Utilizing factor models to simulate emergency shutdowns of power grids

M Polkovskaya\textsuperscript{1,2}, T Buzina\textsuperscript{1} and N Fedurina\textsuperscript{1}

\textsuperscript{1}Irkutsk State Agricultural University named after A.A. Ezhevsky, pos. Molodezhny, Irkutsk district, Irkutsk region, Russia

\textsuperscript{2}E-mail: polk_mn@mail.ru

Abstract. In the article, based on statistics on emergency outages in the Levoberezhniy and Pravoberezhniy districts of Irkutsk and the sums of average daily temperatures in years 2010-2017 regression models are built. As an auxiliary factor for the models built on values that were grouped by year, the seasonality index was calculated using the “Kassandra” model. In the model, built for values that were grouped by month, a trend was added in addition to the seasonal component.

A retrospective prediction of emergency outages based on the data of the Levoberezhniy district, gathered in April 2020 showed that a model with a trend and a seasonal component gives a more accurate prediction. Since the sum of the average daily temperatures can be considered a random variable, the proposed factor models can be used to predict emergency outages only with some probability. The solution of inverse problems, when the factor value is determined for a given number of emergency outages, can be used to assess the risks associated with the influence of low and high temperatures on the objects of the electric grid complex.

1. Introduction

Modern day industry, as well as many other kinds of human activities are extremely reliant on the power supply. Power outages may lead to negative consequences across all economic sectors: industry, agriculture and forestry, construction, transport, trade, healthcare, etc. That is why it is crucial to predict and prevent downtimes of various components of power grids [1–4].

Various studies of emergency power supply shutdowns identify a multitude of factors that affect the uptime of power grid facilities [5–7]. Those factors can be divided into 4 groups: operational, climatic, external, and others [8, 9]. The operational ones include faulty equipment, high network load, operational errors, low-quality maintenance, etc. [10].

Climatic reasons are quite diverse, and the degree of their influence depends primarily on the climatic zone. Various studies examined the way power grids are affected by the following: relative humidity and air temperature, daily rainfall, wind speed, number of thunderstorm hours [8, 11, 12]; magnetic storms [13], as well as extreme natural phenomena (such as a hurricane) [5, 7].

The external factors most often involve human actions (vandalism or theft of electrical equipment, wire breakage, accidents, etc.), as well as plants, animals and birds [8, 14]. Other reasons for emergency shutouts include those for which the classification has not been established (ignition, relay protection being triggered, high-voltage switches being disconnected, etc.)
The study [15] revealed that emergency outages are not just being influenced by climatic factors, but are, in fact, subject to seasonal patterns (in three seasons: summer, winter, autumn-spring). The seasonal component was assessed by monthly data in the study [16], and by the quarterly data in [17].

Thus, the aim of the study is to make regression models for predicting emergency outages on power grids, that would take seasonality into account. With this goal in mind, we evaluated the effect of the average monthly temperatures on the emergency shutdowns. Then, we determined the influence of the seasonal component on the series of failures of the electric network equipment. After that, we built the factoring models to simulate emergency outages taking seasonality into account. Finally, we proposed several algorithms for estimating the number of outages for a certain probability.

2. Materials and methods
In order to build models with climatic parameters for predicting emergency outages on power grids, we utilized daily data on emergency outages at substations of Southern electric networks of the Irkutsk Electric Network Company for 2010–2017. (in the Pravoberezhniy and Levoberezhniy districts of the city of Irkutsk). The climatic factor is the sum of the average daily temperatures for months (observation point at Irkutsk Airport) for the same period [18]. Correlation analysis was used in order to assess the relationship between the temperature and the failures of various elements of the electric grid. Calculations of the parameters of regression equations and selection of the components of the time series (seasonal components) were carried out using the least squares method.

3. Results and discussion
At the first stage, we estimated the effect the sum of the average daily temperatures grouped by months on the number of emergency outages. In the city of Irkutsk, the data on emergency outages is logged for two districts: Levoberezhniy and Pravoberezhniy. Since the number of annual blackouts in these areas has different trends, we performed the study not for the city of Irkutsk as a singular unit, but separately for each district. Note that in the Pravoberezhniy district in 2011 there was a decrease in the number of emergency outages (figure 1). However, the situation is the opposite in the Levoberezhniy district, as the number of emergency shutdowns for 2011 and 2012 compared to 2010 has increased more than twofold. This fact is to some extent explained by the construction of new microdistricts, which in turn led to an increase in the load on electric networks. In subsequent years, there are wave-like changes in the number of blackouts in both districts.

![Figure 1. The number of emergency shutdowns in electric networks by districts of Irkutsk for 2010–2017.](image-url)
Evaluation of the significance of the relationship between the temperature parameter and equipment failures for the entire study period showed that in the Levoberezhniy district the connection is weak and significant ($R = 0.50$), and in the Pravoberezhniy district it is absent ($R = 0.15$). Subsequently, correlation coefficients were calculated using data for a specific year and for a specific month for the entire period.

A strong significant relationship between the number of emergency shutdowns in the Levoberezhniy district ($y_1$) for years and the sum of average daily temperatures ($x$) is observed in 2010, 2014, 2015, 2017 ($R = 0.86; 0.79; 0.74$ and $0.83$, respectively); weak significant relationship is observed in 2011 ($R = 0.50$) and 2013 ($R = 0.55$). According to the data of the Pravoberezhniy district, a strong significant relationship between temperature and blackouts was detected in 2010, 2013, 2014 and 2015 ($R = – 0.64; 0.68; 0.69$ and $0.77$), and a weak significant – in 2016, 2017 ($R = 0.53; 0.59$). In this connection in 2010 is the reverse.

When calculating the correlation coefficients from monthly data on emergency outages and the sum of average daily temperatures, the following results were obtained. According to the data of the Levoberezhniy district, a strong significant relationship between the studied parameters was detected in April ($R = 0.76$) and June ($R = 0.69$), significant – in March ($R = 0.44$), May ($R = 0.35$), July ($R = 0.55$), September ($R = – 0.40$), December ($R = – 0.34$). In the Pravoberezhniy district, the heat parameter has a significant effect on the accident rate in July ($R = 0.87$) and December ($R = – 0.73$). A close relationship between the number of failures and temperature is highlighted in January ($R = – 0.60$), February ($R = – 0.63$), June ($R = 0.60$), and November ($R = 0.43$). It is noteworthy that the correlation coefficients of the winter months are negative. Decreasing air temperature causes the number of accidents to rise, and, conversely the number of accidents decreases as the air gets warmer.

Based on the identified relationships, we constructed regression equations from annual and monthly data. The value chosen as a factor is the sum of the average daily temperatures for months – $x$, effective signs: $y_1$ – emergency shutdowns for years in the Left Bank district; $y_2$ – emergency shutdowns by years in the Right-Bank district; $y_3$ – emergency blackouts for months in the Levoberezhniy district; $y_4$ – emergency shutdowns for months in the Pravoberezhniy district. The obtained dependencies are checked for accuracy and adequacy. The significance of the regression model was checked using the Fisher F-test. Its value is found as the ratio of the variance of the initial series of observations for the studied indicator, and the unbiased estimate of the variance of the residual sequence for this model. The significance of the coefficients of the equation is checked using Student’s criterion ($t$-statistics). The calculated values of the Fisher criterion are shown in table 1, and the tabular value $F_{table} = 4.96$. Since the calculated value of the $F$-criterion is larger than the tabulated one, the equation is considered statistically significant.

**Table 1.** Factor models of emergency power outages grouped by years.

| Year | Levoberezhniy district | The calculated value of the Fisher criterion |
|------|------------------------|--------------------------------------------|
| 2010 | $y_1 = 36.61 + 0.022x$ | 28.7                                       |
| 2014 | $y_1 = 89.70 + 0.076x$ | 16.7                                       |
| 2015 | $y_1 = 73.42 + 0.066x$ | 12.0                                       |
| 2017 | $y_1 = 78.56 + 0.080x$ | 21.5                                       |

| Year | Pravoberezhniy district | The calculated value of the Fisher criterion |
|------|-------------------------|--------------------------------------------|
| 2010 | $y_2 = 92.42 – 0.065x$ | 7.0                                        |
| 2013 | $y_2 = 50.61 + 0.039x$ | 8.6                                        |
| 2014 | $y_2 = 63.59 + 0.031x$ | 8.6                                        |
| 2016 | $y_2 = 53.98 + 0.047x$ | 14.3                                       |
The adequacy of the model was tested according to four conditions: 1) fluctuations in the values of the remainder of the series have to be random (using the series criterion); 2) a series of residues has to correspond to the normal distribution law (RS-criterion); 3) the average value of the sequence $\epsilon_i$ needs to be equal to zero; 4) the values of the residue series have to be independent (Darbin-Watson $d$-test).

Considering significant variations in the number of emergency shutdowns between 2010 and 2012, the equations obtained for 2010 are not suitable for predicting emergency shutdowns, since, despite the high accuracy and adequacy estimates for the obtained equations, they do not reflect the actual data. It is logical that in order to obtain predictions it is better to use the regression equations for 2017 in the Levoberezhniy district and for 2016 in the Pravoberezhniy district, since the influence of unaccounted factors is more accurately reflected in these.

According to the equations given in table 2, significant regression equations were obtained only for the month of April in the Levoberezhniy district; as well as July and December in the Pravoberezhniy district. Despite the high correlation coefficient between equipment failures and the sum of temperatures, the equation for June in the Levoberezhniy district according to the Fisher criterion turned out to be insignificant, since the calculated value is lower than the table value ($F_{table} = 5.98$).

| Month         | Equation       | The calculated value of the Fisher criterion |
|---------------|----------------|---------------------------------------------|
| Levoberezhniy district |                |                                             |
| April         | $y_3 = 45.78 + 0.45x$       | 8.1                                         |
| June          | $y_3 = -230.35 + 0.63x$      | 5.5                                         |
| Pravoberezhniy district |                |                                             |
| July          | $y_4 = -149.32 + 0.39x$      | 18.2                                        |
| December      | $y_4 = 507.76 - 0.65x$       | 6.7                                         |

Next, we analyzed the presence of the seasonal component in emergency outages. We utilized the “Kassandra” model, which is based on the least squares method [19].

The equation includes three components of the initial time series $x_t$: trend ($y_t$), seasonal fluctuations ($s_t$), residual term ($\epsilon_t$):

$$x_t = y_t + s_t + \epsilon_t,$$

The trend is expressed as a polynomial in time

$$y_t = \sum_{t=0}^{n} a_t t^i;$$

The seasonal component $s_t$ is the sum of strictly periodic functions with weights $t_i$:

$$s_t = \sum_{l=0}^{m} s_l(t) t^i.$$  

Here, $s_l(t)$ are functions that reflect the variation in the amplitude and shape of seasonal fluctuations as a function of time. The oscillation period of the functions specified by the expansion in the Fourier series is one year

$$s_l(t) = \sum_{j=1}^{K/2} a_{lj} \cos \frac{2\pi j t}{K} + \sum_{j=1}^{K/2-1} \beta_{lj} \sin \frac{2\pi j t}{K},$$

where $K$ is the number values $x_t$ in a series for a year (for monthly data $K=12$).

To estimate the parameters of the model $a_t$, $a_{lj}$, $\beta_{lj}$, we used the least squares method

$$\sum_{t=1}^{T} b_t \epsilon_t^2 \rightarrow \min,$$
under conditions (1) – (4). Here $b_i$ are some positive informativeness weights used to account for the qualitative, structural changes of the series under consideration in the past and the regular effects of external factors.

In order to estimate the parameters of the trend-seasonal model we used the “Oracle” program created by I.V. Mokriy. Absolute seasonal deviations in the Levoberezhniy and Pravoberezhniy districts have similar seasonal waves (figure 2), as shown by the assessment of the seasonality index. At the same time, the amplitude of seasonality index fluctuations in the Levoberezhniy district is much higher than in the Pravoberezhniy district. The largest number of emergency shutdowns occurs from April to August, followed by a gradual decrease. This may occur due to more difficult operating conditions of the grids caused by heat, as well as increased load on the electric network, e.g. due to the use of air conditioners.

![Seasonality index of the series of emergency outages on power grids in the Levoberezhniy and Pravoberezhniy districts of Irkutsk for 2010–2017.](image)

**Figure 2.** Seasonality index of the series of emergency outages on power grids in the Levoberezhniy and Pravoberezhniy districts of Irkutsk for 2010–2017.

The obtained seasonality indices are included as additional factors in the regression equations with the sum of the temperatures (table 3). Here $s_iL$ is a series of seasonality indices obtained by months in the Levoberezhniy district, and $s_iP$ is in the Pravoberezhniy district. The significance check of the equation yields the tabular value of the Fisher criterion of 4.26.

| Year | Equation | The calculated value of the Fisher criterion |
|------|----------|---------------------------------------------|
|      | $y_1 = 36.70 + 0.029x - 0.18s_{iL}$ | 17.3 |
| 2010 | $y_1 = 62.80 - 0.015x + 1.47s_{iL}$ | 4.4 |
| 2011 | $y_1 = 84.70 - 0.059x + 1.97s_{iL}$ | 9.4 |
| 2012 | $y_1 = 94.03 + 0.006x + 1.35s_{iL}$ | 21.8 |
| 2014 | $y_1 = 77.12 + 0.027x + 0.76s_{iL}$ | 7.5 |
| 2015 | $y_1 = 82.55 + 0.031x + 0.98s_{iL}$ | 18.6 |
It should be noted that the seasonality factor allowed us to obtain models for a larger number of series (2011, 2012 in the Levoberezhniy district, 2015 in the Pravoberezhniy district), however, the significance of some equations according to the Fisher criterion has decreased.

Since the predictions of the models obtained for monthly values are calculated for the next year (s), we included the trend into the model as an additional factor (table 4). The number of regression dependencies with the trend and seasonal deviations for months, satisfying the criteria of accuracy and adequacy, is equal to the factor models shown in table 2. However, the standard error of the equations presented in table 4 is lower (except for the dependence of the effective sign in July for the Pravoberezhniy district, for which the standard error is 1 less than that of a similar dependence with the trend and seasonality).

### Table 4. Factor models of emergency shutdowns on electric networks with the seasonal component by months.

| Month       | Equation                                      | The calculated value of the Fisher criterion |
|-------------|-----------------------------------------------|---------------------------------------------|
|             |                                               | Levoberezhniy district                       |                                           |
| April       | \( y_3 = 28.40 + 0.71x - 9.50t + S_{4L} \)     | 6.6                                         |
| June        | \( y_3 = -96.06 + 0.36x + 5.23t + S_{6L} \)    | 5.7                                         |
|             |                                               | Pravoberezhniy district                      |                                           |
| July        | \( y_4 = -175.82 + 0.42x - 0.76t + S_{7P} \)   | 7.9                                         |
| December    | \( y_4 = 84.97 - 0.043x - 8.20t + S_{12P} \)   | 15.8                                        |

To compare the obtained models, we make a prediction of the number of emergency outages in April 2020 in the Levoberezhniy district and compare it with the actual value of 119 (table 5). The sum of average daily temperatures in April 2020 amounted to 218.4 °C [18].

### Table 5. The results of a retrospective prediction of outages on power grids in April 2020 according to the data of the Levoberezhniy district based on factor models with and without the trend and seasonality.

| Model                     | Forecast value | Deviation from the actual value, % |
|---------------------------|----------------|-------------------------------------|
| \( y_3=45.78+0.45x \)     | 144            | 21.1                                |
| \( y_3=28.40+0.71x-9.50t+S_{4L} \) | 113            | 4.6                                 |

According to the result, a more accurate prediction is yielded by the regression model with the sum of the average daily temperatures for the month, trend and seasonal component.

It should be noted that climatic factors, including the sum of temperatures, are random variables [20]. Therefore, the obtained equations (table 1–4) allow us to simulate an effective attribute only for some probability. We propose an algorithm for modeling emergency outages on electrical networks.
based on factor dependencies (figure 3). According to the algorithm, the first stage determines the statistical parameters of the climatic parameter (for example, temperature). After that, using the acceptance criteria we select the distribution law and randomly model the factor values based on that. The obtained values are substituted into the regression equations, which are then used to calculate the number of failures. The results can be estimated with some probability. It should be noted that inverse problems can be solved using regression dependencies in order to obtain factor values based on the values of emergency shutdowns.

4. Conclusion
Emergency shutdowns on electric networks are influenced by various factors, the careful analysis of which allows for timely measures to be taken in order to prevent them.

When determining the regression dependences of the failures of electric grids, the sum of the average monthly temperatures was taken as a climatic factor. Factor models were built for years and months, utilizing the emergency shutdown data for 2010–2017 in the Levoberezhniy and Pravoberezhniy districts of Irkutsk.

Since the Irkutsk region is a zone with an acutely continental climate, one of the factors affecting the subject parameter is seasonality, which was simulated using the Kassandra model. In addition to the seasonal component in the model for months, a trend is added as a factor.

When comparing models with and without seasonality and trends using indicators of accuracy and adequacy, slight deviations were revealed. However, a retrospective prediction of emergency outages in the Levoberezhniy district in April 2020 showed that a model with a trend and a seasonal component gives a more accurate prediction.

The obtained regression equations can be used to simulate the number of emergency shutdowns only for a certain probability, since the sum of the average daily temperatures is a random variable. In this case, inverse problems can be solved, where the factor value will be calculated on the basis of the set value of emergency shutdowns using the regression equation. This approach can be used to assess the risks associated with the impact on the objects of the electric grid complex of low and high temperatures.

Acknowledgment
The some results study was obtained with funded by RFBR according to the research project no. 19-07-00322.
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