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Study Committee C1

Power System Development and Economics

Paper 10564_2022

Application of a deterministic chaos theory and artificial intelligence methods for predicting accidents in electric grids of European Russia

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Motivation

- **Failure prediction in electric grids is pressing issue due to continuous severization of requirements for reliability and quality of electric power supply to consumers**. Existing approach to reliability characteristics analysis consist in determination of failure rate on the basis of statistical data (more pointedly – mean failure rate or failure frequency), recovery time and frequency and duration of scheduled outages of overhead lines (OHL) and substations, including analysis of cause and effect relationship and key influential factors
- **In 2000s, V.A. Skopintsev offered a theory** of periodicity of emergencies in electric grids. Using statistical data, he assumed **that the rate of accidents in electric grids may be fluctuating in accordance with the period close to the (quasi) eleven-year solar cycle**. He stated that his model reflected the trend of OHL accident rate with the precision acceptable for making forecasts, while the random component might be presented in the form of Gaussian white noise.
- This work aims to check the theory of V.A. Skopintsev and to create a method for OHL failure prediction in the main electric grids with a chaotic dynamics.

Method/Approach

- For prediction of failure rate time series the mathematical apparatus, which includes deterministic chaos theory and artificial intelligence methods, was chosen. The mathematical apparatus is widely used for forecasting the weather, financial markets, demand, population growth, etc. Thus, application of a deterministic chaos theory and artificial intelligence methods for failure prediction in electric grids is a strong research and practical interest:
- Analysis of the failure rate time series was conducted by using the Higuchi algorithm
- The use of Wolfe's method made it possible to determine the maximal Lyapunov exponent value. The positiveness of the maximal Lyapunov exponent means exponential instability (exponential divergence of trajectories) and makes it possible to estimate the forecast depth (in this case, about five years).
- To forecast the 500 kV OHL failure rate, we chose one of the simplest fuzzy Wang–Mendel's neural networks (a special case of the Takagi–Sugeno–Kanga network). It was implemented in Matlab using ANFIS software

Experimental setup & test results

- Analysis was conducted for the frequency of stable failures (i. e., those which cannot be corrected by automatic repeating switching) of 500 kV OHL failures in the Central European Russia (about 8,500 km long) for the period of 1974–2018

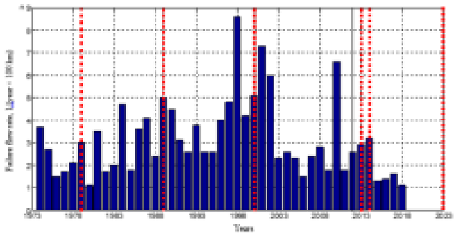

Fig. 1. Failure rate of 500 kV OHLs for the period of 1974–2018, aligned with solar cycles (dashed line)

- According to Fig. 1, ω is fluctuating and changing in the broad range from 0.11 1/(year × 100 km) in 1980 and 2018 up to 0.86 1/(year × 100 km) in 1998 *(historical background: in 1980, the USSR hosted the summer Olympic Games; in 2018, the Russian Federation hosted the FIFA World Cup; and in 1998, default was announced)*. In years with the highest solar activity (Fig. 1), ω showed a slight growth. Nevertheless, between each cycle, there were numerous OHL accidents, more than during the peaks of solar activity. For example, this is true for 1998 or 2010, with fierce wildfires in the European part of the country as a result of a summer heat anomaly.
- **Using the accident reports for the period of 2011–2019**, we have considered the structure of 500 kV OHL failures. **We have established that social and natural factors exhibit approximately equal impact on OHL accidents**. Fig. 1 is an amplitude–time representation of the rate (signal). With this in mind, V.A. Skopintsev described this changes of ω using the mathematical model with a linear trend and a set of harmonic components defined via Fourier series transformation. However, the signal frequency is also important. For this purpose, the time sequence from Fig. 1 was used for a wavelet analysis. It allowed conducting a frequency-time division of the process in Fig. 1.

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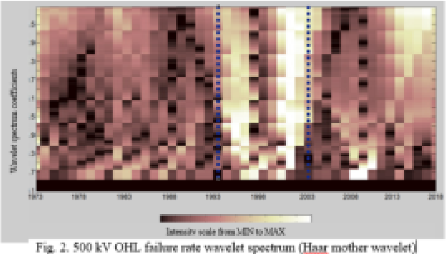

Fig. 2. 500 kV OHL failure rate wavelet spectrum (Haar mother wavelet)

- The **behavior of ω in Fig. 2** provides for **three time periods from the frequency spectrum intensity positions**: from 1974 to early 1990s, from early 1990s to early 2000s, and from early 2000s until nowadays. The **first period is characterized by unperturbed and relatively calm frequency spectrum** (minimum intensity values, dark-colored). The **second cycle is represented by a spectral "storm"** (maximum intensity values, up to clean white). Finally, the **third period is marked by stabilization and pacification of the frequency spectrum**; a certain surge of intensity is likely to be related to the events of 2010 (see above). Arguably, Fig. 2 reflected the events in the USSR/Russia. Specifically, the second period coincides with the disintegration of once a single country and its economy.
- **Based on the analysis of events in Fig. 1 and 2, the theory by V.A. Skopintsev was not proven**. This explanation was too simple in view of reliability. **The cause and effect relationship here is much more complicated.** The resulting impact is defined by a multifactor combination of random environmental impacts and social and economic relations which are hard to formalize.
- We found out that **more than 40% of 500 kV OHLs** in the region **reached the end of the life cycle (50 years long)**. Some authors (e. g., F.L. Kogan et al.) state that as the OHLs age, the wear-related accident rate grows by 3% to 5% annually. In this regard, we have specified the impact of 500 kV OHLs service life on the frequency of failures and defined **the service wear limits of the lines beyond the rated service life**.
- The **revealed statistical patterns allowed assuming** that the **OHL failure flow rate is** not a set of fixed values but **a process within a certain dynamic chaotic system**
- To define the fractal dimension D of the time sequence in Fig. 1, the Higuchi algorithm was used.

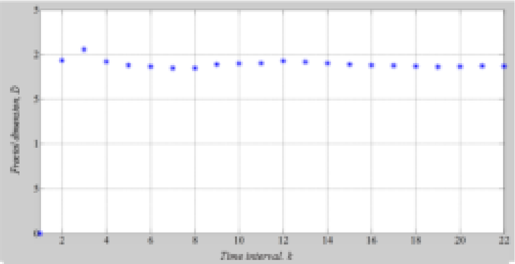

Fig. 3. Fractal dimension $D_{1974-2018}$ of failure rate

- Indicators of chaotic time sequence of OHL failure rate revealed during the assessment of fractality and positive maximal Lyapunov exponent of the time sequence of OHL failure rate. Thus, **OHL accident rate of the main electric grid is clearly chaotic**, so the **forecasting time is** limited and depends on the value of the maximal Lyapunov exponent of the initial time sequence. The permissible forecasting period of T ≈ 1/0.2183 = **4.6 years**
- The theory of dynamic system includes numerous methods of analysis and forecasting of time sequences, including chaotic ones. In the work, we initially applied the method of singular spectrum analysis (SSA) for these purposes. It belongs to the global forecasting methods and is used to distinguish the periodic and quasi-periodic components of the time sequence

Table 1. 500 kV OHL predicted failure rate for 2019–2023 years using singular spectrum analysis

Year	2019	2020	2021	2022	2023
ω, 1/(year × 100 km)	0.12	0.14	0.11	0.25	0.27

- **Alternative approaches to ω forecasting included methods related to artificial intelligence**, specifically, **neural and neuro-fuzzy networks**. One of the possible applications of neural networks are known to be predictions of dynamic system behavior with unknown structure and parameters using a signal pre-generated by it (in our case, for a time sequence in Fig. 1 with the signs of chaotic behavior). We **applied neural networks with two and more layers and direct signal transfer**, i. e., providing no feedback

Table. 2. Results of ANFIS-forecasting for 2019–2023

Year	2019	2020	2021	2022	2023
ω, 1/(year × 100 km)	0.10…0.15	0.10…0.15	0.10…0.15	0.10…0.15	0.15…0.20
Events, %	41	41	38	37	42

- **The research within this work took more than a year**. Thus, **it was possible to compare the expected and actual data for 2019**. By processing the statistic data, we revealed the **failure rate of 500 kV OHL** in the region in question **totaled 0.1** 1/(year × 100 km) **against the forecast of 0.12** 1/(year × 100 km) **resulting from SSA**.

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Conclusion

- **Forecasting method of OHL failure rate** in chaotic conditions using the spectral singular analysis, neural and fuzzy neural networks, **has been developed**.
- **Time sequence forecasting methods for 500 kV OHL failure rate based on regression (SSA) and artificial intelligence produce different results**. From a five-year perspective, **SSA provides about a two-fold or three-fold growth of 500 kV OHL failure rate** in the region for 2022–2023: from 0.1 to 0.25–0.27 1/(year × 100 km). **Neural and fuzzy networks offer a more realistic forecast: from 0.11 to 0.2** 1/(year × 100 km). Nevertheless, **the traditional regression forecast method and the methods related to artificial intelligence indicate that**, in the foreseeable future, **there can be an exponential growth of a failure rate in the main energy grids**. It should be taken into account during the operation of the grids.
- The **developed** mathematic **models and** the obtained related **forecast assessments will help** practically **increase the reliability and economical efficiency of the main electric grids**.
- 8. **The results of on-site inspections of 500 kV OHL technical state allow significantly extending the service life of lines after the end of the life cycle**, which is crucial for development of the investment reconstruction programs of the unified national electric grid.