Predicting Grid Facility Accidents

M Kuznetsova¹, S Zaripova²
¹Department "Engineering Ecology and Labor Safety" FSBEI HE "Kazan State Power Engineering University", st. Krasnoselskaya, 51, Kazan, 420107, Russia
²Department "Industrial and Environmental Safety" FSBEI HE "Kazan National Research Technical University. A.N. Tupolev - KAI ", st. K. Marx, 10, Kazan, 420111, Russia

E-mail: accic@ya.ru, zsn10@mail.ru

Abstract. Open-source statistics on accidents at transmission and generation facilities in Russia for 2014-2018 has been analyzed to identify key accident causes. This analysis established a correlation between accident rates and staff-involving incident rates. The authors were thus able to predictively model accidents, including those at Russian transmission and generation facilities. Accident forecasting is based on trend/cycle models that account for yearly load maxima and minima.

1. Introduction
Russia’s electricity generation and consumption have been on the rise in recent years. In 2014-2018, the output rose by 4.2% and the consumption rose by 3.4%. However, there are challenges and threats that hamper the positive change in the energy industry that seeks to make the existing systems more reliable. First, a significant portion of the energy equipment (>80% in some regions) is obsolete and worn-out; technologically, the industry is lagging behind, making it too dependent on imported equipment and services. Statistics [1] shows that the wear and tear of equipment and infrastructures results in grid failures, which in some cases lead to major accidents with negative social, environmental, and economic impact.

Over the course of 2014-2018, accident rates at grid facilities dropped by 25.7% in total, including a reduction of 24.9% for transmission facilities and 6.9% for generation facilities (note that for space considerations, ‘transmission’ hereinafter stands for transmission and distribution networks alike). However, whilst general accident rates are dropping, more and more accidents occur that pertain to the failures of power-plant and grid automations and telemechanics. The rate of such accidents rose by 21.1% in total over the same period, including an increase of 33.4% for power plants and 18.8% for grids. Not only do such accidents disrupt the workflow, they also jeopardize organizational work, leading to a higher burden on staff, worsening human performance, and resulting in more staff-involving incidents and more severe injuries at work. This finding is reinforced by the linear correlations found herein between staff-involving incidents and accidents at power plants (≥25 MW of installed capacity), a correlation coefficient of 0.74; between staff-involving incidents and accidents within transmission networks (≥110 kV).
2. Relevance
Many research papers dwell upon the causative analysis of grid accidents and modeling various operations by means of digital real-time simulation systems among other methods. However, there are not so many papers that use accident statistics to predict accidents in Russia’s grids. A large-scale study carried out by Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, employed mathematical statistics and regression analysis; using data for 1997-1999, the researchers were able to predict the failure rates of grid facilities. However, the publication is nearly 20 years old as of writing this paper [2]. Over these 20 years, Russia’s grids have transitioned from the traditional industrial model to a competitive model, which has changed the grid structure, as regional vertically integrated grid companies have been split into potentially competing electricity generation and sales, repairs, and service providers [3]. This transition, coupled with an increase in electricity generation and consumption, not only made technological, organizational, and process management issues more challenging; it has also led to a higher risk of failure to deliver electricity to large areas, which might jeopardize public health and life, or disrupt the critical infrastructures. Thus, research into accidents in Russian grids remains relevant to date, now adjusted for the competitive model of the industry.

3. Statement of problem
Statistics shows [1] accidents may be caused by technological shortcomings and by force majeure: third-party actions, bird and animal accidents, Acts of God, etc. Therefore, accidents at electrical facilities can be compared to a black box whose internal structure is unknown and whose response to external or internal stimuli is unpredictable. Simulation modeling is the most suitable toolkit for modeling random events, where the important features include the occurrence itself and its non-periodicity.

A simulation model uses a flow of randomly timed events, each associated with a grid facility accident, as input. These can be written as dynamic series of events occurring at regular intervals [ti, ti+1], at which Δt=ti+1-ti is below the beforehand acceptable error of the first event occurrence if such occurrence does not fall upon a regular time ti or ti+1 [4]. A flow of accident-associated events can be regularized by selecting a time period. This paper uses one month as a period, because energy companies provide monthly performance reports; thus, accident rate will be measured on a monthly basis. Therefore, we have 60 input values for 2014-2018.

Grid statistics shows 62% to 88% of grid accidents happen in the transmission system, and only 10% to 36% happen at power plants, see Figure 1. Input graphs show there are cyclical variations with a one-year period, see Figure 2. Accident rates are the lowest in February, October, and November, and peak in June to August. Since transmission systems show pronounced minima and maxima of accident rates, see Figures 2 and 3, but generation facilities do not, see Figure 4, this paper analyzes accident rates for grids in general (Y1) and 110+ kV transmission networks in particular (Y2).

![Figure 1. Percentage of accidents: transmission vs generation.](image1)

![Figure 2. Accident rates: Y1 across Russian grids, Y2 in transmission networks.](image2)
Thus, this study sought to identify patterns in grid-wide and transmission-specific accident rates in a competitively modeled industry so as to obtain predictive mathematical models capable of projecting accident rates from 2014-2018 statistics [5].

4. Theory

Accident rates $Y_1$ and $Y_2$ were modeled as a dynamic series $Y_t$:

$$Y_t = U_t + V_t + \varepsilon_t, \quad t = 1, 60,$$

where $U_t$ is the trend of the dynamic series, $V_t$ is the seasonal component, $\varepsilon_t$ is a random component resulting from a variety of causes. The model (1) allows filtering the components.

Modeling follows a sequence of procedures: adjust the series (1) to address any incomparability of its terms whatever the cause; calculate the trend $U_t$; find the seasonal component $V_t$; evaluate the random component $\varepsilon_t$. By evaluating all the components of the series (1), one can take into account virtually the entire spectrum of effects the real simulation model is exposed to.

In this research, the dynamic series $Y_{1t}$, $Y_{2t}$ were adjusted by Irwin’s anomaly detection method [6]. Trend components $U_t$ were found by mechanical and analytical alignment. Trend models were found by the least squares (LS). The seasonal component of the series (1) was filtered by two methods: seasonal variation plotting and harmonic analysis [4]. Seasonal variations were plotted by simple average; the analytical seasonality model was obtained using the Fourier series. Since the accuracy of the analytical model depends on how many harmonics are brought into account, one to four harmonics were detected for each times series under analysis depending on the shape of the cyclical component. Relative seasonal variations were found by removing the trend components from the times series $Y_{1t}$, $Y_{2t}$ by five-point smoothing.

Quality assessment was performed once all the components of the series $Y_{1t}$, $Y_{2t}$ had been found. Statistical, the model is best if it is adequate and provides the most accurate description of the original dynamic series. An adequate model should take into account the existing patterns in the process, i.e. feature certain statistical properties of the residual component $y_i - y_{it}$ ($i = 1, ..., n$), which is the difference between actual and calculated values in the approximation segment. These properties are: level randomness and independence, normality of distribution, and zero mean error. This study used the turning point test to verify the randomness of the levels of the series $Y_{1t}$, $Y_{2t}$. The Durbin-Watson statistic was used to test the independence of the random component levels, i.e. to verify there was no significant autocorrelation in the tested residual sequences. The distribution of the random component $\varepsilon_t$ was tested for normality by testing the asymmetry $A$ and the excess $E$. To find whether the mean error (the mathematical expectation of the random sequence) was zero, we used Student’s $t$-test [7].

Grid facility accident rates were predicted by extrapolation, which enabled pointwise and interval forecasting based on adequate and accurate trend-seasonal models; the predictions were verified. When using trend-seasonal models for forecasting, one should not try to look too far, because that will produce too significant an error. Normally, the optimal preemption period is within two years.
Find the interim results and predictive models for the dynamic series $Y_1t$, $Y_2t$ below. The best fit trend models produced by least squares were ($R^2$ is the approximation confidence level):

for $Y_1t$: $y = -7.926t+2038.4$ ($R^2 = 0.610$) и $y = 2008.7e^{-0.005t}$ ($R^2 = 0.519$),

for $Y_2t$: $y = -0.062t^2-4.3286t+1552.8$ ($R^2 = 0.621$) и $y = 2029.6e^{-0.005t}$ ($R^2 = 0.607$).

Since this was not the final stage yet, we further studied all the models as if they had the best characteristics at this stage.

Figure 5 shows relative seasonal variations found by removing the trend components from the time series $Y_1t$, $Y_2t$ by five-point smoothing for the series $Y_1t$, three-point smoothing for $Y_2t$, whilst Figure 6 shows the seasonal variation curves.

Figures 7 and 8 show the Fourier series harmonics. Trend and seasonal component models based on one, two, three, four, or more harmonics were analyzed for accuracy to find out that the four-harmonic models had returned statistically significantly more accurate results than their counterparts featuring a different number of harmonics. Four-harmonic models had the following equations:

for $Y_1t$: $y = -656.24 \cos(t)+86.88 \cos(2t)-82.35 \sin(2t) -30.89 \cos(3t)-37.58 \sin(3t)-0.41 \cos(4t)-4.5 \sin(4t)+2008.7e^{-0.005t}$, $y = -656.24 \cos(t)+86.88 \cos(2t)-82.35 \sin(2t) -30.89 \cos(3t)-37.58 \sin(3t)-0.41 \cos(4t)-4.5 \sin(4t)-7.926t+2038.4$;

for $Y_2t$: $y = -606.15 \cos(900.25 \sin(t)+263.08 \cos(2t)+15.05 \sin(2t)+150.25 \sin(3t)-26.73 \sin(3t)-10.29 \cos(4t)-17.41 \sin(4t)+2029.6 e^{-0.005t}$, $y = -606.15 \cos(900.25 \sin(t)+263.08 \cos(2t)+15.05 \sin(2t)+150.25 \sin(3t)-26.73 \sin(3t)-10.29 \cos(4t)-17.41 \sin(4t)-0.062t^2-4.3286t+1552.8$. 

Figures 7 and 8 show the Fourier series harmonics for the series $Y_1t$, $Y_2t$. 

Figure 7. Fourier series harmonics for the series $Y_1t$. 

Figure 8. Fourier series harmonics for the series $Y_2t$. 

Figure 5. Relative seasonal variations in accident rates for the series $Y_1t$, $Y_2t$. 

Figure 6. Seasonal variation curves for the series $Y_1t$, $Y_2t$. 

Table 1 summarizes the results of verifying the model’s adequacy: level randomness and independence, normality of distribution, and zero mean error.

| Model | No. of turning points, \( K \) | Statistics, \( d \) | Asymmetry, \( A \) | Excess, \( E \) | Statistic, \( t_p \) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|
| (2)   | 38 > \( K=32 \) | 1.62<1.674<2.38 | 0.16<0.45       | 0.22<0.84       | 0.04<1.67       |
| (3)   | 38 > \( K=32 \) | 1.62<1.693<2.38 | 0.08<0.45       | 0.38<0.84       | 0.36<1.67       |
| (4)   | 40 > \( K=35 \) | 1.57<1.612<1.63 | 0.25<0.44       | 0.26<0.81       | 0.25<1.67       |
| (5)   | 40 > \( K=35 \) | 1.57<1.612<1.63 | 0.21<0.44       | 0.11<0.81       | 0.15<1.67       |

At \( \alpha=0.05 \), all trend-seasonal models (2) to (5) of the series \( Y_1t \) and \( Y_2t \) were adequate as obtained by smoothing the adjusted inputs by five (for \( Y_1t \)) for three (for \( Y_2t \)) points. The accuracy of these models was tested by three characteristics (standard error \( S_y \), mean relative error \( m_{cr} \)(%), and mean linear deviation \( B \)):

- (2): \( S_y=229.24 \), \( m_{cr}=1.76\% \), \( B=169.64 \);
- (3): \( S_y=246.52 \), \( m_{cr}=5.82\% \), \( B=192.53 \);
- (4): \( S_y=182.21 \), \( m_{cr}=4.16\% \), \( B=138.03 \);
- (5): \( S_y=189.63 \), \( m_{cr}=3.51\% \), \( B=142.58 \).

Statistically, the most accurate models were (2) and (4), which were then used to predict accident rates for 24 months ahead by calculating the confidence intervals. Using statistics for five months of 2019, the verification of these predictions showed that the models (2) and (4) were highly accurate, see Figures 9 and 10.

5. Applicability
The obtained trend-seasonal models of uncontrolled accident rate prediction, which are based on the dynamic series \( Y_1t \) and \( Y_2t \), do reveal the trends, the peaks, and the drops in accident rates at grid facilities to help take preventive measures so as to significantly cut the number of accidents, reduce their scale, and mitigate their impact. Seasonal variations in accident rates pertain not only due to weather conditions; seasonality does not always stem from (virtually) uncontrollable factors. In most cases, factors affecting accident rates can be controlled; however, even if executing direct control upon such factors is impossible, they need to be borne in mind when attempting to enhance the management of transmission and generation facilities.
6. Conclusions
Statistics for 2014-2018 was used in this research to find patterns in accident rates in Russian grids operating in a competitive energy industry; the research team constructed trend-seasonal accident rate models for Russian grid facilities that enable precise short-term prediction for a specific time period. Relative seasonal variation in transmission and in grids in general peaks at 30-35% in July to August, 36-38% in February, indicating an increase in accident rates in summer (the minimum-load season) and a decrease in winter (the maximum-load season). Similar results were obtained by V.P. Vasin, Ya.Ye. Gonik, and V.A. Skopintsev when analyzing accident rates in Russian grids [2] operating by the traditional industrial model. Therefore, the transition to competitive operation did not significantly change what should be done to reduce the scale of accidents and mitigate their impact by taking preventive measures and improving the production and organizational processes.

7. References
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