

However, in some cases, determining the priority of requests is difficult or impractical (for
example, with a low density of electrical networks). In this case, one of the options for dividing requests into priority and secondary is as follows: all requests are processed by FST, and those that can be eliminated without the involvement of RT are considered priority, and the rest are secondary.

Based on the statistics [6], it can be concluded that approximately 25% of all failures have a recovery time in the range of 0 ... 4 hours, therefore, it can be assumed that it is precisely such a percentage of failures that is restored by FST forces, while the remaining requests (75%) require the involvement of RT. In this case, the recovery time is $T_{REP} = 9$ h, $T_{REP1} = 2 + 0.25 \cdot T_{REPST} \approx 4$ h. The calculations have been carried taking into account these factors.

**Figure 3.** Priority and delay queuing system calculation results for priority requests received under the following conditions: $T_{REP2} = 9$ h, $T_{REP1} = 4$ h, $\lambda_1 = 0.25$, $\lambda_2 = 0.75$, $N_{ST} = 35$, $N_{TEAM} = 2$, the number of equations is 1296, review period is 100 h, step size is 0.1 h.

**Figure 4.** Priority and delay queuing system QS calculation results for secondary requests received under the following conditions: $T_{REP2} = 9$ h, $T_{REP1} = 4$ h, $\lambda_1 = 0.25$, $\lambda_2 = 0.75$, $N_{ST} = 48$, $N_{TEAM} = 8$, number of equations is 2401, review period is 100 h, step size is 0.2 h.

As can be seen from Figure 3, the fulfillment of the criterion $T_{Q1} = 0.3 \cdot T_{REP1}$ occurs at $T = 35$ h, which is a perfectly acceptable result with the number of teams equal to 2. Evaluation of the queue for
secondary requests in calculating such conditions gives the established value of the order $T_{Q2} = 45$ h, $N_{Q2} = 33$, $P_{Q2} \approx 1$, which in turn is a failure to fulfill the criterion $T_{Q2} = 0.3 \cdot T_{REP2}$; the total average time in the system of secondary requests is $T_{SYS2} = T_{Q2} + T_{REP2} = 54$ h.

Figure 4 presents the calculation data for secondary requests at $N_{TEAM} = 8$, which makes it possible to fulfill the criterion $T_{Q2} = 0.3 \cdot T_{REP2}$ in the range $T = 0...60$ h. Evaluation of the queue for priority requests in calculating such conditions gives the established value of the order $T_{Q1} = 0.0001$ h, $N_{Q2} = 0.00001$, $P_{Q2} \approx 10^{-5}$, which in turn shows a sufficiently large redundancy of personnel to satisfy priority requests.

4. Conclusion
Based on the calculations performed, it can be concluded that the application of the separation of requests for fixing of technological disturbances in rural distribution electric networks into priority and secondary ones allows to achieve a criterion for the effectiveness of eliminating interruptions in power supply to consumers (the waiting time for servicing a request should not exceed 30% of the average time for restoration of power supply) using fewer repair personnel. Two methods for determining the priority of requests for the elimination of technological disturbances have been considered: by decision of the duty personnel and the time spent on restoring failures in electric networks. The division of the flow of requests in half into priority and secondary by decision of the duty personnel allows one to eliminate interruptions in consumers power supply for priority requests fulfilling the criterion of efficiency and to reduce the number of attracted repair personnel by about 30%. At the same time, the division of requests into priority and secondary in the proportion of 0.25/0.75 according to the criterion of time to restore failures allows one to achieve the criterion for priority and secondary requests with a decrease in the number of attracted personnel by about 20%.

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