Problem of survivability of energy associations as specific property of complex systems

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Abstract

Introduction. This study examines the factors contributing to the survivability of energy associations, particularly their ability to withstand emergency disturbances and prevent widespread consumer supply disruptions.

Materials and methods. The study employs a systematic approach using quantitative indicators to measure survivability levels. The methodology involves analyzing transient modes of the Unified Power System (UPS) through simulation modeling. This model calculates long transient processes and post-emergency modes, accurately representing system dynamics and considering failures in relay protection, anti-emergency automation, and switching devices.

Results and discussion. The developed simulation model provides an in-depth analysis of the transient behaviors and stabilization processes of the UPS under various emergency conditions. By accurately simulating these dynamics, the model demonstrates the ability to represent the energy systems' performance with satisfactory accuracy. Key findings indicate that the approach effectively identifies potential failures and their impacts, supporting the development of strategies to enhance system resilience. The model's comprehensive accounting for failures in critical components like relay protection and anti-emergency automation highlights the importance of detailed scenario-probabilistic analysis. This method enables a thorough understanding of system vulnerabilities and the effectiveness of preventive measures. The results show that incorporating these detailed analyses into survivability assessments can significantly improve the reliability and robustness of energy associations. The research underscores the necessity of continuous monitoring and updating of simulation models to adapt to evolving system dynamics and emerging threats. By focusing on ergodic scenario-probabilistic approaches, the study provides a robust framework for future research and practical applications in enhancing the resilience of electric power systems.

Conclusions. This methodology offers valuable insights into energy system dynamics, helping identify vulnerabilities and implement effective measures to ensure stable energy supply and resilience.

Introduction

The urgency of addressing the survivability of energy associations is driven by several factors: the existing centralization of electricity production and distribution, the growing influence of renewable energy sources, and the operational challenges of energy systems and associations under wartime conditions (Li S. et al., 2022; Liu J. et al., 2021). These issues are under continuous investigation by scientists and experts in the energy sector (Abedi et al., 2022; Li L. et al., 2022; Yao et al., 2022).

A significant outcome of this ongoing research is the quantitative and qualitative enhancement of the Electric Power Systems (EPS) emergency management system, a critical and integral component of energy associations that ensures their normal functioning (Liu D. et al., 2022). However, these challenges increase the stress on the Unified Power System's (UPS) electrical modes and the operating conditions of all major electrical systems' equipment, which function with minimal permissible stability reserves and limited operational power reserves (Khan et al., 2022; Soni et al., 2022).

These trends elevate the likelihood of significant disturbances occurring and propagating within the EPS as initial emergency situations develop and escalate. Experience with modern power units demonstrates that abrupt, significant disturbances originating in one part of the unit can spread over large areas (due to the increasing "connectivity" of EPS elements and their operating modes). The nature and duration of the resultant transient processes become more complex, leading to cascading (chain) accidents that can disrupt the electricity supply to large populations (Alam et al., 2022).

The reliability of the energy system is a multifaceted property defined by its ability to perform the functions of production, transmission, distribution, and supply of electrical energy to consumers in the required quantity and standardized quality. This is achieved through the interaction of generating units, electrical networks, and consumer electrical installations. The energy system must:

- Satisfy the total electricity demand at any time (both current and prospective).
- Resist disturbances caused by failures of power system elements, including the cascading development of accidents and force majeure conditions.
- Restore its functions after disruptions.

The last function, the ability to return to operational mode after various disturbances, characterizes the system's stability (Zhong et al., 2023). The survivability of the energy system can thus be defined as its ability to withstand emergency disturbances and prevent the cascading development of accidents that cause widespread consumer supply disruptions.

Cascading accidents are characterized by the successive disconnection of a power grid or station equipment due to the activation of relay protection or emergency automation triggered by unacceptable operational conditions. While such serious system accidents are relatively rare (occurring once every few years), they can have the scale of national disasters. In such events, power supply disruptions can affect large areas with several million populations, resulting in tens of millions of kilowatts of power and hours-long outages, leading to significant material losses. An example is the February 2021 Texas, USA, energy crisis, where extreme cold led to failures in the electric power, gas supply, and water supply systems, with the interconnected nature of these systems exacerbating the impacts (Niet et al., 2022; Parrado-Hernando et al., 2022).

Literature review

In the energy system survivability analysis task, it is advisable to highlight two issues: methodical approaches and indicators for quantitative measurement of the level of the Unified Power System survivability (Zhong et al., 2023). The idea of approaches that consider the survivability of a system as a property that manifests itself exclusively under external influences of an undefined nature (intentional or extreme natural influencing factors) was most clearly expressed by I. Ushakov (Agajie et al., 2021; Avramenko et al., 2011), who, in this way, formulates the concept of the survivability indicator, which does not use probabilistic characteristics. Let $\Phi_j(l_i)$ be an indicator of the quality (efficiency) of the functioning of the jth variant of the system under the influence of l_i. The survivability index L_j(E) of the system for a set of possible external influences L is written in the form:

$$L_j(E) = \Phi_j(l_i) \quad (1)$$
$$l_i \in E$$

Thus, in conditions of uncertainty in quality fuse survivability, worst-case functioning is accepted. Optimization systems (according to the indicator survivability) are found during design by finding such an option system from the number of possibilities that L_j have the maximum value.

Concerning electric power systems, the reduction of equal functioning is to be measured by the amount of load paid off during the course accident (Liu J. et al., 2021); maybe her clarification at the expense of accounting for depth outages load. Based on analysis more than 100 types electricity consumers received averaged dependencies specific damage consumers of large power stations from depth emergency shortage capacity. Note that at a depth (Abedi et al., 2022) deficit equal to 60%, the steepness of these characteristics is sharp and growing. It needs to be addressed, and attention to what full indicator survivability (Khan et al., 2022) takes into account duration violation electricity supply, there is a shortage electricity consumers taking into account different importance different components short leave There is a comparison technique options development of the EPS according to the criterion survivability (Soni et al., 2022) This approach allows consider development accident at the expense of violation dynamic stability. Results testify that (Liu D. et al., 2022) this moment, considered a measure of increased adequacy used in the EPS model, significantly impacts the assessment of survivability energy association, separate in parts of which there are large losses capacity. Do not use probabilistic characteristics and indicators, which are determined by the number of large disturbing influences during which the unacceptable development of emergencies occurs (Li S. et al., 2022; Yao et al., 2022). Such an indicator accurately reflects the essence of the concept of survivability, which characterizes achieving the maximum permissible state of the system. However, the practical determination of such indicators based on the analysis of the performance function as the solution of a system of logical equations expressing the dependence of the achievement of the goal (providing power to consumers) on the performance of elements and external disturbances, can be effective only for relatively compact systems limited in number of elements: autonomous systems (ships, airplanes, etc.), switching schemes of generators and power plants of own needs, etc (Khan et al., 2022; Niet et al., 2022). Thus, there is a certain limitation of the scope of application of logical-probabilistic methods modified for the analysis of the survivability of the Electric Power System, which is reflected in taking into account the imposition of external disturbances and calculating the conditional probability of the degree of damage to the system or accounting for the probability of the development of an accident following the failure tree due to possible failures of relay protection and emergency control automatics (Alam et al., 2022).

A regressive factorial model is an extremely generalized form of description of survivability energy systems. Its essence is that it is based on retrospective data to determine shared different factors and their connections to the cause of the beginning and development chain accidents at different depths, shared accidents with an excessively high number of degrees of development, and shared accidents with unsuccessful action anti-emergency automatics. Implementing such an approach may do more justified expert evaluations of settlement influences and rejections concerning those necessary to determine the survivability of the EPS (Yao et al., 2022).

The complex, dynamic nature of the reaction of modern energy unions to resentment and rejection prompts search decision tasks. Analysis of their survivability means imitative modeling, based on which calculations are laid out lasting transitional processes in energy systems. The method also deserves attention when calculating sustainability submission based on annual or seasonal schedule load in the form of equivalent per diem and coverage of these graphics stations. As a result, a seasonal or yearly graph load will be released that (Soni et al., 2022) characterizes the entire spectrum of normal stationary modes. Probability violation emergency stability disconnection line is defined as relationship duration excess admissible under stability overcurrents (Zhong et al., 2023). This approach considers static stability and provides previous definition regimes that are marginal in terms of stability in all respects and intersects, and therefore, is oriented mainly on long ones' energy association.

A method designed for analysis of process development emergencies in concentrated energy systems is as follows. In such systems, the maximum bandwidth ability lines power transmission because of their relatively small length is not determined by a static stability system and is beyond the limits of the transferred one thermal capacity stability elements (Abedi et al., 2022). When this occurs overload, they have turned off protection and the duration of action, which may be calculated as minutes or dozens of minutes. Because load in the system causes overload lines, there are random processes and sequence disconnection lines, which significantly affect development (Parrado-Hernando et al., 2022) accidents, and the consequences are also random. Therefore, instead of a probabilistically deterministic model proposed for research (Agajie et al., 2021) cascading accidents in the power association, which have comparatively weak intersystem connections, developed and used a probable non-stationary mathematical model of electrical long-term load time intervals (up to an hour), using determined probabilities of system transition from one state to another due to emissions overcurrent above a certain level. Note that appropriate imitative modeling is carried out separately from each of the chosen ones' most difficult initiating disturbances, i.e., it is considered a single-rooted tree. Process modeling lasts until it remains in the system branches with overload more than permissible, i.e., before reaching "absorbing" states. As a result of calculation, you can determine that probably not until the holiday electricity as a result of development cascading accidents in the system, and based on analysis of "narrow seats" (min intersections) in graphs of transition states outline measures, thanks to which system with the largest the probability will be to switch to those states which lead to termination further development accident (Avramenko et al., 2011).

The aim of this study is to delve into the issue of energy associations' survivability as a distinctive attribute of complex systems, delineating their capacity to maintain and reinstate fundamental functions even amidst extreme conditions. Additionally, the objective is to establish a comprehensive methodology for scrutinizing the survivability of energy associations through the utilization of simulation modeling techniques.

Materials and methods

The research focuses on power associations, electric power systems, emergency modes, and transitional modes. Simulation modeling serves as the primary research method, understood here as computational experiments conducted on a computer using a digital mathematical model. This model is designed to reflect the properties and features of complex associations in terms of their survivability with necessary completeness and sufficient accuracy for practical purposes. It accounts for all physical processes and emergency control mechanisms essential for accident development, representing major elements of the power association, such as large power plants, load nodes, main power transmission lines, and converting elements (e.g., direct current inserts). The model incorporates a variety of disturbing influences and failures.

The solution involves adequate physical processes, mathematical descriptions, and effective software and computational implementation (Avramenko et al., 2011). Simulation modeling allows for the examination of disturbances and failures in multiple ways: statistically, via pre-defined scripts, or dynamically, with active human participation in the computational experiment. The study focuses on a scenario-based approach to analyze the reliability and survivability of energy associations.

The simplest model of a synchronous machine, which considers its dynamics when calculating electromotive force (EMF) in the EPS but does not explicitly consider electromagnetic processes and automatic excitation regulation, is the representation of a constant EMF machine with some reactivity. In this case, the transient process of the machine is described only by the equation of the mechanical motion of the rotor, which can be written down as

$$\frac{ds}{ds} = \frac{P_t - \left(P_{el} + I^2 R_g\right) - K_d S \cdot P_n}{T_j P_n \left(1+s\right)} \tag{2}$$

$$\frac{d\delta_E}{dt} = s \tag{3}$$

$$P_{el} = \frac{E_{sm} U sin\left(\delta_E - \theta\right)}{x_{sm}} \tag{4}$$

where s – rotor slip; T_j - inertia constant P_{el} - electric power (active); P_t - mechanical power (active); P_n - rated power (active); I – electric current of the generator, R_g – resistance of the generator; U, θ - are module and angle with respect to the reference axis (for example, the voltage vector of the balancing node in the calculation of the pre-emergency mode) of the voltage vector at the machine terminals; δ_E is an angle of electromotive force relative to the same axis; E_{sm} is electromotive force; k_{ds} is damping coefficient, intended for simplified consideration of electromagnetic and other damping moments proportional to the deviation of the absolute speed of rotation of the machine rotor; x_{sm} - synchronous machine reaction resistance.

The calculation of the transition process involves taking into account the electrical mode of the power system and its effect on the load in the Unified Power System nodes. The dynamics equations of individual machines in the electrical network nodes of the power system are numerically integrated separately, one by one, based on the model of individual movement. The use of implicit methods of numerical integration (methods of forecasting and correction) allows you to combine the differential equations of the dynamics of synchronous machines and their excitation and speed control systems with a system of algebraic equations in a complex form that describes the quasi-steady state of the Electric Power System. The apparatus of such unification is the iterative process of calculation of integrated variables at the stage of corrections, which is combined with the iterative process of calculation of the system of nonlinear algebraic equations of the steady-state Electric Power System.

Traditionally, in the calculations of the dynamic stability of the Unified Power System, fast-moving electromagnetic processes in the electrical network and stator windings of synchronous machines are neglected. This leads to the fact that the Electric Power System dynamics model turns into a degenerate system

$$\frac{dX_1}{dt} = F_1\left(X_1, X_2, t\right) \tag{5}$$

$$F_2\left(X_1, X_2\right) = 0 \tag{6}$$

where X_1 is a vector of variables to be integrated; X_2 is a vector of variables that are not integrated; F_1 is a vector function that characterizes a subsystem of variables determined by numerical integration of differential equations; F_2 is a function that determines the quasi-stationary electrical mode of the Electric Power System at any instant of time t.

Fixing at time t the conductivity of nodal loads according to the static characteristics or slip of an equivalent induction motor, which is an integrated change in the case of using dynamic load characteristics, and using the EMF of synchronous machines, which reflect the electromagnetic state of the machine at time t, leads to the linearization of the system of quasi-steady-state equations:

$$YU = GE \tag{7}$$

where Y is a square symmetric matrix of electrical network conductances; G is the diagonal matrix of the conductances of the generators; U is a column vector of stresses at the nodes; E is the electromotive force column vector of generators.

The solution of the linear system is performed by the method of ordered Gaussian elimination, using an efficient algorithm that takes into account the high sparsity of the conductivity matrix of the electrical network.

As the basic method of numerical integration, the implicit Adams method of the second order is chosen, in which the forecast is made by the Euler method, and the corrections are made by the trapezoidal method.

The method is modified by increasing the order of the prediction and correction formulas for the rotor motion equation (i.e., with respect to the slip s) and implementing the numerical analytical solution for the equations of the machine's electromagnetic state and automatic regulators of excitation and frequency of rotation of generators.

Implementing this approach involves significant challenges, particularly in forming a set of initial modes that accurately reflect the loading of intersystem connections within the Unified Power System (Avramenko et al., 2016; Kuznetsov et al., 2018). This implementation is based on developed methods and programs for calculating the reliability of parallel power system operations, especially with weak intersystem connections during emergency power imbalances caused by mutual shutdowns of power plants and loaded transmission lines (Baliuta S., Zinkevych P., 2022).

Results and discussion

The operational experience of power systems underscores that within a well-designed and properly operated power system, even the failure of the most critical element (such as the disconnection of a major power unit, busbars, or an overloaded line) constitutes a controlled disturbance and should not precipitate unplanned consequences. Only an accident's cascading, chain-like progression can result in such outcomes, highlighting the system's inadequate survivability.

To elucidate the concept of cascading accident progression, it's essential to consider three distinct types of emergency processes:

1. Deterministic Cascading Shutdowns entail successive shutdowns of Unified Power System elements (e.g., lines, transformers) triggered by sequential overloads or the surpassing of protection or automatic settings. The deterministic nature of these shutdowns relies on the physical properties of the system and the characteristics of relay protection and emergency automatic devices. A set of Unified Power System elements that disconnect deterministically form a calculation group of dependent failures.
2. Probabilistic Cascading Failures: This involves failures of relay protection, emergency automatics, and switching devices intended to localize the consequences of primary and previous failures. Given the probabilistic nature of these devices' reliability, the corresponding failure chains have a probabilistic characteristic, making this type of accident development probabilistic.
3. Multiple Failures due to External Influences: This type is typical for extreme natural events (e.g., hurricanes, thunderstorms, earthquakes) or deliberate actions, where subsequent impacts occur before the consequences of previous ones are resolved. The nature of these influences is highly uncertain.

The behavior of power plants significantly influences the development and exacerbation of accidents, particularly concerning parts that are inadequately controlled by anti-emergency control devices or operate inefficiently in complex emergency modes (e.g., during asynchronous operation). With their increasing share in generating capacity, nuclear power plants impose stringent requirements on electricity quality. Consequently, accidents characterized by increased frequency, especially in cases of UPS separation from the rest of the power association, have become common in power systems with nuclear power plants.

For instance, in one power system containing a nuclear power plant, the disconnection of a power transmission line led to synchronous oscillations lasting 25 seconds and an asynchronous mode concerning the UPS. This event resulted in the system's isolation for isolated operation, causing the system frequency to increase to 52 Hz, leading to the shutdown of nuclear power plant units and sharp frequency decreases, necessitating emergency system operation modes (Baliuta S., Zinkevych P., 2022).

It should be noted that a similar incident also occurred in a highly redundant system powered by a large hydroelectric power plant, albeit due to the failure of emergency automatics. Significant system accidents demonstrate that the emergency shutdown of power units with severe technological process violations at thermal power plants and nuclear power plants complicates their restart and restoration to normal mode, thereby magnifying the consequences of such incidents. The ability to swiftly restore the scheme and regime of energy systems and power supply to consumers following emergency violations is a key aspect of survivability, and the duration of system restoration indicates UPS survivability. Another factor affecting the survivability of energy associations is the effectiveness of operational dispatch personnel (Kulkarni and Shingare, 2016; Machowski et al., 2008). Correct or incorrect actions, as well as personnel inactivity, can significantly impact accident development and its subsequent consequences. It is worth noting that the growth of energy associations objectively exacerbates the survivability challenge, particularly evident in cascade accidents where the properties of a complex closed system can undergo significant changes, potentially rendering dispatcher actions ineffective based on their experiences under normal conditions.

The methodology for analyzing the survivability of energy associations is based on calculations of transient modes of the Electric Power System. The dynamic nature of the EPS response to disturbances and failures, along with the complexity of transient processes, warrants the use of simulation modeling. At the core of this approach lie calculations of the EPS's transient modes, including long transient processes and self-setting post-emergency modes. Experience from EPS operations and calculations confirms the significant increase in transient process duration in large power plants and the notable spread of emergency disturbances. This necessitates the development of a simulation model based on calculations of long transient processes, not solely focused on dynamic stability.

Another aspect of the simulation modeling challenge lies in the effectiveness of mathematical modeling of the EPS as a complex dynamic object. Certain essential features of the EPS make it practical to utilize the adaptive dynamics model (ADM) of the EPS, which automatically forms EPS models at various transition stages, considering the fundamental nature of movement at each stage. The use of ADM allows for a significant reduction in computational costs without sacrificing decision accuracy, which is crucial for analyzing EPS survivability, which demands numerous transient mode calculations during varying disturbances and failures (Okakwu and Ogujor, 2017; Petinrin and Shaaban, 2016). Furthermore, simulation modeling involves automating computational experiments and processing their results, tasks largely addressed by specialized programs developed at the Institute of Electrodynamics of the Academy of Sciences of Ukraine for analyzing disturbed modes of complex power systems.

The first principle of the methodology for analyzing the survivability of energy associations underscores the necessity of employing simulation modeling, ensuring satisfactory accuracy in representing the dynamics of energy systems and enabling comprehensive accounting of relay protection, emergency control automatics (EA), and switching devices failures through EPS transient mode calculations. The second principle of the methodology involves focusing on an ergastic scenario-probabilistic approach to survivability analysis. This approach entails partially predefining and partially determining during calculation the type, location, magnitude, and sequence of external disturbances and system element failures based on intermediate result analysis by the technologist. The resulting emergency frequency is determined by the frequency of primary disturbances and the probabilities of secondary failures (disturbances), thus concentrating on disturbances and failures of an uncertain nature. Essentially, this approach represents a refinement of UPS reliability analysis methods, considering secondary failures comprehensively and the dynamics of UPS element interaction.

In contrast to existing approaches, our proposed egoistic scenario approach centers on the consideration of system emergency automatics. It anticipates scenarios where, following emergency control automatic (EA) failure, the emergency process evolves in a challengingto-predict, formalized manner, initiating EA action in remote areas of the power association, requiring technologist analysis to assign a new failure, determining the energetic and human-technical nature of the situation (Liang, 2017; Dhamanda and Rawat, 2019). EPS survivability is assessed based on a predefined set of disruptive influences, including sudden disconnection of the most powerful generating unit (power unit), group of units, or entire power plant in the receiving system of the power association; disconnection of the most heavily loaded line or the line with the greatest bandwidth in the congested intersection of intersystem connections; occurrence of excess power in the transmission surplus energy system due to disconnection of powerful consumer connections; and disconnection of bus differential protection of all system connections (sections) of buses of a potent nodal substation. The assignment of these disturbances considers the specific scheme-regime situation in the association. As a sequence of disturbances and failures for assessing EPS survivability, scenario formation relies on a retrospective analysis of cascading system accidents and the generalization of their development mechanism. This analysis illustrates a generalized diagram of accident development and localization in energy associations, as shown in Figure 1.

The diagram depicts the failure of switching devices in only one instance, yet switching device failures may accompany any Electric Power System element disconnection. Similarly, repeated short circuits, false activations, and redundant disconnections can occur in any intermediate post-emergency mode. The final post-emergency mode on the diagram represents the established mode meeting technical operation requirements for voltage, frequency, and equipment overloads, serving as the starting point for restoring the power system's normal circuit and mode of operation (reintegration). Modern power units feature a sophisticated emergency management system, with another group of emergency automations serving as backups for individual device failures. For instance, in cases where stability is compromised due to primary fast-acting protection failure or automatic protective device system failures of IPA type (instability prevention automations), the resulting asynchronous mode is addressed by asynchronous mode elimination automations. Automatics intervene to halt accident progression in specific areas, restoring active (or reactive) power balance (automatic unloading by frequency, frequency start of hydro generators, automatics limiting frequency increase, automatics limiting frequency increase or decrease), and supplying power to critical consumers with acceptable parameters. However, there are instances (posing a challenge to Unified Power System survivability) where successive failures of Relay Protection, emergency automation, and circuit breakers form a chain of accidents resulting in significant emergency consumer disconnections. From the perspective of forming scenarios for survivability analysis, both the quantity and severity of failures are crucial. Analysis indicates that in large-scale system accidents, the presence and combination of 3-4 severe failures (considering factors such as the initial mode's reduced stability margin due to dispatcher instructions to increase flows or unscheduled equipment repairs) significantly impact the scenario's severity.

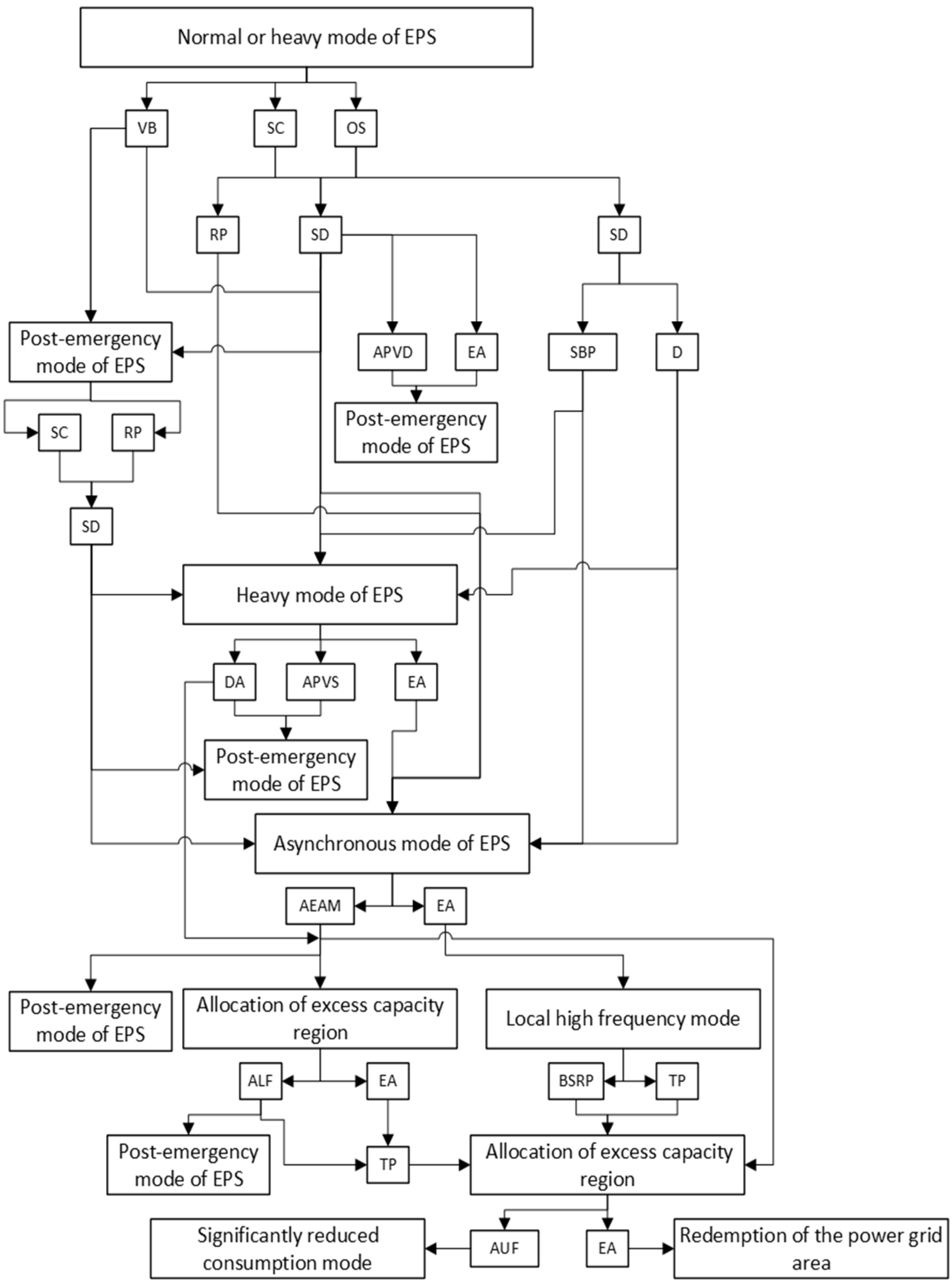

Figure 1. Scheme of accident development and localization in energy associations.

Marking in the Figure 1:

- VB, violation of the balance of active power in the system due to loss of generating power, disconnection of the external intersystem line, or heavy load;
- SC, short circuit, on EPS elements;
- OS, operation system (RP, relay protection, EA, emergency control automatic, operational personnel), failures of which lead to the disconnection of lines;
- RP, relay protection, failure of RP and EA type of erroneous or unnecessary disconnection of EPS elements;
- SD, switching devices;
- D, failure of the circuit breaker failure backup device;
- APVD, automatic for preventing violation of the dynamic stability of the UPS, which affects the disconnection of part of the generators, electrical braking of the generators, as well as the emergency power management of steam turbines;
- APVS, automatic for preventing violation of the static stability of the EPS, which includes automatic unloading and loading of power plants and special automatic load disconnection and provides unloading of intersystem connections;
- DA, dividing automatic, divides the power pool into electrically unconnected non-synchronous parts in the event of exceeding the overcurrent at the intersection of the specified value;
- AEAM, automatic elimination of asynchronous mode, which prevents or terminates such mode by dividing the scheme into non-synchronously working parts;
- ALF, automatics of limiting the increase of frequency, which affects the disconnection of part of the generators;
- AUF, automatic unloading by frequency;
- BSRP, backup sets of relay protection or automatics;
- TP, technological protections, of power plants, leading to disconnection of generating equipment.

The proposed scenario for analyzing the survivability of energy associations focuses on severe failures, including:

- A primary disturbance of significant magnitude leading to stability violation or a decrease in cleanliness in the segregated area, possibly combined with a large output load mode or other failures.
- Failure of one of the main protections.
- Failure of one of the main switches.
- Rejection or absence of instability prevention automatics.
- Rejection of the asynchronous mode elimination automatic.
- Failure or insufficiency of automatic unloading by frequency.
- Serious errors by operational dispatch personnel, equivalent in consequences to the failures mentioned above.

To form this scenario, it is suggested to rely on the most reliable statistical information about cascading accidents, considering three consecutive failures in the chain, including a generalized failure (such as deterioration of the initial mode leading to decreased stability reserves or significant weakening of the scheme) as a standard. The application location and type of primary disturbances, as well as the second rejection, are determined by the technologist for implementing calculations of electromechanical transitional processes. The task involving the third rejection typically requires calculating transitional processes under the given conditions of two rejections and identifying specific emergency control automatic devices (most often asynchronous mode elimination automatics) expected to function simultaneously. The technologist selects the refusals likely to result in the most serious consequences and repeats the calculation with three refusals. This approach results in a multi-rooted rejection tree, with different roots corresponding to various primary disturbances and branches reflecting potential paths of accident development based on the identified refusals.

Conclusions

The methodology for analyzing the survivability of power associations has been presented, with its primary principle being the use of simulation modeling based on calculations of transient states of the Unified Power System. This ensures satisfactory accuracy in representing the dynamics of electrical power systems and allows for the consideration of relay protection failures, emergency automation, and switching devices. This methodology is oriented towards an ergodic scenario-probabilistic approach to survivability analysis and, unlike those discussed in the literature, has the advantage of adapting to the changing structure and operational conditions of the Unified Power System of Ukraine during wartime. This is achieved by utilizing the most adequate mathematical models of elements, which are implemented in software packages for analyzing Unified Power System operating modes.

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