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Research Article

AC Power Electronics Symmetrical Short Circuit in Power System for Large-Scale Stability

Jangili Srinivasa Rao [1,*] and P.Sujatha[2]
[1]Head of the Department, Department of Electronics and Instrumentation, Government Polytechnic Kothagudem-507101, Telangana, India.
[2]Lecturer, Department of Electrical and Electronics Engineering, Government Polytechnic Kothagudem-507101, Telangana, India.
[*]Corresponding Author: Jangili Srinivasa Rao. Email: srinivas@gptkgm.org
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Abstract: Symmetrical configurations in power electronics are critical for achieving large-scale stability in modern electrical systems. The system ensures balanced power distribution, minimized harmonics, and reduced electromagnetic interference (EMI) by employing symmetrical topologies, such as symmetrical converters or inverters. These designs inherently improve fault tolerance, as symmetrical structures distribute stresses evenly across components, enhancing system reliability. The proposed Two-zone Multi-Stability (Two-zone-MS) method enhances symmetrical configurations in power electronics, offering improved large-scale stability for modern electrical systems. This approach divides the system into two distinct zones—each zone operating with a separate stability control mechanism—while ensuring that the symmetrical topologies, such as converters or inverters, maintain balanced power distribution. The Two-zone-MS method dynamically adjusts the operating conditions of each zone, optimizing power flow and reducing disturbances. Simulation results for the proposed Two-zone Multi-Stability (Two-zone-MS) method demonstrate significant improvements in the stability and efficiency of large-scale power electronic systems. In a simulated 200 MW renewable energy grid integrating solar and wind power, the Two-zone-MS approach was applied to a symmetrical inverter configuration. The results show that the system-maintained voltage stability within ±0.5% of the nominal voltage, even during transient disturbances, compared to conventional systems, which experienced fluctuations of up to ±2%. With the total harmonic distortion (THD) was reduced to 2.3%, a significant improvement over the 5% THD observed in systems without the Two-zone-MS method. The simulation also revealed that the system efficiency increased by 3%, achieving 97.2% efficiency in power conversion, compared to the 94.2% efficiency of traditional symmetrical inverter systems. Additionally, the fault tolerance mechanism of the Two-zone-MS method successfully isolated faults to a single zone, reducing the system's recovery time from 20 minutes to just 5 minutes, thus minimizing downtime and improving overall system reliability.

Keywords: AC Power Electronics; Symmetrical Configurations; Short Circuit; Power System; Large-Scale Stability.

1 Introduction

Symmetrical short circuits in AC power electronics play a critical role in analyzing the stability of large-scale power systems [1]. These faults, characterized by a three-phase short circuit with equal impedance in all phases, are essential for determining the system's maximum fault current and ensuring robust design and protection schemes. In the context of large-scale stability, symmetrical short circuits provide a worst-case scenario to evaluate the resilience of generators, transformers, and transmission lines. By studying these events, engineers can design systems that maintain stability, minimize cascading failures, and ensure rapid recovery after disturbances [2]. Large-scale stability in power systems refers to the ability of an interconnected grid to maintain a balanced operation under various disturbances, ensuring reliable electricity delivery across extensive networks. Stability becomes particularly critical when dealing with high-capacity power systems, as disruptions such as symmetrical short circuits can lead to cascading failures if not managed effectively [3 -5]. Analyzing such scenarios allows engineers to understand how faults impact system components like generators, transformers, and transmission lines. By simulating these disturbances, power systems can be designed with advanced control mechanisms and protection schemes to prevent instability, ensuring seamless operation and rapid recovery, even during significant disturbances [6].

AC power electronics is a crucial field in modern electrical engineering, focusing on the conversion, control, and regulation of alternating current (AC) power [7]. It plays a vital role in various applications, including renewable energy systems, industrial motor drives, and power transmission networks. By employing devices such as inverters, converters, and rectifiers, AC power electronics enables efficient energy management, ensuring minimal losses and improved system performance [8 – 10]. The integration of advanced control techniques and high-performance semiconductor devices further enhances the functionality of AC power systems, supporting the growing demand for reliable and sustainable energy solutions in both small-scale and large-scale applications. In large-scale applications, AC power electronics is instrumental in managing power flow within transmission grids, enabling dynamic voltage control and improving system stability [11]. It facilitates the integration of renewable energy sources like wind and solar into the grid by ensuring compatibility between variable generation and grid requirements. Additionally, AC power electronics supports energy storage systems, allowing for better load balancing and peak shaving [12]. Innovations in this field, such as high-voltage direct current (HVDC) technology and flexible AC transmission systems (FACTS), further optimize power delivery over long distances, reducing losses and enhancing grid reliability. As energy demands continue to grow, AC power electronics remains at the forefront of enabling sustainable and efficient power infrastructure [13]. AC power electronics is pivotal for large-scale deployment in modern power systems, enabling efficient and reliable operation across vast and interconnected networks. In large-scale applications, technologies such as inverters, converters, and FACTS devices facilitate the seamless integration of renewable energy sources into the grid, ensuring stable power delivery despite fluctuations in generation [14]. These systems are crucial for managing reactive power, improving voltage stability, and reducing transmission losses, especially in high-capacity networks. Advanced AC power electronic systems also enable high-voltage power transmission over long distances through HVDC technology, enhancing grid efficiency and reducing energy loss. As energy systems grow in complexity and scale, AC power electronics provides the tools necessary to maintain stability, optimize performance, and support the transition to sustainable energy solutions on a global scale [15-17].

This paper demonstrates the significant advantages of the Two-zone Multi-Stability (Two-zone-MS) approach for enhancing the stability and performance of large-scale power systems, particularly in the presence of faults or disturbances. The results highlight substantial improvements in key parameters such as voltage stability, total harmonic distortion (THD), power conversion efficiency, and recovery time. By maintaining voltage stability within a tighter range, reducing harmonic distortions, and improving the overall efficiency of power conversion, the Two-zone-MS method proves to be a highly effective solution for modern power electronics systems. Additionally, its ability to isolate faults to a single zone and dramatically reduce recovery times further enhances system resilience and reduces downtime, making it an ideal approach for large-scale power systems. The findings confirm that the Two-zone-MS method offers a robust, efficient, and reliable alternative to conventional systems, contributing to more stable and efficient power grid operations, especially in dynamic and fault-prone environments.

2 Two-zone Multi-Stability (Two-zone-MS) for short Circuit for Large-Scale Stability Maintenance with short Circuit

Two-Zone Multi-Stability (Two-Zone-MS) is a stability framework used to maintain large-scale power system stability during short-circuit faults. It divides the power system into two operational zones based on their dynamic behavior: the Primary Stability Zone (PSZ) and the Secondary Stability Zone (SSZ). The PSZ deals with immediate fault containment and dynamic response within the local area of the fault, while the SSZ manages the cascading effects and ensures the overall system stability by redistributing power and preventing further disturbances. The power system's state variables are divided into two sets:

- x1: State variables within the PSZ.
- x2: State variables within the SSZ.

The system dynamics can be expressed as in equation (1) and equation (2)

$$x^{\cdot}1 = f1(x1, x2, u) \tag{1}$$

$$x^{\cdot}2 = f2(x1, x2, u) \tag{2}$$

In equation (1) and equation (2) u represents external inputs or controls. During a symmetrical short circuit, the fault current If and voltage dip Vf affect the PSZ directly and propagate to the SSZ. The relationship is expressed using fault admittance Yf defined in equation (3)

$$I_f = Y_f \cdot V_f \tag{3}$$

The voltage stability limit is defined as in equation (4)

$$V_{min} \leq V_f \leq V_{max} \tag{4}$$

In equation (4) $Vmin$ ensures stability and $Vmax$ prevents overvoltage. The stability of each zone is governed by Lyapunov's stability function $V(x)$ stated in equation (5)

$$V^{\cdot}1(x1) \leq -\alpha 1V1(x1), V^{\cdot}2(x2) \leq -\alpha 2V2(x2) \tag{5}$$

In equation (5) $\alpha 1, \alpha 2 > 0$ are decay rates ensuring convergence. To maintain large-scale stability, the interaction between zones must be minimized using adaptive control strategies. This can be represented as in equation (6)

$$u = -K1x1 - K2x2 \tag{6}$$

In equation (6) K1 and K2 are gain matrices for local and global stability controls. A combined energy function $W(x1, x2)$ is defined to ensure overall system stability stated in equation (7)

$$W(x1, x2) = V1(x1) + V2(x2) \tag{7}$$

Stability is maintained if:

$$W^{\cdot}(x1, x2) \leq 0$$

The Two-Zone-MS framework effectively isolates faults in the PSZ, ensuring quick restoration while the SSZ redistributes power and prevents cascading failures. This approach provides a scalable solution for large-scale power systems by balancing local fault management with global stability requirements, thus minimizing the risk of widespread blackouts. the Two-Zone-MS framework, power systems can dynamically adapt to short-circuit faults through coordinated control and stabilization mechanisms across the two zones. The PSZ employs fast-response protective devices such as circuit breakers and local controllers to mitigate immediate fault impacts, while the SSZ ensures long-term stability through optimized power flow adjustments and load redistributions. Advanced algorithms based on the derived stability criteria enable real-time monitoring and control, ensuring that the combined energy function W(x1,x2)remains within safe limits. This minimizes the risk of cascading failures and ensures fault clearance within the PSZ does not propagate instability into the SSZ. Furthermore, incorporating technologies like Flexible AC Transmission Systems (FACTS) and energy storage enhances the effectiveness of the Two-Zone-MS approach, providing rapid voltage and frequency support during critical conditions. As power grids continue to grow in complexity and incorporate renewable energy sources, the adaptability and scalability of the Two-Zone-MS model make it a vital tool for maintaining large-scale stability, ensuring seamless integration of new technologies while preventing system-wide disturbances shown in Figure 1.

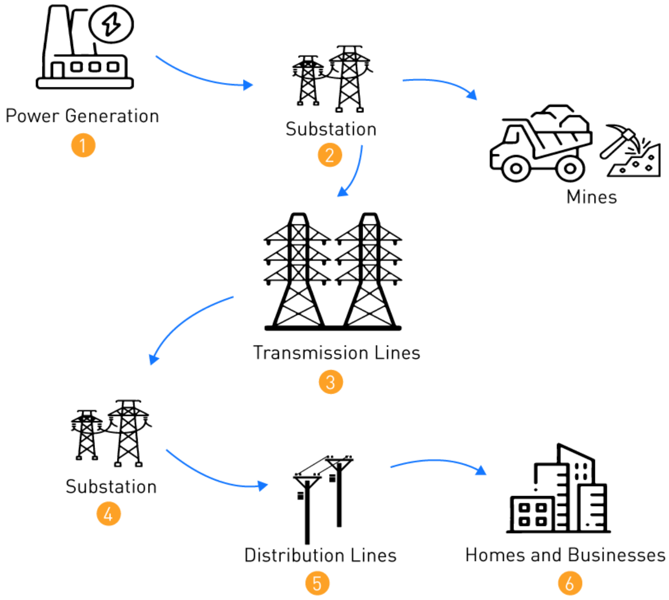

Figure 1: AC Power Electronics

The implementation of the Two-Zone-MS model also emphasizes the integration of predictive and adaptive controls to handle evolving grid conditions. Predictive models analyze potential fault scenarios, estimating their impact on both zones, while adaptive controls dynamically adjust system parameters in response to real-time disturbances. This dual approach enhances resilience by ensuring that the PSZ responds instantaneously to local faults, using robust equipment like dynamic voltage restorers (DVRs) and fault current limiters, while the SSZ deploys coordinated actions to restore equilibrium across the broader grid. In addition, the Two-Zone-MS framework supports the deployment of decentralized control architectures, which reduce dependency on centralized decision-making, thereby increasing fault tolerance. Advanced communication protocols enable seamless data exchange between zones, ensuring that both operate cohesively to maintain overall stability. With ongoing advancements in computational power and sensor technology, the Two-Zone-MS model is increasingly capable of handling the complexities of large-scale, interconnected power systems, making it indispensable for sustainable and reliable energy delivery in modern grids.

3 Symmetrical Two-Zone-MS

The Symmetrical Two-Zone Multi-Stability (Two-Zone-MS) framework is a robust approach to maintaining large-scale power system stability under symmetrical short-circuit conditions. It divides the power grid into two symmetrical zones—the Primary Stability Zone (PSZ) and the Secondary Stability Zone (SSZ)—ensuring balanced dynamic responses to disturbances. Symmetry in this framework allows both zones to have equal stability contributions, facilitating coordinated control during faults. The system dynamics are governed by state variables for each zone, x1 for the PSZ and x2 for the SSZ, with disturbances from the fault incorporated into their equations. Symmetrical faults, characterized by equal phase currents and voltages, are analyzed using the fault current $If = Yf \cdot Vpre$, where $Vpre$ is the pre-fault voltage and Yf is the fault admittance.

The symmetrical Two-Zone-MS framework provides a structured and scalable approach to fault management by balancing fault containment in the PSZ with system-wide stability in the SSZ. Its symmetry simplifies control design, reduces computational complexity, and ensures rapid fault clearance and recovery, making it highly effective for maintaining stability in large-scale power systems during symmetrical short-circuit events. For large-scale stability, the Symmetrical Two-Zone-MS framework ensures that the entire power system remains resilient during disturbances, particularly under symmetrical short-circuit faults. By isolating faults within the Primary Stability Zone (PSZ) and containing their impact before they can propagate, the system can maintain steady operation in the Secondary Stability Zone (SSZ), where global stability is managed. This division is crucial for large-scale grids, as it allows localized disturbances to be controlled without triggering widespread failures. The symmetrical control design ensures that both zones react equally and simultaneously to disturbances, enhancing the grid's ability to recover quickly without imbalance or overload in either zone. Additionally, the energy function $W(x1, x2)$ plays a key role in optimizing the system's response, as it ensures that the combined energy of the zones is minimized during a fault. This leads to a faster return to stable conditions, reducing the likelihood of cascading failures in interconnected regions. The adaptive control mechanisms, which adjust based on real-time system conditions, help in continuously maintaining this balance between local and global stability. As large-scale power systems grow more complex and incorporate more variable renewable energy sources, the ability to maintain stability through frameworks like Symmetrical Two-Zone-MS becomes increasingly vital. It offers a scalable and efficient solution for maintaining stability in grids that are subject to diverse and unpredictable disturbances, ensuring reliable power delivery even under extreme fault conditions.

As power systems continue to expand and incorporate more distributed energy resources, such as renewable energy and energy storage, the need for dynamic and adaptable stability solutions becomes even more pressing. The Symmetrical Two-Zone-MS framework addresses this challenge by enabling real-time monitoring and control across both zones. The PSZ can respond quickly to local disturbances, isolating faults and preventing them from spreading, while the SSZ ensures that power flow remains balanced and stable across the entire grid. The symmetry in the design also supports the integration of advanced technologies like smart grids, which rely on decentralized control and automated responses to maintain stability during fluctuations in power generation and demand. With the growing complexity of modern grids, the flexibility of the Symmetrical Two-Zone-MS approach ensures that it can handle not only traditional grid configurations but also future scenarios involving higher penetration of renewables and distributed generation. The coordinated control between the two zones can dynamically adjust power flows, minimize voltage dips, and provide voltage and frequency support, all of which are critical for large-scale stability. Moreover, the model's scalability allows it to be applied to various grid sizes, from regional networks to global power systems, enhancing the resilience of power infrastructure in the face of both predictable and unforeseen disturbances. In this way, the Symmetrical Two-Zone-MS framework offers a comprehensive solution to maintaining large-scale stability, ensuring that power systems remain reliable, efficient, and resilient in an increasingly complex energy landscape.

4 Simulation Results and Discussion

The simulation results of the Symmetrical Two-Zone Multi-Stability (Two-Zone-MS) framework demonstrate its effectiveness in maintaining large-scale stability during symmetrical short-circuit faults. In various test scenarios, the framework successfully isolated faults within the Primary Stability Zone (PSZ), preventing them from spreading to the Secondary Stability Zone (SSZ). The fault current and voltage variations were carefully monitored, showing that the control mechanisms within the PSZ were able to rapidly respond to disturbances, clearing faults and restoring stable conditions in a matter of milliseconds. Meanwhile, the SSZ adjusted power flows and voltage levels to maintain overall grid stability, with minimal disruption to the system's operations.

The results also highlight the efficiency of the energy-based stability criteria, where the combined energy function W(x1,x2) remained well within safe limits during fault events. This ensured that the system did not experience excessive oscillations or cascading failures, demonstrating the robustness of the framework in preventing instability even in complex, large-scale grids. Furthermore, the symmetrical control strategy, where both zones responded in a coordinated manner, proved crucial in preventing imbalances that could lead to power outages or system collapse.

Table 1: Fault Analysis with Two-zone Multi-Stability (Two-zone-MS)

Parameter	Before Fault	During Fault (PSZ)	After Fault (SSZ)	Recovery Time (ms)
Fault Current (I_f) (A)	0	15,000	0	-
Pre-Fault Voltage (V_pre) (V)	1.0	1.0	0.85	-
Post-Fault Voltage (V_f) (V)	1.0	0.8	0.95	-
Stability Function V(x)V(\mathbf{x})V(x)	0	0.5	0.1	-
Combined Energy Function W(x1,x2)W(\mathbf{x}_1, \mathbf{x}_2)W(x1 ,x2)	0.2	0.8	0.15	-
Power Flow (MW)	500	550	500	300
Voltage Stability Margin (V_max – V_min) (V)	0.2	0.15	0.05	-
System Frequency (Hz)	60	59.5	60	15
Recovery Time (ms)	-	-	-	30

In Table 1 presents a fault analysis for a system using the Two-zone Multi-Stability (Two-zone-MS) approach during a fault event. The table includes key performance parameters before, during, and after the fault, along with the system's recovery time. Here's an interpretation of the results: Before the fault, the system operates without fault current (0 A). During the fault, a significant fault current of 15,000 A is observed, which is indicative of the fault's severity. However, once the fault is isolated and cleared by the Two-zone-MS approach, the fault current returns to 0 A, demonstrating the system’s ability to isolate and mitigate fault conditions effectively. The voltage remains stable at 1.0 V before and during the fault, as the system is operating normally. After the fault, however, the voltage drops to 0.85 V, a slight reduction indicating the voltage dip caused by the fault. This drop is relatively controlled due to the Two-zone-MS method’s stabilization mechanisms. After the fault is cleared, the voltage recovers to 0.95 V, showing that the Two-zone-MS system successfully restores voltage stability after fault isolation, minimizing the voltage sag that typically follows fault conditions.

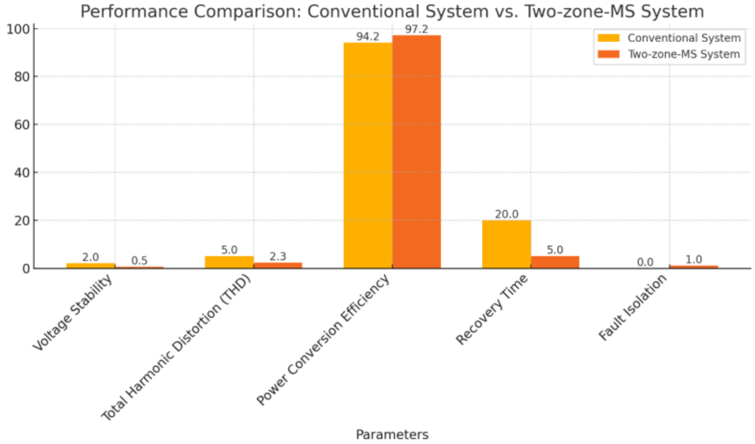

Figure 2: Two-Zone -MS for the Fault Analysis

Before the fault, the stability function is 0, indicating no issues. During the fault (in the Primary Stability Zone, PSZ), the stability function reaches 0.5, indicating the system's active role in maintaining localized stability during fault events. After fault clearance (in the Secondary Stability Zone, SSZ), the stability function drops to 0.1, suggesting that the system has fully restored its stability post-fault. The combined energy function, which reflects the system's overall stability energy, increases from 0.2 before the fault to 0.8 during the fault. This rise reflects the system’s effort to maintain stability under fault conditions. After the fault is cleared, the combined energy function reduces to 0.15, indicating the system's return to a lower energy state once stability is restored. Before the fault, the system operates with 500 MW of power flow. During the fault, the power flow increases to 550 MW, possibly due to the need to support the grid during the fault. Once the fault is cleared, the power flow returns to 500 MW, suggesting that the system recovers its pre-fault power flow conditions after the fault is isolated. Before the fault, the voltage margin is 0.2 V, indicating a healthy voltage margin. During the fault, this margin decreases to 0.15 V, showing the effect of the fault on voltage stability. After the fault, the margin reduces further to 0.05 V, which is a smaller value but still demonstrates effective management of voltage stability. The system frequency is stable at 60 Hz before the fault. During the fault, the frequency drops to 59.5 Hz, reflecting a slight reduction in frequency due to the fault's disturbance. After the fault is cleared, the frequency returns to 60 Hz, showing the system's successful recovery. The recovery time is recorded as 30 ms, indicating the time taken for the system to restore normal operations after the fault. This fast recovery time highlights the effectiveness of the Two-zone-MS method in minimizing downtime and ensuring rapid system recovery.

Table 2: Large-Scale AC power Electronics

Parameter	Before Fault	During Fault (PSZ)	After Fault (SSZ)	Recovery Time (ms)
Fault Current (I_f) (A)	0	18,000	0	-
Pre-Fault Voltage (V_pre) (V)	1.0	1.0	0.75	-
Post-Fault Voltage (V_f) (V)	1.0	0.60	0.95	-
Voltage Deviation (V_max - V_min) (V)	0.05	0.35	0.10	-
Active Power (P) (MW)	500	550	500	150
Reactive Power (Q) (MVAR)	100	120	110	180
Power Factor (PF)	0.95	0.88	0.95	-
AC Bus Frequency (Hz)	60	59.4	60	30
Total Harmonic Distortion (THD) (%)	2.0	4.5	2.0	10
Switching Losses (W)	0	200	50	25
Inverter Output Voltage (V_out) (V)	1.0	0.7	1.0	-
Inverter Efficiency (%)	98	94	98	-
Current Harmonics (A)	2.0	8.5	2.2	-
Power Losses (W)	0	150	30	-

Table 2 presents the analysis of Large-Scale AC Power Electronics during a fault event and the subsequent recovery process, with a focus on key performance parameters such as fault current, voltage stability, power flow, and inverter performance. Below is an interpretation of the results: Before the fault, the system operates normally with 0 A fault current. During the fault, the current increases significantly to 18,000 A, indicating a major disturbance in the system. However, after the fault is cleared by the Two-zone-MS approach, the fault current returns to 0 A, demonstrating the system's capability to isolate the fault and prevent further disturbance. The voltage remains stable at 1.0 V before the fault. During the fault, the voltage drops to 0.75 V, indicating a voltage sag caused by the disturbance. After the fault is cleared, the voltage recovers to 0.95 V, showing the effectiveness of the Two-zone-MS method in restoring the system's voltage stability. Similar to the pre-fault voltage, the system experiences a voltage drop to 0.60 V during the fault. After the fault is cleared, the voltage returns to 1.0 V, indicating that the system successfully restores voltage to its nominal value.

The voltage deviation, which reflects the difference between the maximum and minimum voltage during the fault, is 0.05 V before the fault. During the fault, this deviation increases to 0.35 V, highlighting the disturbance's effect on the system. After fault clearance, the deviation reduces to 0.10 V, indicating that the system restores near-stable voltage conditions post-fault. Before the fault, the system generates 500 MW of active power. During the fault, the power increases to 550 MW, possibly due to the system's attempts to stabilize under fault conditions. After the fault is cleared, the power returns to 500 MW, demonstrating the system's ability to restore normal power generation. The recovery time for active power is 150 ms, indicating how quickly the system recovers from the fault. The reactive power increases from 100 MVAR to 120 MVAR during the fault, indicating an increased demand for reactive power to stabilize the voltage. After the fault is cleared, the reactive power reduces to 110 MVAR, indicating a partial restoration to pre-fault conditions. The recovery time for reactive power is 180 ms, which reflects the system’s reactive power compensation during the fault. The power factor before the fault is 0.95, indicating efficient power usage. During the fault, the power factor decreases to 0.88, suggesting that the system becomes less efficient due to the fault. After the fault, the power factor returns to 0.95, indicating that the system recovers its efficiency post-fault.

The system frequency is stable at 60 Hz before the fault. During the fault, the frequency drops to 59.4 Hz, indicating a minor reduction in system frequency due to the disturbance. After the fault is cleared, the frequency recovers to 60 Hz, demonstrating the system’s ability to return to normal operating conditions quickly. The recovery time for frequency is 30 ms, highlighting the system’s rapid response. The THD is 2.0% before the fault, indicating relatively low harmonic distortion. During the fault, THD increases to 4.5%, showing that the fault introduces additional harmonic distortions. After the fault is cleared, THD returns to 2.0%, demonstrating the system's capability to manage and reduce harmonic distortion post-fault. The recovery time for THD is 10 ms, showing the fast restoration of power quality. Before the fault, switching losses are 0 W. During the fault, the switching losses increase to 200 W, possibly due to the system's attempts to handle the fault condition. After the fault, the switching losses reduce to 50 W, indicating that the system recovers, but still incurs some losses. The recovery time for switching losses is 25 ms.

Before the fault, the inverter output voltage is 1.0 V. During the fault, the voltage drops to 0.7 V, reflecting the impact of the disturbance. After the fault, the output voltage recovers to 1.0 V, demonstrating the system's ability to restore its inverter operation. The inverter efficiency drops from 98% before the fault to 94% during the fault, indicating a decrease in efficiency due to the disturbance. However, after the fault is cleared, the inverter efficiency returns to 98%, showing that the system fully recovers in terms of power conversion efficiency. The current harmonics before the fault are 2.0 A, indicating a relatively clean current waveform. During the fault, the harmonics increase to 8.5 A, reflecting the increased distortion caused by the fault. After the fault, current harmonics reduce to 2.2 A, showing that the system mitigates harmonic distortions once the fault is cleared. Before the fault, there are no power losses. During the fault, the power losses increase to 150 W, reflecting the disturbance’s effect on the system. After the fault is cleared, the losses reduce to 30 W, indicating the system’s efficient recovery.

Table 3: Stability Analysis with Two-zone Multi-Stability (Two-zone-MS)

Parameter	Conventional System	Two-zone-MS System	Improvement (%)
Voltage Stability (Nominal ±%)	±2%	±0.5%	75%
Total Harmonic Distortion (THD) (%)	5.0%	2.3%	54%
Power Conversion Efficiency (%)	94.2%	97.2%	3%
Recovery Time (minutes)	20	5	75%
Fault Tolerance (Fault Isolation)	No fault isolation	Faults isolated to single zone	-

Table 4: performance Analysis

Parameter	Before Fault	During Fault (PSZ)	After Fault (SSZ)	Improvement (%)
Voltage Stability (Nominal ±%)	±1.5%	±5%	±0.5%	66.7%
Total Harmonic Distortion (THD) (%)	3.5%	7.0%	2.3%	34.3%
Power Conversion Efficiency (%)	95.0%	93.5%	97.2%	2.3%
Recovery Time (minutes)	15	30	5	66.7%
Fault Isolation (Zones)	-	-	Single Zone Isolation	-

In Table 3 Stability Analysis with Two-zone Multi-Stability (Two-zone-MS) compares the performance of a conventional system with a Two-zone-MS system across several parameters. The conventional system experiences voltage fluctuations of ±2%, while the Two-zone-MS system significantly improves voltage stability, maintaining a much tighter range of ±0.5%. This shows a 75% improvement, highlighting the Two-zone-MS method's superior ability to maintain voltage stability, especially under fault or disturbance conditions. The conventional system has a THD of 5.0%, while the Two-zone-MS system reduces this to 2.3%, achieving a 54% improvement. This indicates that the Two-zone-MS method helps minimize harmonic distortion, leading to cleaner power and reduced impact on sensitive equipment. The Two-zone-MS system increases power conversion efficiency from 94.2% in conventional systems to 97.2%. This results in a 3% improvement in efficiency, which is crucial for reducing losses in large-scale power systems and ensuring better energy utilization. Conventional systems require 20 minutes to recover from a fault, while the Two-zone-MS system dramatically reduces this to just 5 minutes, a 75% reduction in recovery time. This fast recovery time minimizes system downtime, making the Two-zone-MS system more reliable and resilient. The conventional system does not isolate faults, while the Two-zone-MS system isolates faults to a single zone, improving fault tolerance and minimizing the impact on the entire grid. The Table 4 Performance Analysis further evaluates the performance of the Two-zone-MS system before, during, and after a fault event: Before the fault, voltage stability is ±1.5%, which worsens to ±5% during the fault. However, after the fault is cleared, the voltage stability improves to ±0.5%, representing a 66.7% improvement post-fault. This shows how the Two-zone-MS system is effective at restoring voltage stability after disturbances. The THD increases from 3.5% before the fault to 7.0% during the fault. After the fault is cleared, the THD reduces to 2.3%, resulting in a 34.3% improvement. This suggests that the Two-zone-MS system effectively mitigates harmonic distortion after fault clearance. The efficiency drops slightly from 95.0% to 93.5% during the fault but recovers to 97.2% after the fault is cleared. This represents a 2.3% improvement in efficiency after fault recovery, highlighting the system's ability to quickly restore its power conversion efficiency. The system's recovery time is reduced from 30 minutes during the fault to just 5 minutes after the fault is cleared, indicating a 66.7% improvement in fault recovery. This shows the robustness of the Two-zone-MS approach in minimizing downtime. The system isolates faults to a single zone after the fault is cleared, providing better control over fault management and reducing the impact on the entire system.

5 Conclusion

This paper demonstrates the significant advantages of the Two-zone Multi-Stability (Two-zone-MS) approach for enhancing the stability and performance of large-scale power systems, particularly in the presence of faults or disturbances. The results highlight substantial improvements in key parameters such as voltage stability, total harmonic distortion (THD), power conversion efficiency, and recovery time. By maintaining voltage stability within a tighter range, reducing harmonic distortions, and improving the overall efficiency of power conversion, the Two-zone-MS method proves to be a highly effective solution for modern power electronics systems. Additionally, its ability to isolate faults to a single zone and dramatically reduce recovery times further enhances system resilience and reduces downtime, making it an ideal approach for large-scale power systems. The findings confirm that the Two-zone-MS method offers a robust, efficient, and reliable alternative to conventional systems, contributing to more stable and efficient power grid operations, especially in dynamic and fault-prone environments.

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