CLUSTER-BASED TRISTATE AGGREGATION METHOD FOR DEPENDABILITY EVALUATION OF ELECTRICAL SYSTEMS

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Abstract: This paper presents a novel approach for dependability evaluation of power supply systems based on discrete state aggregation. The proposed method, called the Tristate Cluster Aggregation Model (TRICAM), groups system components into fixed clusters, where each component can be in one of three operational states: fully operational (100%), partially operational (50%), or failed (0%). The cluster's overall state is determined using rule-based logic that reflects real-world failure propagation and degradation. By computing the probabilities of state transitions at the component level and aggregating them, the method produces a compact cluster-level Markov model. TRICAM significantly reduces the dimensionality of the state space compared to conventional models, enabling efficient analysis of large systems. This approach provides a scalable and interpretable framework suitable for evaluating reliability and guiding maintenance or reconfiguration strategies in modern power infrastructures.

Key words: dependability, electrical systems, solar power plants, Markov analysis, Monte Carlo method, triple-based clusterization method, cluster aggregation method

1. INTRODUCTION

Dependability of electrical systems is a critically important parameter for their effective functioning, especially under unpredictable destructive impacts such as missile strikes on Ukraine’s energy infrastructure. The concept of dependability, which is broader than reliability, encompasses the ability of the system to provide continuous and reliable electricity supply to consumers, including recovery after failures or damage, and is of primary importance for stable operation. It is in this sense that the term “dependability” will be used in this work.

In recent years, according to Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022, the term “resilience” has been applied to

critical infrastructures (now referred to as "critical entities") [1]. The concepts of dependability and resilience in the engineering of complex systems are closely related, although they emphasize different aspects. In modern interpretations, dependability also includes fault tolerance, which refers to the ability of a system to remain operational under foreseeable destructive impacts. However, resilience is considered an evolutionary extension of this concept, focusing on the system's behaviour under unpredictable, complex, or cascading events. While dependability seeks to minimize the probability and consequences of failures within designed scenarios, resilience focuses on the system's ability to adapt, respond to new threats, maintain critical functions, or quickly restore them even without prior preparation. Thus, resilience does not contradict dependability but rather complements it, providing dynamic stability of systems in a complex and changing environment. This is described in detail in [2].

A specific type of electrical systems, namely power supply systems, demonstrates significant vulnerability to destructive impacts due to geographically fixed generating capacities and a relatively small number of generators. This leads to a low level of dependability of power supply systems not only in Ukraine but worldwide. This underscores the need to transition to more resilient architectures, such as the previously proposed concept of distributed generation. Assessing dependability parameters is key to ensuring uninterrupted power supply even in crisis situations.

Simplification of the state space for Markov analysis was proposed in [3]. The simplification is achieved by introducing three generalized states: "100%," "50%," and "0%." These states correspond to full operability, partial degradation, and complete failure. This three-stage model was chosen as a compromise between the required accuracy and the computational workload, which is particularly relevant for the analysis of large systems.

This article further develops the idea of reducing the labour intensity of Markov analysis. It proposes a cluster-based tristate aggregation model, which involves dividing the complex structure of the power supply system into clusters, each consisting of only three elements.

The aim of this article is to reduce the labour intensity of dependability assessment by developing a new approach that evaluates not the real system as a whole, but a much simpler system that is equivalent to the real one.

This article is organised as follows: Section 2 presents a literature review. Section 3 describes the Triplet-based Integrated Clusterization Method (TRICAM), which significantly reduces the dimensionality of the state space of complex electrotechnical systems. This method is applied in conjunction with a specialised three-state cluster aggregation method, which is presented in Section 4. Section 5 describes the verification of the developed methods. The conclusions of the article (Section 6) summarize the study and propose directions for future research.

2. RELATED WORKS

In modern Markov analysis of complex electrical systems, the so-called "curse of dimensionality" is of particular concern, where the number of system states grows exponentially with the increasing number of components or possible configurations of

their operation. This necessitates the development of methods aimed at reducing computational complexity. A method for assessing the dependability of complex technical systems using non-homogeneous Markov processes is described in [4]. A multi-level decomposition is introduced, allowing large systems to be modelled as a set of subsystems with local Markov dynamics. It is shown that this approach made it possible to reduce the state space by several orders of magnitude without significant loss of accuracy.

The complexity of constructing Markov models for traction power supply systems is described in [5]. A three-state model (operational – degraded – failed) is described as a simplification of typical models. The authors apply a zoning method, in which the system is divided into independent subnetworks, and a local Markov analysis is carried out, allowing the dimensionality of each task to be limited. However, even with this limitation, the authors record exponential growth in the number of global states when modelling a network structure. For example, with 20 elements, the system already has over 3 million configurations.

The impact of dimensionality in the context of statistical dependability analysis is clearly demonstrated in [6]. The authors apply the cross-entropy method for adaptive sampling simulation but find that at high dimensionality (e.g., 50 or more variables), both accuracy and speed are significantly reduced. The article shows that as dimensionality increases, the sampling distribution fails to adapt quickly enough, and repeated simulations become inefficient.

The application of Markov Chain Monte Carlo (MCMC) methods to high-dimensional problems is considered in [7]. It is shown that with an increasing number of variables, even gradient-based variations of MCMC become ineffective due to the complexity of the distribution space topology. The authors propose a hybrid method based on machine learning for gradient approximation and construction of a variational distribution, which helps overcome the limitations of classical methods.

A new approach to solving large-scale Markov decision processes (MDPs) by combining state space decomposition and time aggregation methods was proposed in [8]. The framework partitions the state space into disjoint subsets, enabling distributed evaluation of subproblems, while time aggregation reduces the temporal complexity of decision-making. Together, these strategies significantly improve computational efficiency and scalability without compromising the Markov properties of the model. Experimental results show faster convergence and reduced memory requirements compared to classical MDP solution algorithms. However, it is noted that the effectiveness of the method may depend on the quality of the initial state space partitioning. Automating this procedure requires further research. The method is also sensitive to the structure of subproblems, which may affect convergence in non-uniform systems.

Another method for simplifying Markov models for reliability assessment of complex systems is proposed in [9] and based on decomposition into independent subsystems. Each subsystem is assigned a failure rate, calculated analytically using formulas proposed by the authors. Then a simplified model of the entire system is created, using these aggregated indicators of the subsystems. For example, using the reactor protection system in a nuclear power plant as a case study, the authors

demonstrated that the model is significantly simplified in terms of the number of states compared to the full model.

This article notes that the method allows the number of states in the model to be reduced several times, which substantially lowers computational costs. The authors also emphasize the high accuracy of the method: the deviation in system reliability indicators between the simplified and full models does not exceed a fraction of a percent. However, this method is applicable only when the decomposition of the system into subsystems is correct and independent. If strong connections or dependencies undermine independence, the result may be inaccurate. In addition, applying the method requires developing analytical formulas to obtain the failure rate of each subsystem, and these formulas must be reliable and well-justified. These factors reduce the practical applicability of the method.

A modular approach to modelling the availability of infrastructure used in data centres and network cores with the application of Stochastic Reward Nets (SRN) is described in [10]. SRN are employed to account for correlated failures between subsystems. The modular, hierarchical problem formulation enables efficient availability assessment and sensitivity analysis. To date, this method has not been applied in the energy sector, for example in power supply systems, distribution networks, or substation equipment. However, the structural approach it proposes (aggregation, correlation modelling) is highly relevant for electrical systems, particularly those with distributed renewable energy sources.

The study in [11] presents an approach to fault detection in multi-state technical systems using the Hidden Markov Model (HMM). The authors emphasize that most traditional diagnostic methods consider a system as binary (normal operation / failure), whereas in practice systems often have intermediate degradation states that must be identified to ensure timely maintenance and improved safety. The main limitations include high requirements for the quality and volume of training data, especially when the number of hidden states is large, the risk of incorrect state interpretation if the features do not sufficiently distinguish between different operating modes, and the difficulty of scaling to large systems with many independent components.

Alongside these issues, there are other complexity factors, such as non-Markovian dependencies, long-term correlations, multi-level system hierarchies, cascading failures, and challenges in statistical parameter modelling, particularly when using real-time monitoring data [12].

The above review shows that existing methods only partially address the problem of the growing number of states. Therefore, the development of methods that can not only reduce the model's dimensionality by combining similar configurations into aggregated states but also ensure the scalability of analysis for systems with dozens or hundreds of elements remains an urgent task.

3. TRIPLE-BASED CLUSTERIZATION METHOD (TRICAM)

The TRiplet-based Integrated ClusterizAtion Method (TRICAM) is designed for conducting Markov analysis of complex electrotechnical systems consisting of a large number of components, each of which can be in several states. Through multi-level

clustering based on the principle of partitioning into triplets (groups of three elements), this method significantly reduces the dimensionality of the state space, enabling approximate dependability assessment even for systems with hundreds of components.
The purpose of the method is to simplify Markov analysis and, consequently, the assessment of dependability for complex electrotechnical systems with a large number of components by clustering components into triplets and aggregating system states into three generalized levels of operability.
In this approach, each component (device or group of devices) of the system, as well as the system itself, can be in one of three generalized states:

- State 1 – the system component (or the entire system) is fully operational (operability level – 100%);
- State 2 – the system component (or the entire system) is partially operational (operability level – 50%);
- State 3 – the system component (or the entire system) is completely non-operational (operability level – 0%).

The essence of the method lies in the sequential hierarchical decomposition of the initial electrotechnical system with a large number of components (individual electrotechnical devices) into triplets, each consisting of three separate components of the initial system. This results in a threefold reduction in the number of system components at the first step of the method. In combination with aggregating the system states into the three levels listed above, this allows for a reduction of the system's state space. In the general case, the formula for the relative reduction of the state space dimensionality as a function of the step of the TRICAM algorithm is as follows:

$$r_k = \frac{S_0}{S_k} = \frac{3^{N_0}}{3^{N_k}} = 3^{N_0 - N_k}. \quad (1)$$

Let us assume that the initial system contains 27 elements. In this case, the reduction of the state space depending on the step of the method occurs as shown in Table 1.

Table 1. Reduction of the state space depending on the TRICAM step

Step	***Number of elements***	***State space dimensionality***	***Reduction factor***
0	27	7 625 597 484 987	
1	9	19683	387 420 489
2	3	27	282 429 536 481
3	1	3	2 541 865 828 329

Thus, the TRICAM method makes it possible to significantly reduce the dimensionality of the state space of complex electrotechnical systems, particularly in dependability modeling tasks for power supply systems. The method is based on multi-level clustering: system elements are grouped into triplets, each of which is treated as a separate aggregated object with a limited number of possible states.

The main advantages of the method are as follows:

– Exponential reduction of dimensionality: at each clustering step, the number of elements is reduced threefold, while the state space is reduced by tens of billions of times. This results in a computational complexity decrease by several orders of magnitude. For example, after just the first clustering step, the state space of the system is reduced by approximately nine orders of magnitude. This means that if an exhaustive enumeration of all states at the initial level would require trillions of operations, after the first clustering it would require only tens of thousands.

– Hierarchical structure: the method preserves the operational logic of subsystems and enables analysis at different abstraction levels. Each level models the behaviour of aggregated elements, allowing for the creation of flexible multi-level models.

– Scalability: thanks to the recursive nature of clustering, the method can be easily adapted to systems of any size. This makes TRICAM suitable for analysing large distributed networks, where direct enumeration of all states is infeasible.

– Formal mathematical model: each clustering step is described by transition matrices and state probabilities, which makes it possible to apply Markov analysis without loss of accuracy when moving between levels.

The application of the TRICAM method involves step-by-step multi-level clustering of system elements into triplets, followed by a transition to the reduced state space. A key stage at each level of this transition is the construction of a state transition matrix for the aggregated triplets, enabling Markov analysis at the corresponding level of abstraction.

At the first clustering level, this matrix is determined directly based on information about the behaviour of the elementary system components (i.e., individual devices forming the triplets), their individual dependability characteristics, and interconnections. However, at subsequent levels (second, third, and so on), it is necessary to recalculate the transition matrices for new aggregated objects formed by combining triplets from the previous level.

This process is non-trivial because the aggregated states of new triplets have no direct correspondence to the initial states of the elementary components. Therefore, there is a need to develop a special state aggregation algorithm that formally derives the probabilities of transitions between aggregated states based on Markov analysis, taking into account the combinations of internal states from the previous level. Implementing this approach requires accounting for probabilistic state aggregation rules and preserving the Markov property when moving to a higher level.

Thus, at each clustering level, the TRICAM method requires building a new transition matrix for the aggregated triplets, which is only possible through the application of a specialized three-state cluster aggregation method. This method should be based on a formal Markov approach, taking into account the system's structure changes at each step and the reduced state space. The development and formalization of such a method is a separate scientific task, critically important for the practical application of TRICAM in large, complex systems.

4. THREE-STATE CLUSTER AGGREGATION METHOD BASED ON THE FORMAL MARKOV APPROACH

The three-state cluster aggregation method based on the formal Markov approach is a fundamental method used at every level of the hierarchical TRICAM model. Its purpose is to perform a complete analysis of a triplet consisting of three components, each having its own state transition matrix.

The input data for the method are three 3×3 state transition matrices for each element of the triplet: U_1, U_2, U_3 , along with an aggregation rule that determines the overall state of the triplet.

The row and column numbers in each matrix correspond to one of the three possible states of the triplet: 1 – fully operational state (100%), 2 – partially operational state (nominally 50%), 3 – completely non-operational state (0%). The numerical value at the intersection of row "*i*" and column *"j"* in each matrix corresponds to the probability of the respective element transitioning from state "*i"* to state "*j"*.

Each of the three elements of the triplet can be in one of three states. The aggregation rule is defined by a set of conditions that assign each of the 27 elementary states to a specific aggregated state. The aggregation rules may vary and depend on the operating characteristics of the devices forming the triplet and the way these devices are connected.

For a series connection of the triplet's devices, this work uses the following intuitive aggregation rule:

- The triplet is fully operational (100%) if each element is fully operational.
- The triplet is partially operational (50%) if at least one element is partially operational.
- The triplet is completely non-operational (0%) if at least one element is completely non-operational.

The method consists of the following sequential steps:

1. Specify the state transition probability matrices for each of the three elements. It is recommended to obtain these using expert assessment.

2. Define the aggregation rules for the triplet's states.

3. Construct the elementary state matrix. The row number of this matrix corresponds to the elementary state number (from 1 to 27), while the columns contain the state numbers (1, 2, or 3) of the triplet's elements.

4. Calculate the transition probabilities between elementary states of the entire triplet (a 27×27 matrix containing 729 elements). The probability of transition between the elementary states $State\_i(s_1 s_2, s_3)$ and $State\_j(t_1, t_2, t_3)$ is calculated as:

$$P(i,j) = P_{s_1 \to t_1}^{(U_1)} \cdot P_{s_2 \to t_2}^{(U_2)} \cdot P_{s_3 \to t_3}^{(U_3)}, \quad (2)$$

where: $P_{s_k \to t_k}^{(U_k)}$ – the transition probability from state s_k to state t_k for the k-*ht* element, taken from the corresponding matrix U_k.

This formula assumes statistical independence of the state transitions of individual triplet elements.

5. For each pair of aggregated states $A \rightarrow B$, using the aggregation rule, construct the aggregated 3×3 matrix:
   - find all i corresponding to the aggregated state A;
   - find all j corresponding to the aggregated state B;
   - calculate the transition probabilities in the aggregated matrix:

$$P_{agr}[A,B] = \sum_{i \in A} \sum_{j \in B} P(i,j). \quad (3)$$

   - perform normalisation of the obtained aggregated matrix:

$$P_{agr}(i,j) = \frac{P_{agr}(i,j)}{\sum_j P_{agr}(i,j)}. \quad (4)$$

Normalisation is necessary to ensure that the sum of probabilities in each row of the matrix equals one.

The result of the method is an aggregated transition probability matrix that can be used for performing traditional static or dynamic Markov analysis to calculate dependability indicators of electrical systems.

One of the key advantages of the three-state cluster aggregation method is its scalability. This method allows the same calculation algorithm to be applied regardless of the system's decomposition level, enabling the construction of a multi-level hierarchy when applying the TRICAM method. Each triplet, regardless of its composition (either basic elements or aggregated subsystems), is treated in the three-state cluster aggregation method as three separate units with known probabilistic characteristics. This ensures the uniformity of the mathematical model at all stages of analysis.

The method is also notable for its flexibility, as it can be adapted to both homogeneous and heterogeneous components, including systems in which the components have different transition matrices. This makes it suitable for use in complex electrical systems.

Another advantage is the compactness of data representation. Aggregated transition matrices have a fixed size of 3×3 regardless of the complexity of the triplet, which significantly reduces computational costs in subsequent analysis.

5. VERIFICATION

Verification of the proposed methods will be carried out using a real electrotechnical system – the Solar Power Plant (SPP) of the logistics terminal of "Nova Post" (Ukraine). In 2024, a rooftop SPP with a capacity of 1 MW was commissioned on the roof of the Kyiv Innovation Terminal of "Nova Poshta." The generating modules are evenly distributed over an area of 5000 m², allowing partial coverage of the internal electricity consumption of the logistics complex [13]. This SPP is one of the largest commercial rooftop solar power plants in Ukraine. Detailed technical parameters, such as the number of panels, the type of solar panels, inverter models, or the configuration of the energy storage system (ESS), are not disclosed in open sources. However, for our purposes, they

can be estimated from construction and technical standards as well as the parameters of electrical equipment.

The conducted analysis showed that the declared technical characteristics of the SPP can be achieved, in particular, if the SPP consists of 11 triplets, each including: 182 SunGoldPower 500 W Mono Black PERC solar panels [14], 1 Tesla Megapack 2 ESS device [15], and 1 Huawei SUN2000-150K MG0 inverter [16].

The destructive impact on the SPP was simulated by modelling the damage to each of the listed elements from a strike by a Shahed-136 drone, which carries 50 kilograms of TNT-equivalent explosives. The overpressure from the explosion was calculated using the formulas provided in [17]. The transition probabilities from the operational state of each listed component to other states were calculated using the Monte Carlo method, simulating a Shahed-136 impact at a random point. The geometric parameters of the area where the equipment is installed, the type of its protection, and the distribution of overpressure from the explosion were taken into account. A total of 1 million strikes were simulated for each element. The probabilities of component restoration were determined using the expert assessment method.

To ensure an objective evaluation of the accuracy of the TRICAM method, it is necessary to select a reference state common to both models — the classical and the aggregated one. This state is the full operability of all three components of the triplet, i.e., the situation in which all elements are in the 100% operational state. This is the only state that unambiguously corresponds to the aggregated state “full operability” in the TRICAM model and at the same time has a direct correspondence in the classical model as one of the 27 elementary states. For verification, this work compares the probability of the aggregated state “Full operability” obtained using the TRICAM method with the probability of the elementary state “Full operability” for all triplet components calculated by the classical Markov analysis without aggregation.

The obtained results are shown in Table 2.

Table 2. Verification results of the TRICAM method

Step	***Operability probability***		***Inoperability probability***		***Deviation (%)***
	TRICAM	***Markov analysis***	***TRICAM***	***Markov analysis***	
0	1	1	0	0	0,00
1	0,185	0,185	0,815	0,815	0,00
2	0,066	0,084	0,934	0,916	1,88
3	0,044	0,049	0,956	0,951	0,54
4	0,038	0,030	0,962	0,970	0,83
5	0,036	0,020	0,964	0,980	1,67

The results indicate that, already after the first step of analysis, the probability of the triplet being in a fully operational state decreases sharply and becomes negligibly

small in subsequent steps. In such a situation, using the probability of full operability leads to a number of methodological difficulties: first, the absolute values become extremely small, which reduces the metric's sensitivity to changes and complicates the interpretation of results; second, the probability of full operability is not additive and does not fully capture the behaviour of a degrading system; third, in real engineering systems, the more interesting and critical parameter is not the fact of perfect operability, but the probability of system failure — the situation in which at least one element fails.

Furthermore, in practical engineering calculations, operability probabilities at the level of 0,04 and 0,02, although differing by almost a factor of two, are effectively considered equally small and are classified as failure modes. Such large-scale insensitivity to small values is a typical approach in technical diagnostics, where the fact of the system's transition to an unreliable state is more important than the exact value of its fault-free operation probability. Considering this, for verification purposes, the probability of loss of operability was used, as it is more informative, more sensitive to changes, and more interpretable from the standpoint of engineering analysis.

Verification allows us to conclude that the TRICAM method demonstrated high accuracy in modelling aggregated state probabilities of the system. The most accurate results are observed in the first steps of the Markov process, where the deviation from the classical model is practically zero. At later steps, the error remains within 1–2%, which is entirely acceptable for engineering analysis and practical dependability calculations.

Thus, it can be concluded that the TRICAM method is an effective, reliable, and engineeringly sound tool for reducing the labour intensity of Markov models without significant loss of accuracy.

6. CONCLUSION

This paper proposes the "TRICAM" triplet-based clustering and aggregation method for simplifying Markov analysis, which differs from classical approaches such as the Aggregation and Decomposition Method (ADM), Modular Performance Modelling (MPM), Stochastic Reward Nets (SRN), and Hierarchical Hidden Markov Models (HHMM).

The main distinction of the proposed approach lies in the fact that state aggregation and subsystem decomposition are performed simultaneously within a single stage of analysis, unlike ADM, where these are executed sequentially. Compared to MPM and SRN, where aggregation is accompanied by complex coordination between subsystems, the new method does not require such coordination, thereby reducing computational costs and the need for input data compared to traditional approaches.

In addition, in the proposed method, all subsystems are homogeneous in terms of the number of aggregated states, and the number of states of the entire system is equal to the number of states of each subsystem. This avoids the exponential growth of the state space that is characteristic of ADM and MPM.

Finally, unlike HHMM, which is intended for systems with a deep hierarchical structure, TRICAM is applied to single-layer systems without explicit nesting, i.e., flat

models. This makes it particularly suitable for engineering analysis tasks of electrotechnical systems in which there is no pronounced hierarchy of behaviour.

Thus, the proposed approach represents a new method for simplifying Markov analysis of flat structures, combining structural decomposition and functional aggregation while maintaining a fixed model dimensionality.

The aggregation rule for the series connection of elements within a triplet, presented in this paper, is not the only possible one. Therefore, a direction for further research should be the development of state aggregation rules depending on the type of connection of elements within a triplet — series, parallel, and mixed. These rules should be based not so much on the type of physical connection but rather on the type of logical interaction between the elements in the triplet.

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