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Impact of Single-Phase Automatic Recloser of Critical Transmission Line on the Stability of the Power Transmission Network

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Abstract

In order to increase the stability of the Mongolia power system, a single-phase automatic reclosing device (SPAR) was introduced on double-circuit power lines built with a size of 330 kV, operating on a voltage of 220 kV and a length of 250 km. These overhead power lines (L-213, L-214) connect the 220/110/35 kV "Songino" substation with the "Mandal" substation and form system networks. This paper presents the challenges encountered when implementing single-phase automatic reclosing (SPAR) devices and compares the changes in power system parameters before and after SPAR deployment for a long 220 kV line. Simulations and analyses were carried out using DIgSILENT PowerFactory software, focusing on rotor angle stability, and the overall impact on the power system during short-circuit faults. The evaluation also utilized measurement data from the Wide Area Monitoring System (WAMS) to compare system behavior pre- and post-implementation of SPAR. The findings reveal that SPAR significantly enhances system reliability and stability, effectively mitigating the risk of oscillations and stability loss triggered by short circuits. This improvement contributes to a more resilient power system, reducing the potential for disturbances caused by faults.

Keywords

Automatic Reclosing, Single-Phase Automatic Reclosing, Relay Protection, Overhead Power Lines, System Stability, Rotor Angle Stability

1. Introduction

When a short circuit occurs in the power grid, it leads to a sharp increase in current and a voltage drop. Relay protection isolates the faulty section from the system, dividing it into parts that remain in stable operation. However, when a fault occurs on a critical transmission line, its isolation significantly reduces the transmission capacity and deteriorates the stability of the remaining system compared to pre-fault conditions.

According to long-term statistical studies, most faults (75% - 80%) in Mongolia's power transmission network are temporary single-phase ground faults on overhead lines [1] [2]. In these cases, isolating the faulty phase while keeping the other two phases operational, and then using automatic reclosing to restore the isolated phase, can improve the dynamic stability of the system. During this process, specific sections of the power grid operate in an incomplete phase mode, transmitting about two-thirds of the usual power, which allows steam generators and renewable generators to remain synchronized and prevents the system from falling into an asynchronous state.

This combined operation of relay protection and automation is carried out under the framework of single-phase automatic reclosing (SPAR). In Mongolia's power system, SPAR is applied to critical 220 kV transmission lines such as L-203, L-204, L-208, L-211, L-212, L-213, and L-214 (see **Figure 1**) [3].

SPAR is a critical automation device for system stability, requiring detailed consideration of its impact on normal and reliable operation as well as on secondary circuit design solutions. This paper explores challenges and solutions for introducing SPAR into Mongolia's power grid, characterized by its relatively low voltage level (220 kV), long transmission lines, high fault frequency, and the extensive use of reactors and Static Var Compensators (SVC) to maintain voltage levels [2].

According to the study, the requirements and criteria for using single-phase automatic reclosers in line with the above characteristics are unclear, and there is no unified standard methodology. On the other hand, Mongolia's power system has a widely distributed network, extremely long lines, no primary generator backup, and no ability for subsystems to operate independently in the event of a line failure or power plant failure. In this situation, this study was conducted because it was considered practical to improve system reliability by using a single-phase reclosing device in the lines connecting the system subsystems.

We aim to solve the following problems in this study:

1) To determine whether it is possible to use single-phase reclosing devices in the transit lines of the Mongolian power system.

2) To determine the impact of incomplete phase modes that may occur during the operation of single-phase reclosing devices, and to assess the effect of incomplete phase modes on the selectivity of relay protection at line substations.

3) To determine how long-term line parameters affect voltage stability during the operation of single-phase reclosing devices.

The study includes numerical modeling of the SPAR performance on the 220 kV L213 and L214 parallel lines with strong shunt connections. It examines methods to improve the successful reclosing rate of SPAR, as well as voltage and angular stability at adjacent substations, through simulation and analysis of transitional state parameters.

Nowadays, the direction of studying and solving the transition processes, mode control, relay protection, and automation systems of power systems based on numerical modeling that reflects the characteristics of the power system and network has been adopted. The research modeling was carried out using DIgSILENT PowerFactory software, which is widely used in educational and research institutions in our country. Because the Mongolian power system is selected due to its relatively low voltage level (220 kV) compared to the grids of developed countries, the small number of nodes, the absence of a DC network, and its simple structure, we believe that DIgSILENT PowerFactory software will provide sufficient results in our study.

By analyzing the transient recordings of this system, it is possible to compare and judge how the system parameters and their rate of change changed during the operation of the three-phase automatic recloser and the single-phase automatic recloser, and to make recommendations for the project. The state of the network section where the Mongolian power system study was conducted is shown in Figure 1.

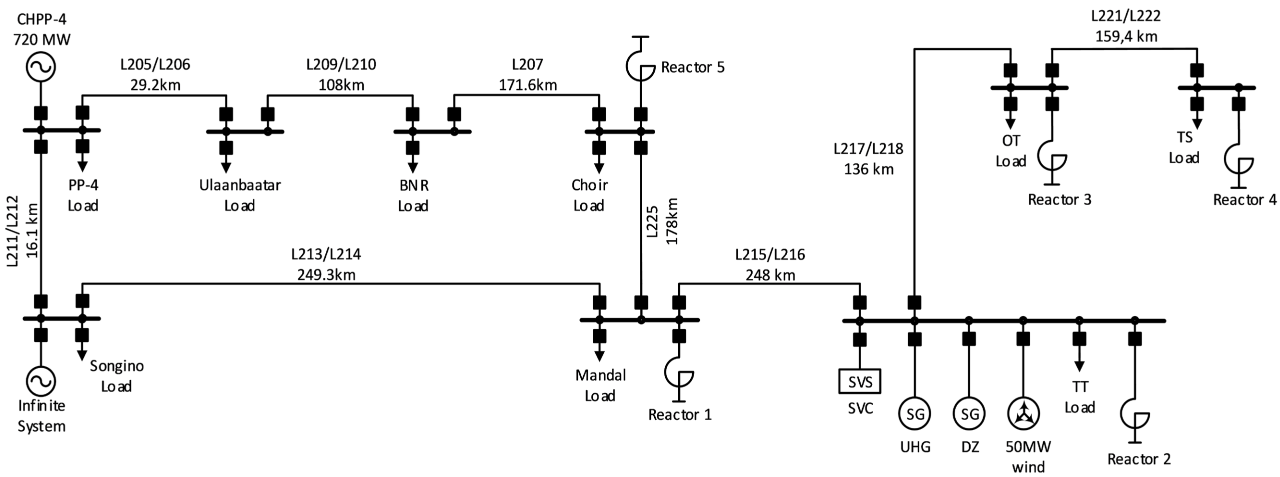

Figure 1. General scheme of the network modeled and studied.

2. Conditions and Requirements for Implementing SPAR

In Mongolia, the number of overhead power line failures is relatively high. For example, if we look at the statistics for the past 10 years, the average number of trips of 110 - 220 kV lines per year is 20, and the success rate of automatic reclosing equipment is 88%. During this period, the 110 kV parallel line "Kharkhorin A, B" was shut down the most times—66 times [4], which is very alarming. Therefore, the use of automatic reclosing devices, including SPAR devices, can be seen as an important factor in ensuring the continuity of power supply.

For power supply lines or terminal lines, the installation of single-phase automatic reclosing (SPAR) devices is simple and the requirements are lighter. When introducing SPAR into a line with two-way power supply or into a system-forming line, the following conditions should be taken into account [5]. It includes:

a) The impact of SPAR on system stability and the necessity of its implementation on the transmission line.

b) The effect of incomplete phase operation during the SPAR cycle on generators and consumers, and whether the impact remains within acceptable limits for consumer operations.

c) The complexity and potential operational challenges due to fault phase identification devices, SPAR schemes, settings, and breaker controls. It is necessary to account for these factors, conduct detailed studies, modeling, and evaluations.

d) Precise calculation of the effects of secondary arcs during the reclosing cycle and determining appropriate SPAR settings.

e) Evaluating conditions to ensure the selectivity of relay protection regarding reverse-sequence currents generated during SPAR operation.

The 220 kV "Songino" to "Mandal" system-forming parallel transmission lines, L213 and L214, were chosen for this study, with the following characteristics (**Figure 1**):

- This line is the primary transmission line linking the largest power plant in Mongolia (CHPP-4, 720 MW) to major mining production hubs such as Tavan Tolgoi, Oyu Tolgoi, and Tsagaan Suvarga substations.
- The line was constructed with a 330 kV design but currently operates at 220 kV, extending 250 km with strong shunt connections (L205, L206; L209, L210; L207; L225).
- The line features a large generator with virtually infinite capacity at one end and distributed sources such as wind farms (50 - 100 MW), solar plants (10 MW), and reactive power regulation equipment (reactors, SVC) at the other end.

Given these characteristics, modeling and analyzing the transitional process during SPAR operation, focusing on voltage and angular stability, is crucial.

3. Rotor Angle Stability during SPAR Operation

When a single-phase-to-ground short circuit occurs on a major transmission line, a three-phase trip can lead to system instability. Implementing SPAR allows the line to operate in an incomplete phase mode during a single-phase-to-ground fault, improving rotor angle stability. A three-phase trip is only executed in the event of phase-to-phase faults. The Equal-Area Criterion is a suitable method to demonstrate the advantages of SPAR concerning rotor angle stability [5] [6].

When a three-phase trip is executed for a temporary single-phase-to-ground fault, power flow through the line stops, causing generators on the source side to accelerate while consumers on the load side experience a power deficit. This can result in system instability and an asynchronous state. By contrast, SPAR isolates the faulted phase while maintaining power flow through the other two phases, reducing rotor acceleration and enhancing system stability.

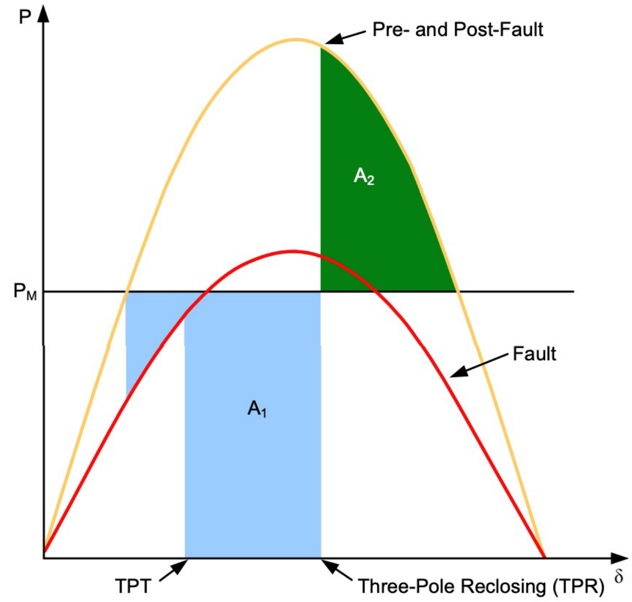

Figure 2. Equal area criterion for three-phase disconnection [5].

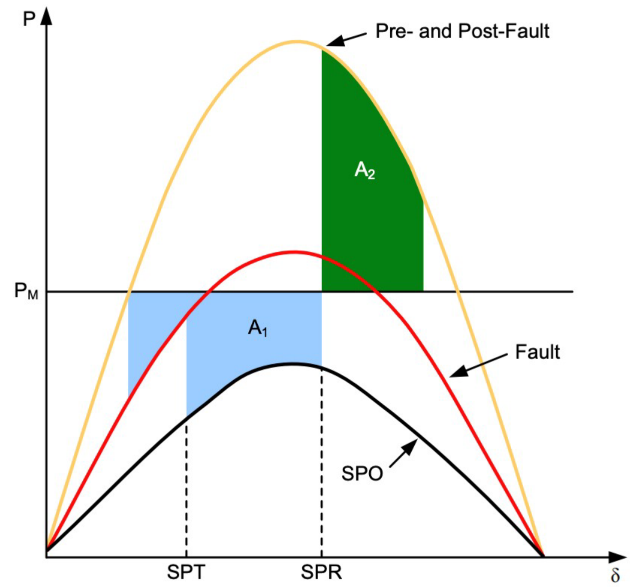

Figure 3. Equal area criterion for single-phase disconnection [5].

During a temporary single-phase-to-ground fault, performing a three-phase trip halts power transmission through the line. This causes the generators on the source side to accelerate, while a power deficit occurs on the load side. This scenario significantly increases the likelihood of system instability and transition into an asynchronous state.

When a three-phase trip is executed, the acceleration energy of the generator rotors equals the area A1. If A1 > A2 (as shown in **Figure 2**), the system transitions into an asynchronous state, leading to instability [5] [6].

Explanation: With SPAR implemented, the faulted phase is isolated through relay protection, and power transmission continues through the healthy two phases during the SPAR cycle. This reduces the risk of rotor acceleration, loss of angular stability, and transition to an asynchronous state.

As shown in the diagram, A2 > A1 (**Figure 3**), meaning the oscillatory energy accumulated by the rotor is effectively stabilized [5] [6].

The L213 and L214 lines connect critical substations "Songino" and "Mandal" in the power system. The calculations, modeling, and comparative analysis of transitional processes during SPAR operation were performed using the "DIgSILENT Power Factory 2021" software. Scenarios included interconnected lines L210 and L214, and operational modes of power plants such as Ukhaa Khudag, Dalanzadgad, Tsetsii, and Shand (**Figure 1**). Simulations for two fault-clearing methods were conducted and compared as follows:

Scenario 1: A temporary single-phase-to-ground fault is cleared by a three-phase trip 0.1 seconds after occurrence, with all three phases reclosed simultaneously 1.5 seconds later using three phase automatic reclosing (TPAR).

Scenario 2: A temporary single-phase-to-ground fault is cleared by isolating only the faulted phase 0.1 seconds after occurrence, with the isolated phase reclosed 1.5 seconds later using SPAR.

Simulation results show that during SPAR operation, the rotor angle stability of the turbo-generators at Ukhaa Khudag and Dalanzadgad is significantly improved compared to the TPAR cycle. Additionally, SPAR causes smaller frequency deviations (**Figure 4** and **Figure 5**).

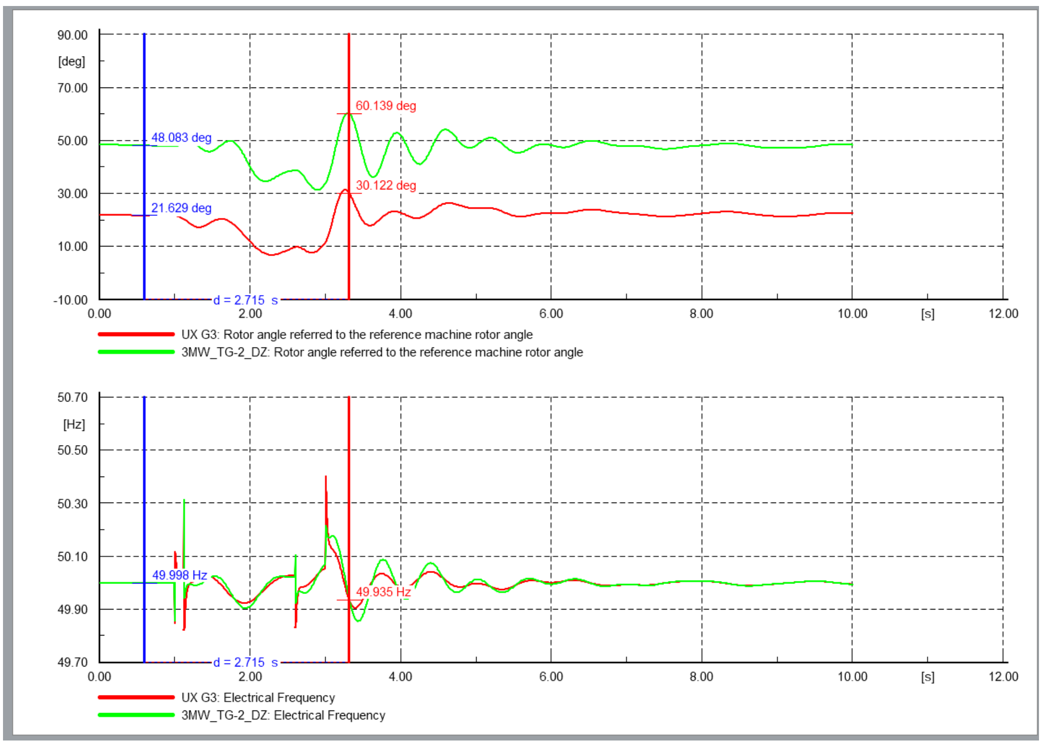

Figure 4. Simulation during three phase reclosing: Frequency and rotor angle stability, as well as frequency fluctuations, of Uhaa Khudag TG-3 and Dalanzadgad TG-2.

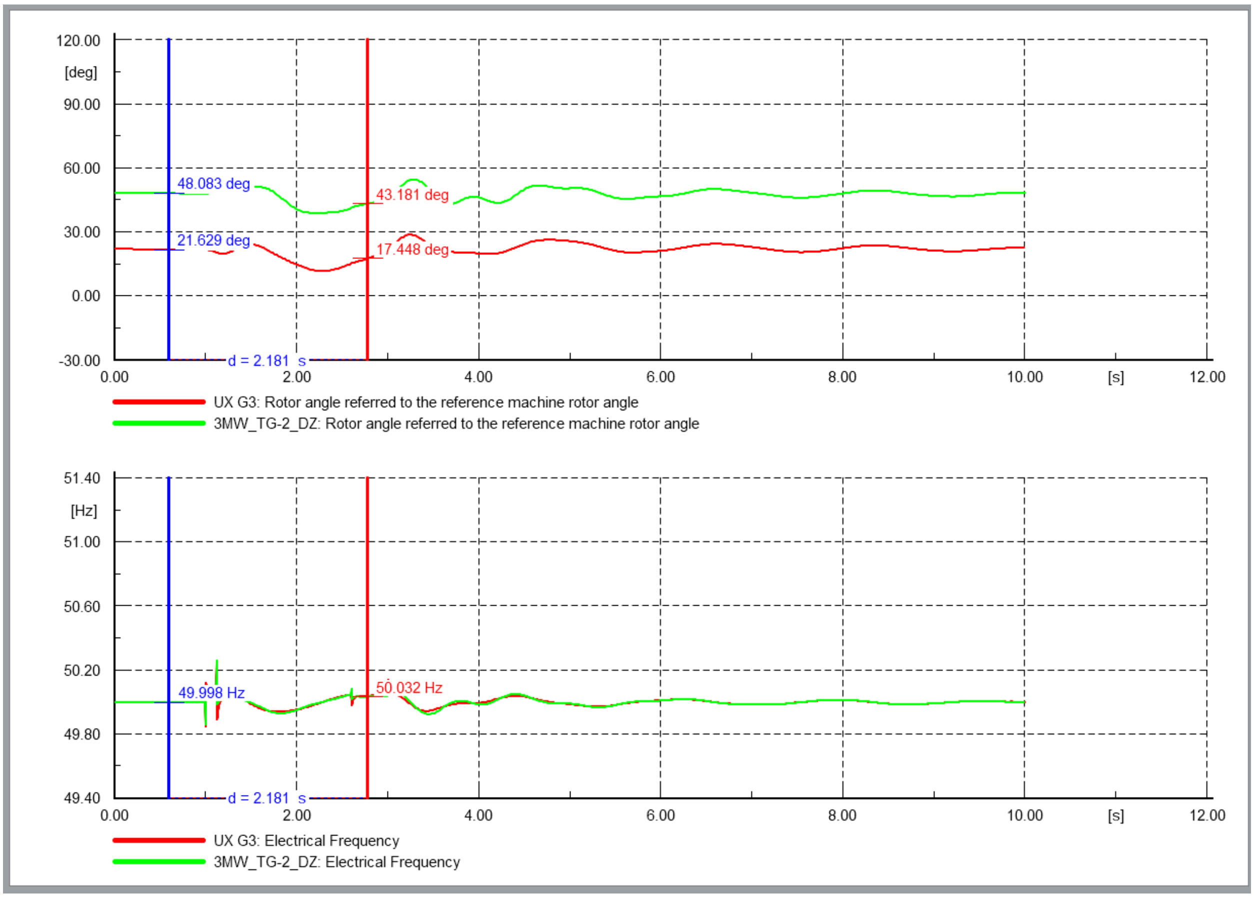

Figure 5. Simulation during single-phase automatic reclosing: Frequency and rotor anglestability, as well as frequency fluctuations, of Uhaa Khudag TG-3 and Dalanzadgad TG-2.

Key Findings:

- With TPAR, the rotor angle reaches 60.2 degrees.
- With SPAR, the rotor angle is limited to 50.5 degrees.
- During TPAR, frequency deviates instantaneously to 50.4 Hz.
- During SPAR, frequency deviates instantaneously to 50.2 Hz.

The oscillation stabilization time is reduced from 8 seconds to 6 seconds, demonstrating that SPAR significantly improves generator stability at Ukhaa Khudag and Dalanzadgad.

4. Voltage Stability Analysis

For too-long transmission lines, voltage stability is a very important issue, especially when performing a three-phase automatic reclosing function, it is necessary to consider what the voltage values at the system points are. However, in the case of a single-phase automatic recloser, the voltages of the phases become unbalanced during the reclosing cycle, which is also important to consider and evaluate in detail [2] [7].

For voltage stability analysis, scenarios with interconnected lines L210 and L214 and power plants such as Ukhaa Khudag, Dalanzadgad, and Tsetsii were modeled.

Simulations were performed for the following fault-clearing scenarios:

1) A temporary single-phase-to-ground fault is cleared by a three-phase trip 0.1 seconds after occurrence, with all three phases reclosed simultaneously 1.5 seconds later using TPAR.

2) A temporary single-phase-to-ground fault is cleared by isolating only the faulted phase 0.1 seconds after occurrence, with the isolated phase reclosed 1.5 seconds later using SPAR.

Simulation results quantified the transient voltage rises at key substations during the automatic reclosing process. The comparison is shown in **Table 1**.

Table 1. Comparison of maximum voltage changes on critical substations.

Substation	Busbar voltage during TPAR, kV	Busbar voltage during SPAR, kV
Songino	235.1	233.5
Mandal	266.6	263.1
Choir	251.8	241.6
Tavantolgoi (TT)	261.2	258.1
Oyutolgoi (OT)	258.3	251.0
Tsagaansuvarga (TS)	255.5	247.7
Darkhan	251.3	240.9

When both ends of the line are isolated by relay protection and voltage is applied from the "Songino" substation to the 250 km long line, the voltage surge caused by SPAR is significantly lower compared to traditional methods. This not only contributes to system stability but also plays a critical role in extending equipment lifespan and ensuring the reliable operation of Tavantolgoi's SVC. Conversely, performing a three-phase trip increases system impedance, reduces transmission capacity, and adversely affects stability. SPAR improves reactive power balance and voltage stability compared to TPAR. Voltage fluctuations at key substations are illustrated in **Figures 6-9** based on simulation results.

However, during SPAR cycles, the line operates in an incomplete phase mode, causing voltage asymmetry. This uneven loading of Tavantolgoi's SVC-1 and SVC-2 may trigger SVC's protective mechanisms. After analyzing the protection schemes and settings, it was determined that SPAR reclosing time settings need to be coordinated with the relay protection settings of the SVCs on L213 and L214. The SVC overvoltage protection setting is 40.5 kV for 2 seconds, and the under voltage protection setting is 30.5 kV for 2 seconds. Therefore, the selectivity of SPAR reclosing time must be verified using Equation (1).

$$t_{\text{ОАПВ}} \leq t_{svc\ x.a} - t_{н} \quad (1)$$

$t_{н}$ —Reliability coefficient for operating delay.

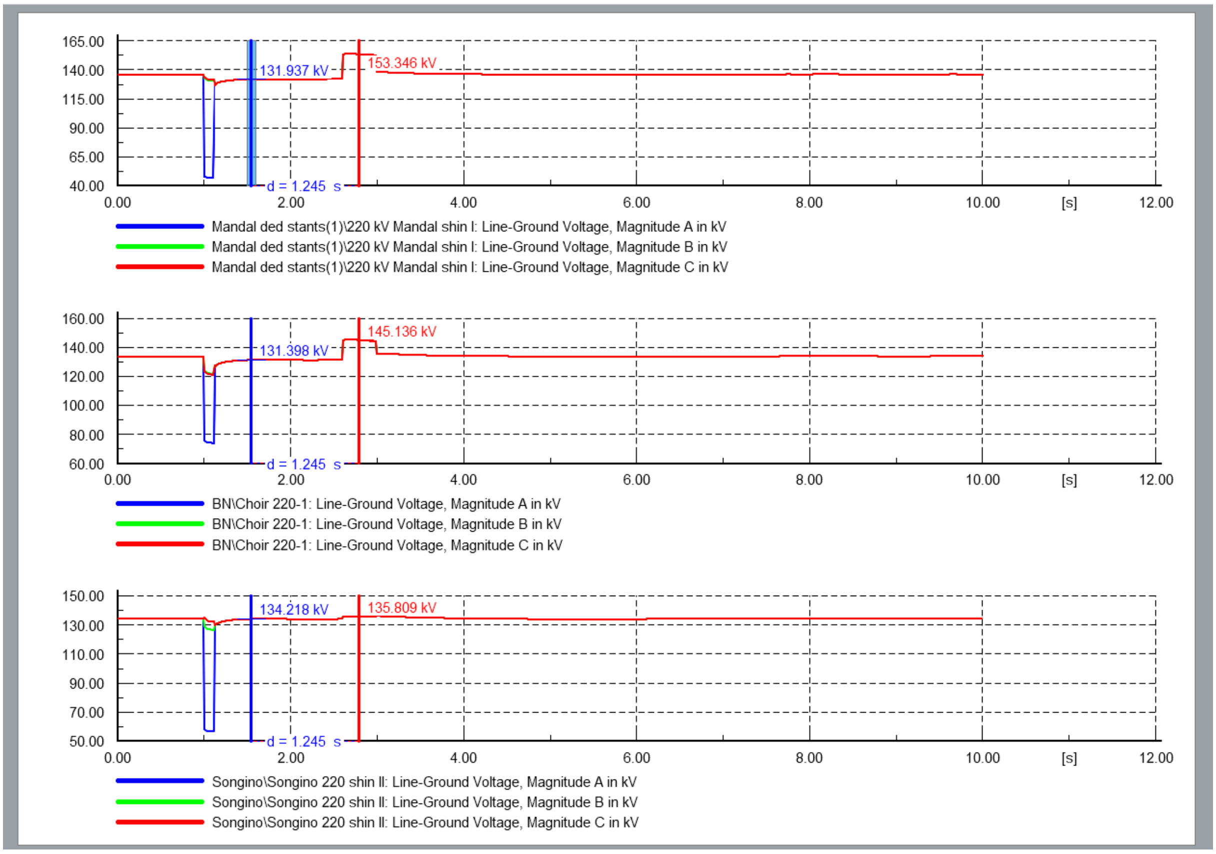

Figure 6. Voltage at the 220 kV side of the Songino, Mandal, Choir substation during TPAR.

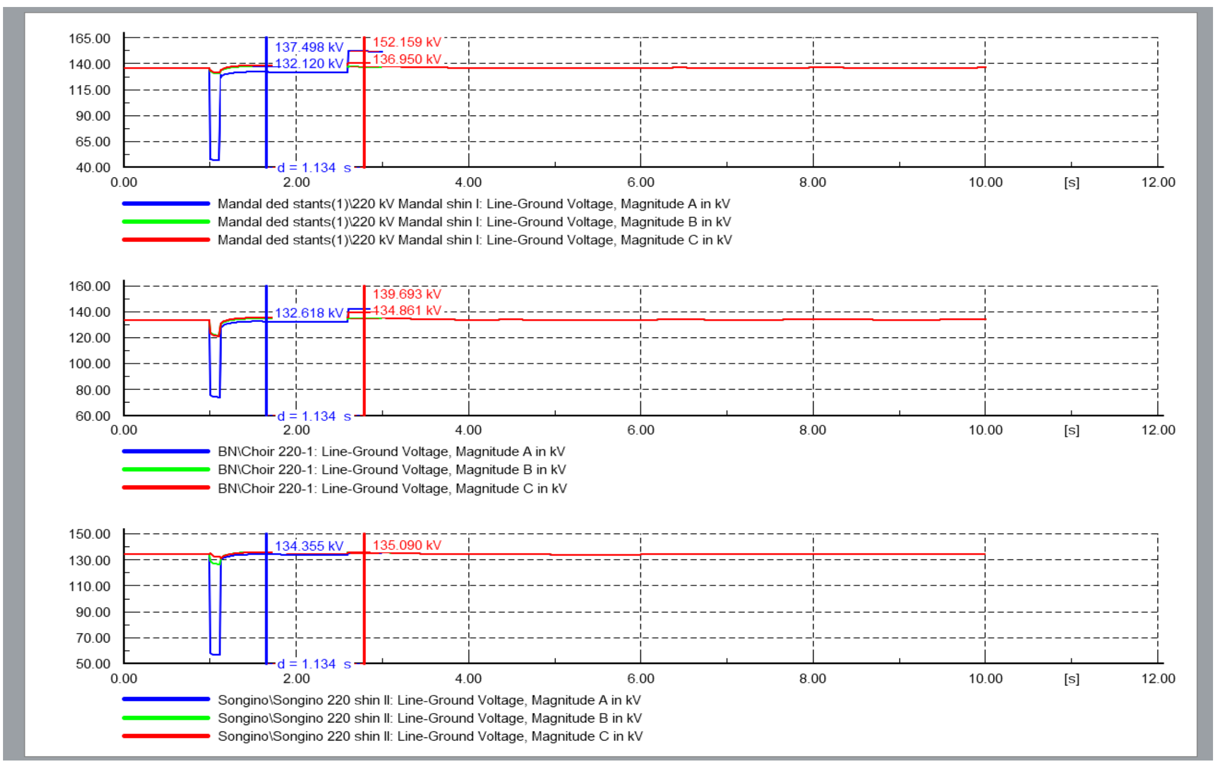

Figure 7. Voltage at the 220 kV side of the Songino, Mandal, Choir substation during SPAR.

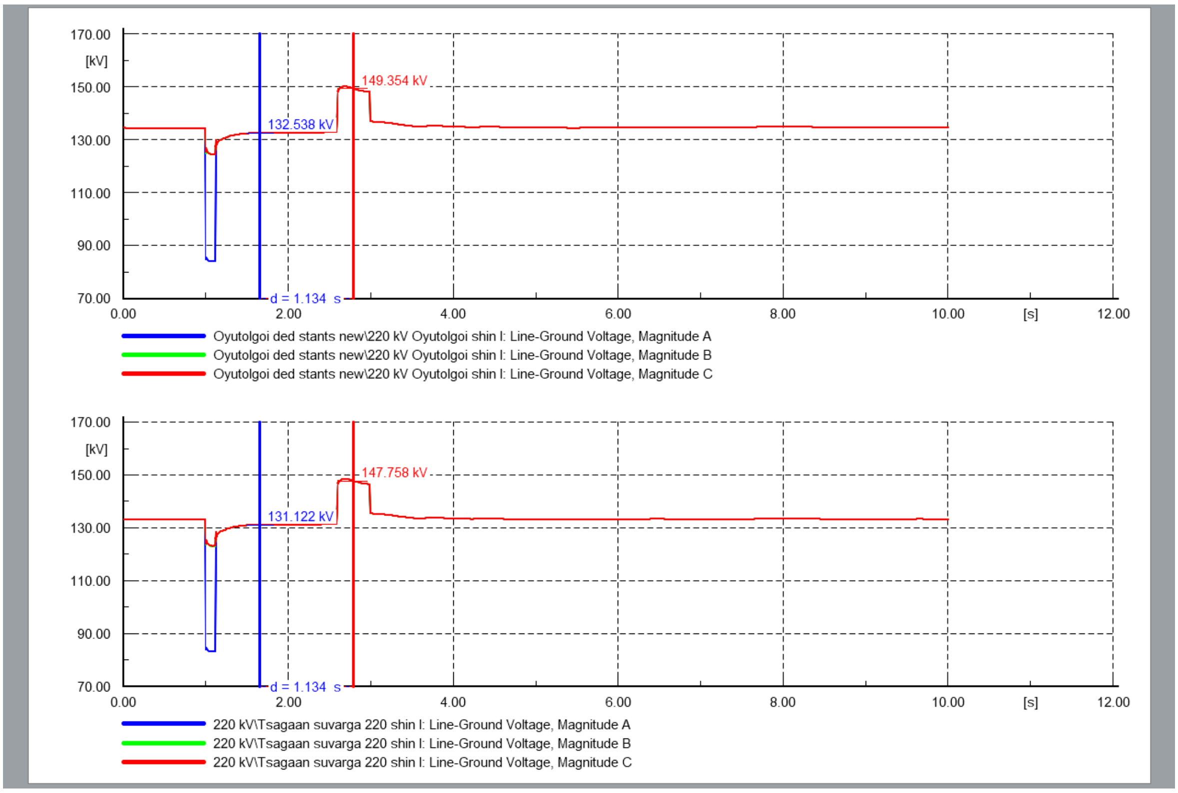

Figure 8. Voltage at the 220 kV side of the Oyu Tolgoi and Tsagaan Suvarga substations during TPAR.

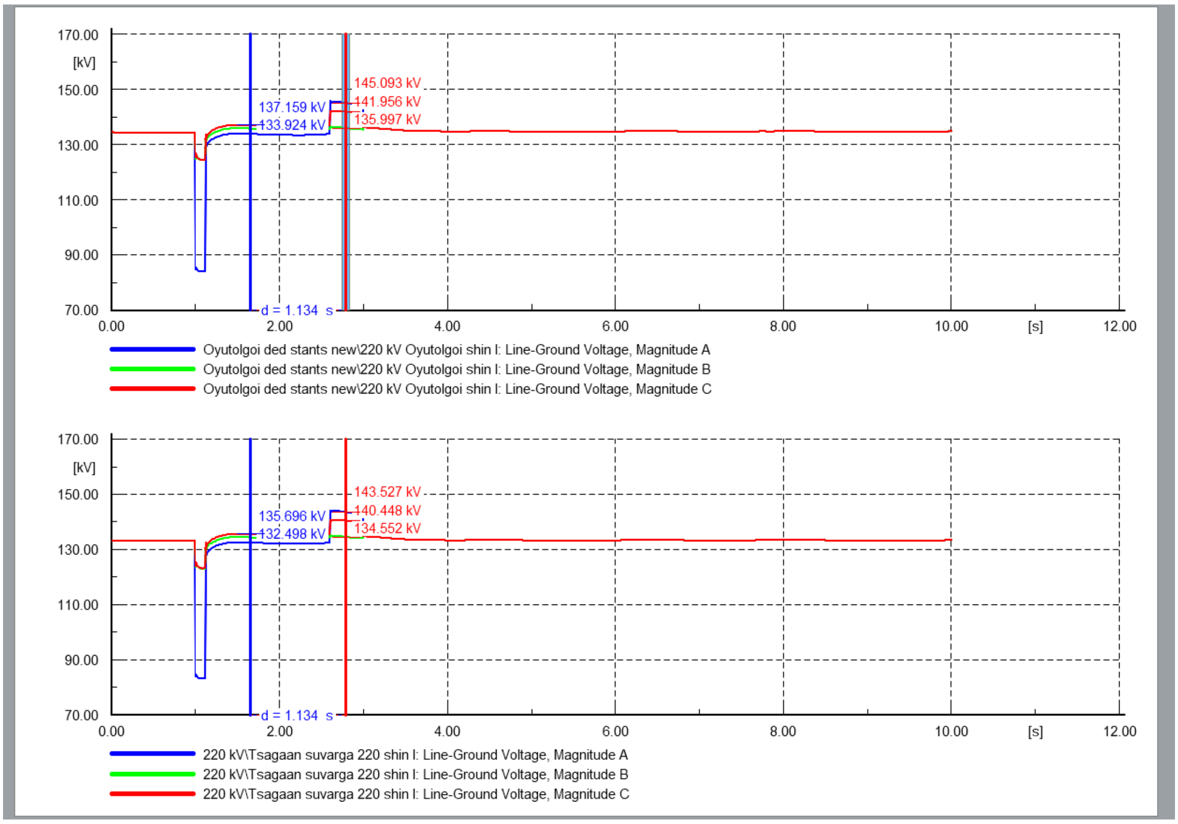

Figure 9. Voltage at the 220 kV side of the OyuTolgoi and Tsagaan Suvarga substations during SPAR.

5. Secondary Arc Considerations

When a single-phase fault is isolated by relay protection, the faulted phase is disconnected on both sides but retains a certain voltage due to the capacitance and mutual coupling of the healthy two phases. This is evident in the vector diagram and simplified circuit in Figure 10. The voltage on the isolated phase primarily arises from capacitance and is influenced to a smaller extent by inductive coupling [7].

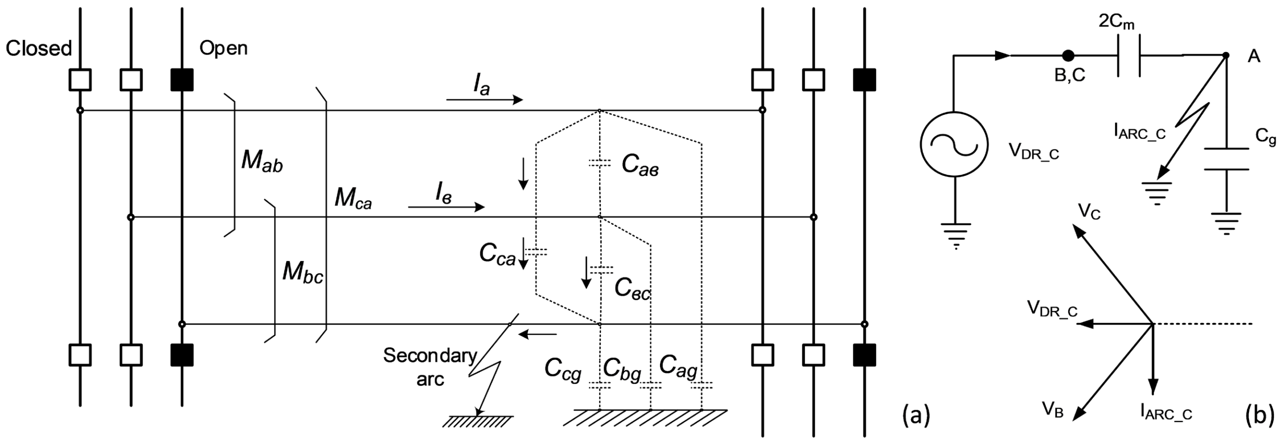

Figure 10. Secondary arc ignition and current-voltage vector diagram.

The magnitude of this voltage depends on the capacitance between phases and the capacitance to ground, which are functionally related [7] [8]. This induced voltage allows a secondary arc to remain stable for a certain duration after the faulted phase is isolated. The arc remaining on the isolated phase after disconnection is called a secondary arc.

The secondary arc depends primarily on the transmission line's voltage level and length, with additional effects from the fault location, reactors, and transposition of the line. The capacitive component of the arc is largely independent of the fault location and load current, whereas the inductive component strongly depends on load current and fault location. Faults at the center of the line result in minimal inductive effects, while faults near the line ends produce maximum inductive effects.

Key findings from previous studies include [7]:

- For 765 kV lines, the capacitive component is approximately 50 A per 160 km.
- For 345 kV lines, the capacitive component is approximately 30 A per 160 km.
- For 765 kV lines, the inductive component reaches 10 - 15 A at maximum load current.

A secondary arc current of up to 40 A on compensated lines or up to 20 A on uncompensated lines typically extinguishes within 0.5 seconds [7] [8]. If these thresholds are exceeded, measures to reduce the line capacitance become necessary.

The L213 and L214 lines are 330 kV hybrid lines with a length of 250 km and are currently operating at 220 kV. The hybrid design (average phase-to-phase radius of 11 meters) reduces the impact of capacitive coupling on the secondary arc. However, the twin AC-240x2 conductors increase mutual capacitance, resulting in a secondary arc current of approximately 50 A. Electromagnetic transient simulations were used to determine SPAR operating times to extinguish the arc effectively.

For example, the 220 kV L203 line (249.3 km, AC-400 conductors) requires an SPAR operating time of 1.5 seconds. The SPAR operating time for L213 and L214 must be at least equal to this value.

6. Results and Observations from WAMS

Based on the above calculations, SPAR was implemented on L213 and L214 in December 2023. On April 20, 2024, during a severe dust storm, two faults occurred on L213 one minute apart, triggering both SPAR and TPAR. The oscillations caused by these operations were recorded by the wide area measurement system (WAMS). Figure 11 and Figure 12 show the voltage, current, power, and frequency fluctuations observed at CHP-4's TG-4 during the events.

From the WAMS recording, it is possible to observe the oscillations occurring in the system when L-213 is disconnected in 3 phases and 1 phase using the parameters of TG-4 of CHP-4. The results are shown in Table 2.

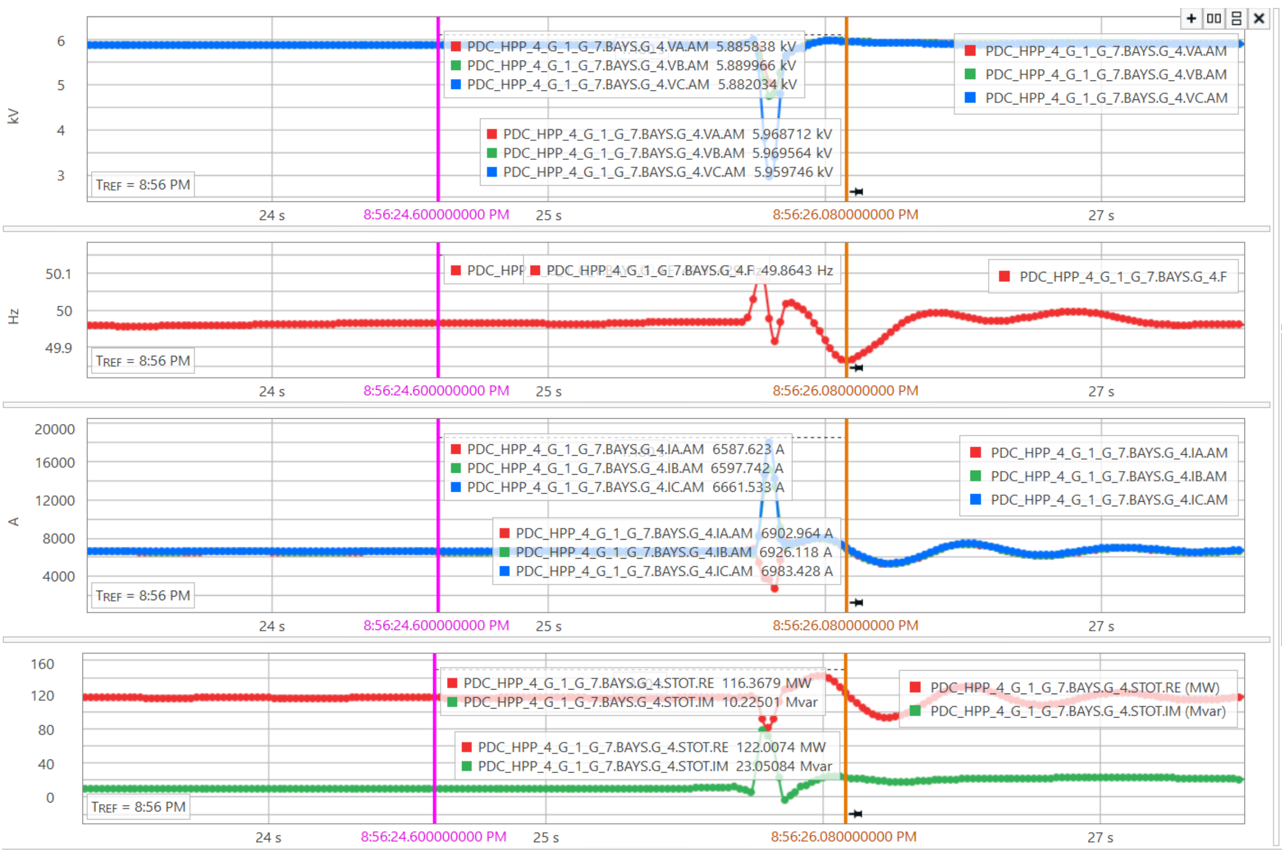

Figure 11. Voltage and frequency fluctuations of CHP-4 TG-4 observed on WAMS during single-pole reclosing (TAPV) on L-213 at 08:56:26 on April 20, 2024.

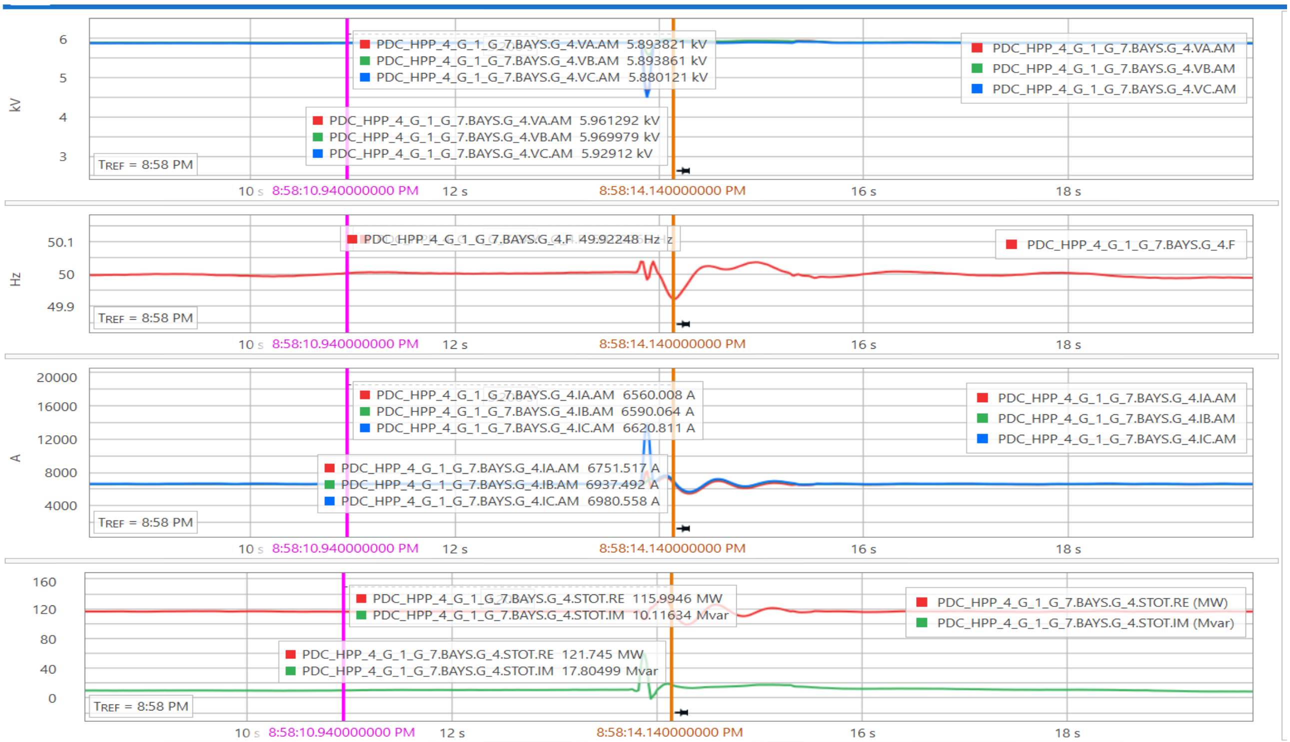

Figure 12. Voltage and frequency fluctuations of CHP-4 TG-4 observed on WAMS during auto reclosing (OAPV) on L-213 at 08:58:13 on April 20, 2024.

Table 2. Comparison of voltage and frequency fluctuations of CHP-4 TG-2.

CHP-4 Generator-4/largest generator in system	SPAR	TPAR
Voltage nadir, kV	7.8	8.2
Frequency nadir, Hz	49.80	49.92

The recordings reveal that rotor angle and voltage fluctuations are significantly higher during three-phase tripping than during single-phase tripping. SPAR reduces system shock and impact on major transmission lines during faults, improving generator stability, relay settings, and compensation device lifespan and reliability.

7. Conclusions

1) Simulations, modeling, and observations from WAMS demonstrate that implementing SPAR on the 220 kV critical transmission lines (L213, L214) in Mongolia's power system has a positive impact on stability. Rotor angle stability during faults improves significantly, and voltage stability is enhanced under SPAR operation, as confirmed by real WAMS recordings of April 20, 2024.

2) SPAR also positively affects the operation of SVCs and other reactive power compensation devices, contributing to the overall reliability and stability of the protection and automation systems. These results demonstrate that SPAR enhances system fault resistance and prevents large-scale outages and accidents in

Mongolia's 220 kV transmission network.

3) It is recommended that SPAR implementation be extended to newly planned 220 kV lines. Detailed technical solutions should be developed to address potential adverse effects arising from incomplete phase operation.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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