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Simulation-based modeling of distance relay protection for a high-voltage transmission line

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Abstract. Relay protection remains a key component in maintaining the reliability and operational security of modern power systems, which is especially critical for 220-kV and higher overhead transmission lines operating within the interconnected power system of Central Asia. The predominance of electromechanical protection devices, many of which have reached the end of their service life, underscores the growing need for a transition toward microprocessor-based relay protection technologies built on advanced digital platforms. Within this context, an imitation model of the relay protection system for the newly commissioned 220-kV L-2–K-4 transmission line connected to the Keles substation was developed using the DIgSILENT PowerFactory environment. The constructed model incorporates a Siemens 7SA6 microprocessor-based protection relay and enables detailed simulation of operational conditions on the line. Validation of the model under near-real operating scenarios demonstrated a high degree of correspondence between simulated and expected performance. The simulated operation of the relay protection showed that the first, second, and third distance-protection zones remained within the circular characteristic, with calculated zone impedances of 10.67 Ω, 44.99 Ω, and 63.998 Ω, respectively, and with time delays of 1 s and 3 s for the second and third zones. These results confirm the adequacy of the developed digital model and its applicability for engineering analysis of relay protection performance in high-voltage transmission networks.

INTRODUCTION

In modern electric power systems, relay protection plays a fundamental role in maintaining the reliability and operational security of transmission networks. This is particularly significant for high-voltage transmission lines rated at 220 kV and above, which operate within the Unified Power System of Central Asia. The primary functions of relay protection include the detection and isolation of faults, mitigation of the consequences of emergency conditions, and prevention of equipment damage.

Across the interstate transmission corridors operating at 220–500 kV and linking the Unified Power System of Central Asia with the Unified Power System of Kazakhstan, a total of 30 transmission lines are currently in operation, all equipped with modern relay protection devices. These systems play a critical role in maintaining the stability and operational security of the interconnected power network. To assess their current condition and performance, a statistical evaluation was carried out covering 193 relay protection and automation devices installed on these interstate lines. The analysis indicates that 129 of the devices are electromechanical, 61 are microprocessor-based, and 3 employ microelectronic designs.

Electromechanical devices constitute the majority of the installed relay protection and automation equipment, accounting for 67%, while microprocessor-based units represent 32%; microelectronic devices are deployed only on three 220-kV interstate transmission lines. A significant portion of the equipment (67%) has exceeded its standard service life. The number of technically and physically obsolete devices includes 127 electromechanical units and 3 microelectronic units. These findings underscore the need for systematic modernization of the existing protection systems—particularly electromechanical and microelectronic devices—through their replacement with advanced multifunctional digital relay protection and automation technologies [1, 2].

METHODS AND MATERIALS

In recent years, the number of emergency events caused by both external disturbances and internal equipment faults has been steadily increasing. At the same time, the growing penetration of renewable energy sources within the power system has led to a reduction in short-circuit current levels, which may negatively affect the sensitivity and correct operation of existing relay protection devices. Developing and analyzing models capable of accurately reproducing relay protection behavior under various operating conditions make it possible to improve the detection of fault scenarios and enhance the overall response of the protection system [3, 4].

The study focuses on the Keles substation, which operates under the Tashkent Main Electrical Networks branch. The substation supplies reliable and continuous electrical power to the districts of Olmazor and Shaykhontokhur in Tashkent city, as well as to consumers in the Tashkent, Yangiyol, and Chinoz districts of Tashkent region, including social infrastructure, commercial facilities, and residential loads.

TABLE 1. Information on the incoming and outgoing overhead transmission lines of the Keles substation.

№	Name of the overhead transmission line	Voltage (kV)	Line Length (km)	Conductor Type	Permissible Load (A)
Incoming overhead transmission lines					
1	L-2-K-1	220	18,133	AC-500/10	945
2	L-2-K-2	220	29,716	AC-400/51	825
3	L-2-K-3	220	29,087	AC-400/51	825
Newly commissioned overhead transmission line					
1	L-2-K-4	220	18,447	AC-500/10	945
Outgoing overhead transmission lines					
5	L-K-F-1	220	88,867	AC-400/51, AC-240/39	945
6	L-K-F-2	220	88,867	AC-400/51, AC-240/39	945
7	L-Yuksak	220	28,471	AC-500/10	945

The Keles substation was commissioned in 2013 and has a total installed capacity of 400 MVA. The 220-kV side of the substation is equipped with a double-busbar system and is connected to three operational 220-kV overhead transmission lines originating from the Tashkent Thermal Power Plant: L-2–K-1, L-2–K-2, and L-2–K-3. Outgoing connections from the Keles substation include the L-Yuksak 220-kV line to the Yuksak substation, as well as the L-K-F-1 and L-K-F-2 220-kV lines supplying the Feruz substation.

The 110-kV section of the substation is also configured with a double-busbar system and includes two outgoing 110-kV overhead transmission lines: L-Navoi-1 and L-Navoi-2. A new overhead transmission line, L-2–K-4, planned for commissioning at the substation, was modeled using the DIgSILENT PowerFactory software environment, where its distance-protection settings were computed and verified.

DIgSILENT PowerFactory is a software environment designed for modeling, simulation, and analysis of electrical power systems. In the context of relay protection studies, PowerFactory provides a comprehensive platform that enables engineers to perform detailed evaluation and testing of protection schemes under a wide range of operating conditions [5].

The use of DIgSILENT PowerFactory for relay protection analysis involves several technical stages:

1. Development of the Power System Model:

o The process begins with the construction of a three-phase network model that includes generators, transformers, transmission lines, and loads. Each component is parameterized using its electrical characteristics, such as power ratings and impedance data.

o Model elements are interconnected according to their geographical configuration and electrical properties, with particular attention to phase coordination and grounding arrangements.

o Operating conditions—such as normal operation, overload states, and fault scenarios—are incorporated based on real system data.

o Dynamic load behavior is represented by including different types of loads and their time-dependent characteristics, as well as possible sudden variations.

o A crucial step is the verification of the developed model using actual operational measurements to ensure that it accurately reproduces the behavior of the real power system.

2. Configuration of relay protection systems

The configuration stage involves specifying the protection schemes applied to each network element, including differential, overcurrent, voltage, and other types of relay functions. Detailed parameterization of each device is performed by assigning time delays, scaling coefficients, sensitivity zones, and threshold settings. Coordination between the protective elements is established to prevent undesired tripping and to ensure accurate fault localization. Feedback parameters such as time-current characteristics and operational logic dependent on system conditions are also incorporated. Additionally, the influence of system parameter variations on the performance of protection devices is analyzed.

3. Time-domain and frequency-domain simulations

Time-domain simulations are used to investigate the dynamic response of the system to disturbances such as short circuits or line outages, capturing the evolution of electrical quantities over time. Frequency-domain simulations evaluate how system events affect network frequency, providing insight into protection stability under dynamic operating conditions. Numerical techniques, including differential equation solvers, are employed to model electromagnetic processes. The application of both time- and frequency-domain methods enables the assessment of relay protection response to various fault scenarios and facilitates evaluation of their operational timing characteristics.

4. Evaluation of relay operating time

The analysis of relay operating times includes consideration of signal transmission delays, protection device processing delays, and equipment response times. The effects of system variations—such as load changes or impedance fluctuations—on operation time are also examined. Simulation outcomes for different protection types are compared across multiple scenarios to refine the accuracy of timing assessments. This evaluation is essential for optimizing relay settings and ensuring rapid and selective fault clearance.

5. Adjustment of protection settings

Simulation results are used to optimize relay settings, balancing the need for minimal operation time with the requirement to avoid false tripping. Threshold values and time delays are adapted to reflect system behavior under various operating conditions. Additional simulations are performed to validate the updated settings and assess their effectiveness.

6. Modeling of additional test scenarios

Test scenarios are introduced to analyze relay performance under different influencing factors, including variations in load dynamics, simultaneous disturbances, and other operational conditions. High-frequency fault scenarios are simulated to assess relay resilience under repeated events. Test cases are developed to verify coordination among protection devices and automation systems.

7. Data collection and result analysis

Data on relay operation under various system conditions are collected and analyzed, forming the basis for technical reports that guide further refinement of protection settings. DIgSILENT PowerFactory provides comprehensive tools for such in-depth evaluation, enabling engineers to enhance the reliability and effectiveness of relay protection in complex power system environments [5].

RESEARCH RESULTS

In modeling the relay protection of the newly commissioned 220-kV L-2–K-4 transmission line connected to the 220/110/10 kV Keles substation, the study employs the Siemens 7SA6 microprocessor-based relay model available in the DIgSILENT PowerFactory library [5]. This model is selected as a reference because its functional structure closely corresponds to relay protection devices commonly used within the power system of Uzbekistan. The model incorporates several protection elements, including:

- distance protection blocks with quadrilateral and circular characteristics;
- overcurrent protection elements;
- thermal overload protection for high-voltage transmission lines;
- multi-stage earth-fault protection;
- overvoltage and undervoltage protection functions;
- overfrequency and underfrequency protection functions.

To ensure full compatibility of the model with relay protection devices used in the power system of Uzbekistan, an additional power-swing blocking function was integrated into the distance protection blocks.

The operating principle of the Siemens 7SA6 relay model implemented in the DIgSILENT PowerFactory environment is illustrated in Figure 1. Current and voltage transformers are connected to the measurement unit, which receives the phase currents and voltages of the protected line. The measurement unit processes these quantities using mathematical algorithms to compute active, reactive, zero-sequence, and negative-sequence components, and then forwards the resulting signals to the respective protection blocks. Each protection block, upon receiving the required input parameters, executes its internal logical and mathematical evaluation routines and issues control outputs to the circuit breaker trip or close units [5].

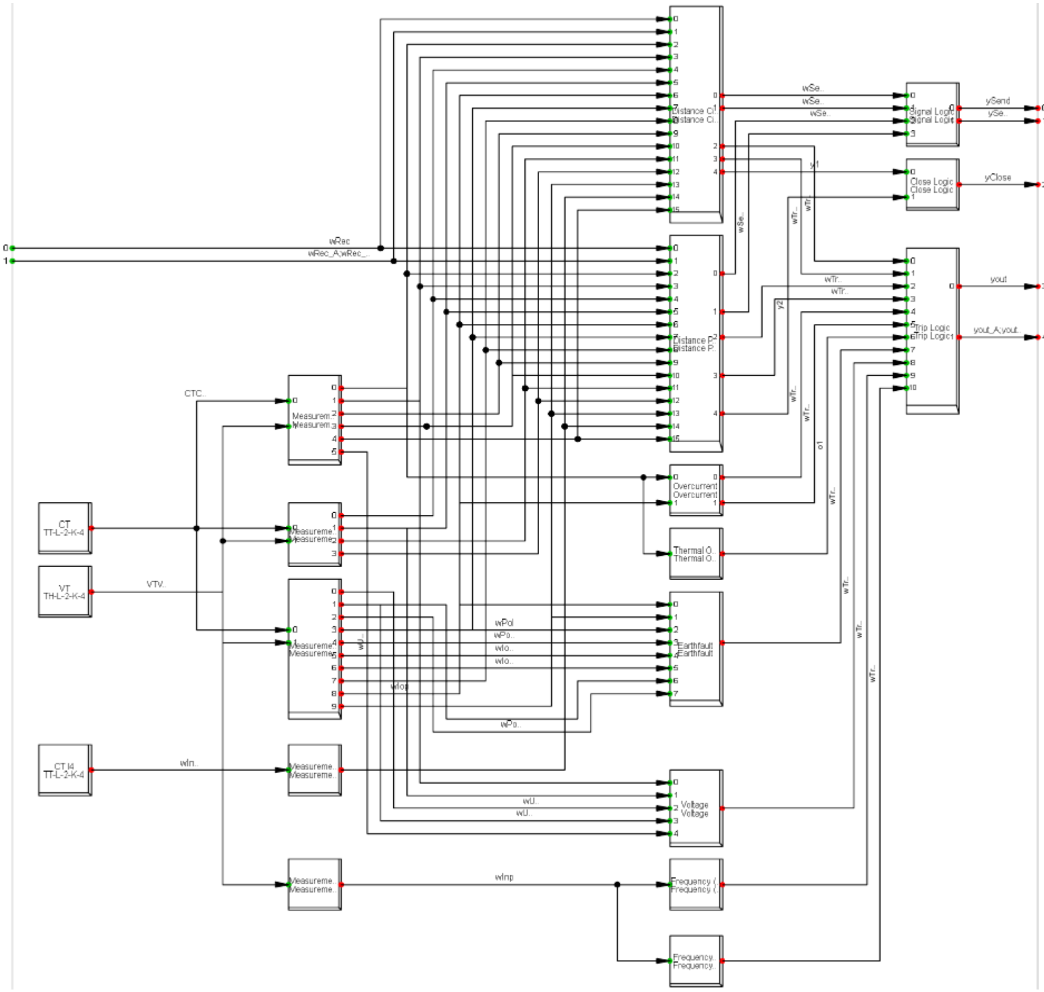

FIGURE 1. Structural representation of the Siemens 7SA6 microprocessor-based relay model from the DIGSILENT Power Factory library.

The input parameters of the distance protection block include the phase currents and voltages, as well as their zero-sequence and negative-sequence components, along with the corresponding active and reactive power quantities.

- I_A, I_B, I_C - phase currents;
- U_A; U_B; U_C - phase voltages;
- $3I_0$, $3U3$ - zero-sequence current and voltage components;
- $3I_2$ - negative-sequence current component.

These input signals, as shown in Figure 2, are connected to the internal elements responsible for polarization and initiation of the protection functions. The polarizing element subsequently processes the input quantities through mathematical calculations, converts them into output signals, and forwards them to the subsequent functional blocks. A subset of these signals is presented below [5]:

- R_A, R_B, R_C; Ri_A, Ri_B, Ri_C - active (resistive) components
- X_A, X_B, X_C; Xi_A, Xi_B, Xi_C - reactive components.

These signals are connected to the distance protection relays with circular characteristics, as well as to other protection elements, as illustrated in Figure 2. The aforementioned components incorporate dedicated pickup and dropout functions, which enable detailed analysis of the operating and non-operating states of each individual element.

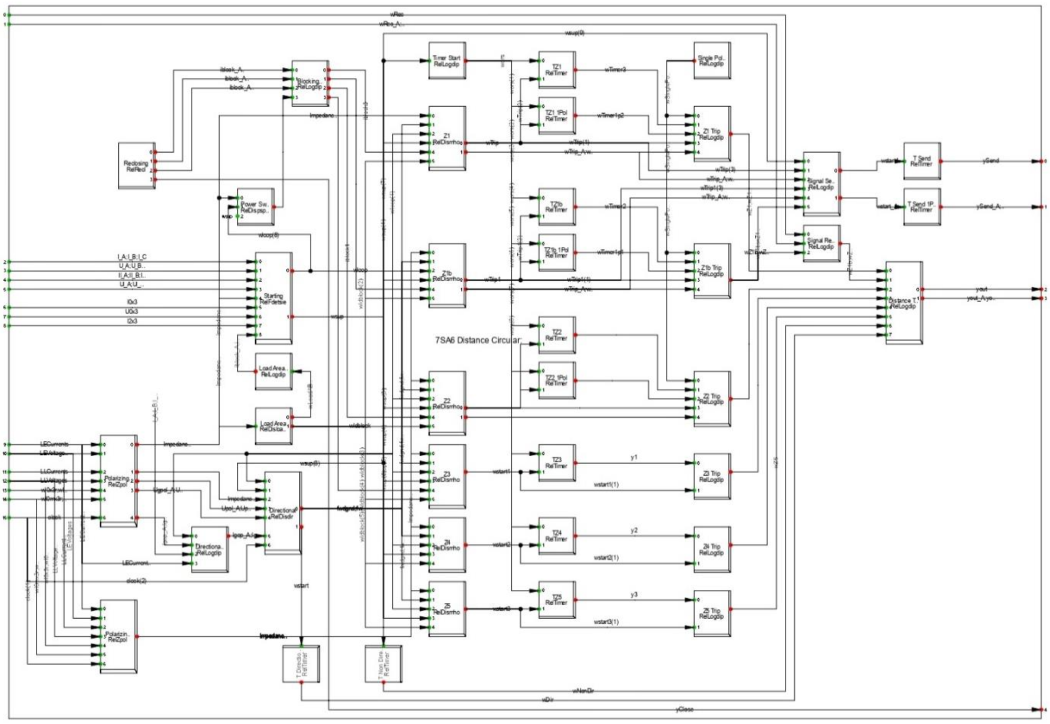

FIGURE 2. Distance protection block with circular operating characteristics.

The relationship between the newly designed three-zone distance protection settings for the L-2-K-4 overhead transmission line - calculated in accordance with methodological guidelines - and the currently operating three-zone distance protection settings of the L-2-K-3 line has been analyzed. In both transmission lines, the distance protection function employs a three-zone circular characteristic, with the corresponding settings presented in Table 2.

TABLE 2. Distance Protection Settings

№	Protection Device	Location	Branch	Stage (Phase)	Impedance [pri. Ohm]	Impedance [sec. Ohm]	Angle [deg]	Time	Diraction
1	Relay L-2-K-3	SS Keles 220	L-2-K-3	Z1	10,6	4,8	75,00	0,00	Forward
				Z1b	10,67	4,85	75,00	0,00	Forward
				Z2	44,99	20,45	75,00	1,00	Forward
				Z3	63,998	29,09	75,00	3,00	Forward
2	Relay L-2-K-4	TashTPP-220	L-2-K-4	Z1	10,67	4,85	82,00	0,00	Forward
				Z2	44,990003	20,45	70,00	1,00	Forward
				Z3	63,998002	29,09	70,00	3,00	Forward

In Figure 3, the circular operating characteristic of the distance protection installed at the GES-2 side of the L-2-K-4 overhead transmission line (Relay L-2-K-4) is shown in red, while the three-zone circular characteristic of the distance protection installed at the Keles substation end of the L-2-K-3 line (Relay L-2–K-3) is depicted in blue. The diagram illustrates the relative positioning of the L-2–K-3 relay characteristic with respect to the protection characteristic of the L-2–K-4 line. In the characteristic plot, the Cartesian coordinates X and Y are replaced by the resistive (R) and reactive (X) components, respectively.

The fact that most of the protection zones lie within the first quadrant indicates that both relays operate in the same forward-direction protection mode [6, 7].

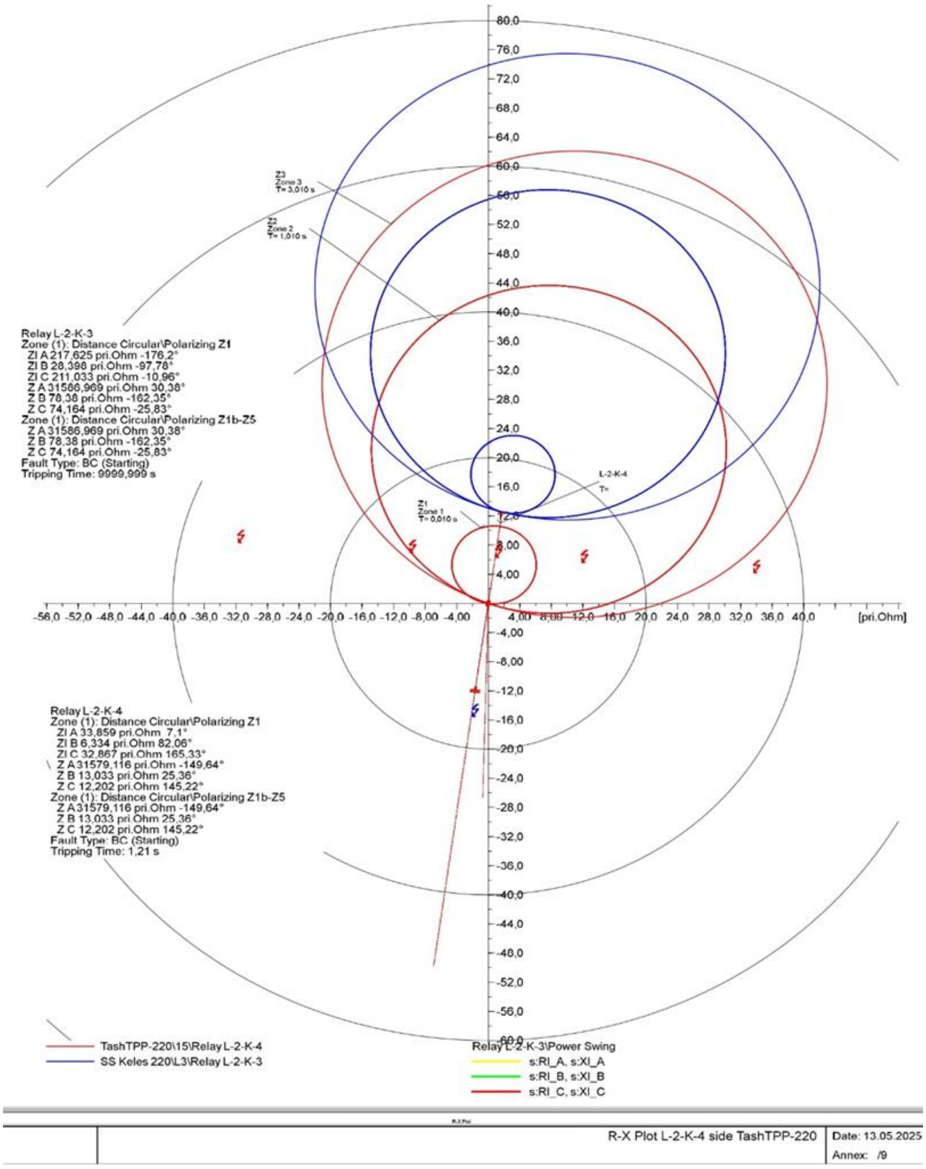

FIGURE 3. Correlation diagram of the three-zone circular distance protection characteristics for the L-2–K-4 overhead transmission line (Relay L-2–K-4) installed at the Tashkent TPP side and the L-2–K-3 line (Relay L-2–K-3) installed at the Keles substation.

When a short circuit occurs on an overhead transmission line, the apparent impedance measured by the distance relay decreases toward a value close to the line impedance [8, 9, 10]. Distance relays continuously monitor the line impedance and rapidly detect such changes. In the simulated fault scenario, a two-phase short circuit (phases B and C) was applied at the midpoint of the L-2–K-4 line, and the operation of both protection devices was evaluated. The fault points for each relay are marked in their respective colors in Figure 3 [11, 12, 13]. Based on the positions of these markers and the computed impedance magnitude and angle for phases B and C, it can be observed that the short-circuit point lies within all three circular protection zones of the L-2–K-4 distance relay. Consequently, the relay operates according to its preset time delays for the first, second, and third zones.

For the L-2–K-3 line, however, the corresponding impedance point falls outside the first, second, and third circular zones-specifically in the third quadrant-despite both relays being oriented in the same forward direction. This is due to the direction of the short-circuit current flow, which in this case is from the GES-2 side toward the Keles substation. As a result, the distance relay installed at the Keles end of the L-2–K-3 line identifies the fault as occurring outside its protection zone and therefore does not operate. This behavior confirms the correct directional operation of the relays and demonstrates that the simulation model accurately reproduces the performance of the real protection devices under the present system operating conditions.

CONCLUSIONS

The study demonstrates that the use of DIgSILENT PowerFactory for modeling and analyzing relay protection systems provides a robust methodological framework for evaluating the behavior of protection algorithms under realistic operating and fault conditions. Simulation-based modeling significantly enhances the ability to assess the dynamic response of distance protection, enabling the identification of critical factors affecting selectivity, sensitivity, and operational reliability.

The implementation of a three-zone distance protection model tailored to the L-2–K-4 and L-2–K-3 overhead transmission lines shows that the developed settings accurately reflect the impedance characteristics and directional dependencies of the interconnected 220-kV network. Verification through simulated two-phase short-circuit scenarios confirmed that the proposed protection zones operate strictly within their defined boundaries and comply with established time-delay coordination principles. The model also demonstrated correct non-operation of the L-2–K-3 relay when the fault was located outside its protection reach, validating the effectiveness of the directional logic and ensuring proper coordination with adjacent lines.

The results confirm that the model closely replicates the performance of real relay protection devices, validating both its structural accuracy and its suitability for practical engineering applications. The developed methodology ensures that protection settings derived from the model can be reliably implemented in the actual power system environment of Uzbekistan.

Overall, this approach contributes to improving the operational reliability of high-voltage transmission networks, enabling selective and rapid isolation of faulted sections, and supporting the transition toward advanced digital relay protection technologies across the power infrastructure. The findings underscore the importance of simulation-driven analysis as an essential tool for modernizing protection systems and achieving higher levels of stability, security, and resilience in interconnected power grids [14, 15].

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