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AUTOMATIC PREVENTION OF TRANSIENT STABILITY VIOLATION BASED ON THE RESULTS OF THE STABILITY MARGIN MONITORING SYSTEM CALCULATIONS

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Abstract. The growing share of renewable energy sources (RES) and the decommissioning of synchronous generators significantly reduce power system inertia, making transient stability a critical challenge for modern power grids. Traditional emergency automation with fixed threshold settings is no longer effective under these conditions. This study argues for a shift from static to adaptive control methods using real-time monitoring. The proposed approach relies on a Stability Margin Monitoring System (SMMS), which calculates critical voltage angles between nodes using WAMS and SCADA data. This enables dynamic adjustment of emergency control parameters based on the actual grid state and inertia level. The approach is demonstrated on transient simulations of the Mangystau power system in Kazakhstan. The results show that reduced inertia leads to loss of synchronism, but adaptive control with targeted load shedding (e.g., 300 MW) restores stability, whereas smaller volumes are insufficient. This highlights the importance of accurately selecting control actions. The method helps avoid excessive disconnections and increases the reliability and efficiency of low-inertia systems. Despite risks such as telemetry failures, adaptive control offers a modern tool for preventing cascading outages in grids with high-RES penetration.

Keywords: steady-state stability, transient stability, stability margin monitoring system, emergency automation, inertia constant, inverter-based resources.

Introduction and background

Maintaining stable parallel operation of power systems has been a key issue since the emergence of large interconnected grids. Loss of stability leads to loss of synchronism between generators, causing asynchronous operation with differing rotor speeds. This is one of the most dangerous modes because it produces severe voltage fluctuations [1], potentially disconnecting auxiliary systems of thermal and nuclear plants [2]. To prevent such events, emergency control schemes were developed—load shedding, generator tripping, excitation boosting, and reactive power control [3]. These actions are triggered by predefined events or parameter thresholds, calculated in advance for worst-case operating conditions.

However, with growing penetration of inertia-less RES and the shutdown of synchronous thermal units, transient stability becomes more problematic [4,5]. Even if RES support voltage and reactive power, reduced inertia weakens the link between steady-state and transient stability. From the rotor motion equation, the rate of rotor angle change is inversely proportional to inertia; thus lower inertia increases the chance of reaching critical angles and losing synchronism.

Advances in digital technologies—SCADA and WAMS—now provide wide-area real-time visibility of grid parameters. This enables centralized stability calculations through systems such as the Stability Margin Monitoring System (SMMS). Its concepts and operation principles are detailed in [6–9]. SMMS allows adaptive emergency settings rather than fixed thresholds.

This paper continues previous studies of the Mangystau power system [4,5] by introducing an adaptive emergency control method not previously used in Kazakhstan.

The main contributions are:

1. addressing transient stability challenges caused by high RES penetration;
2. proposing adaptive emergency control using WAMS and real-time stability calculations instead of fixed thresholds;
3. demonstrating the effectiveness of this approach through simulations;
4. reducing unnecessary load shedding inherent to fixed-parameter schemes.

Section 2 explains the transient simulation methodology, scenarios, inertia reduction, emergency control implementation, and PowerWorld Simulator 23 settings. Section 3 presents and discusses the results using angular characteristics. Section 4 concludes the paper.

Methodology

For analysis purposes this paper refers to the computational model of the Mangystau power system developed in [4]. The initial parameters of the power system mode is as follows (Figure 1).

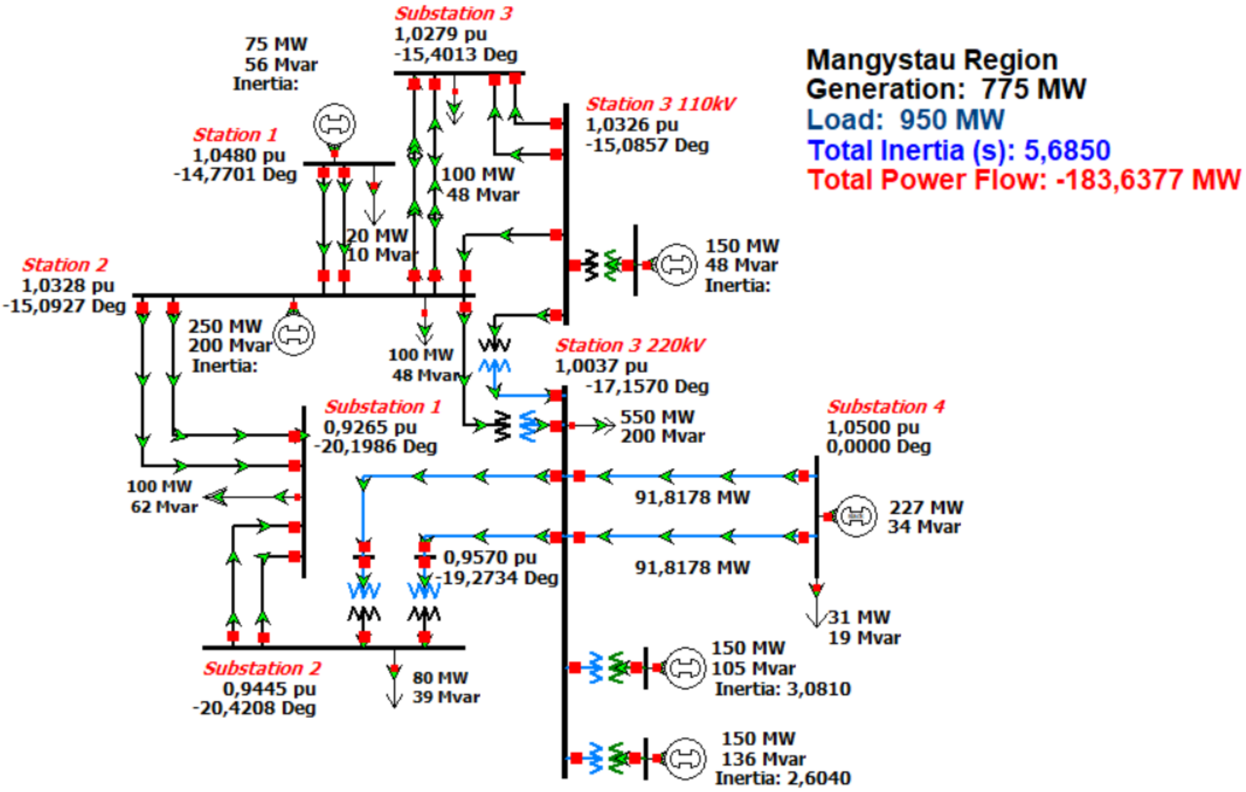


Figure 1. Initial operation mode of Mangystau power system

The emergency mode of operation of this circuit is the emergency shutdown of one of the 220 kV interconnect lines. After disconnection, the circuit weakens, and all the power flowing through the disconnected line is transferred to a parallel undamaged line. According to the Newton-Raphson method the solution of regime in the post-accident regime has convergence, so we can assume that the steady-state stability is preserved. However, due to the weakening of the circuit and the decrease in the angular characteristic, the voltage angle δ increases from 17.157 to 40.08 degrees. The electrical parameters in the post-emergency mode are shown on Figure 2.

Thus, using expression $\delta_{crit} = 180 - \delta_{post\text{-}emergency}$, it is possible to calculate the critical stress angle according to the criterion of transient stability (140 degrees). Therefore, this angle parameter can be integrated into an emergency automation system that implements a control action using a special load shedding automation (SLSA).

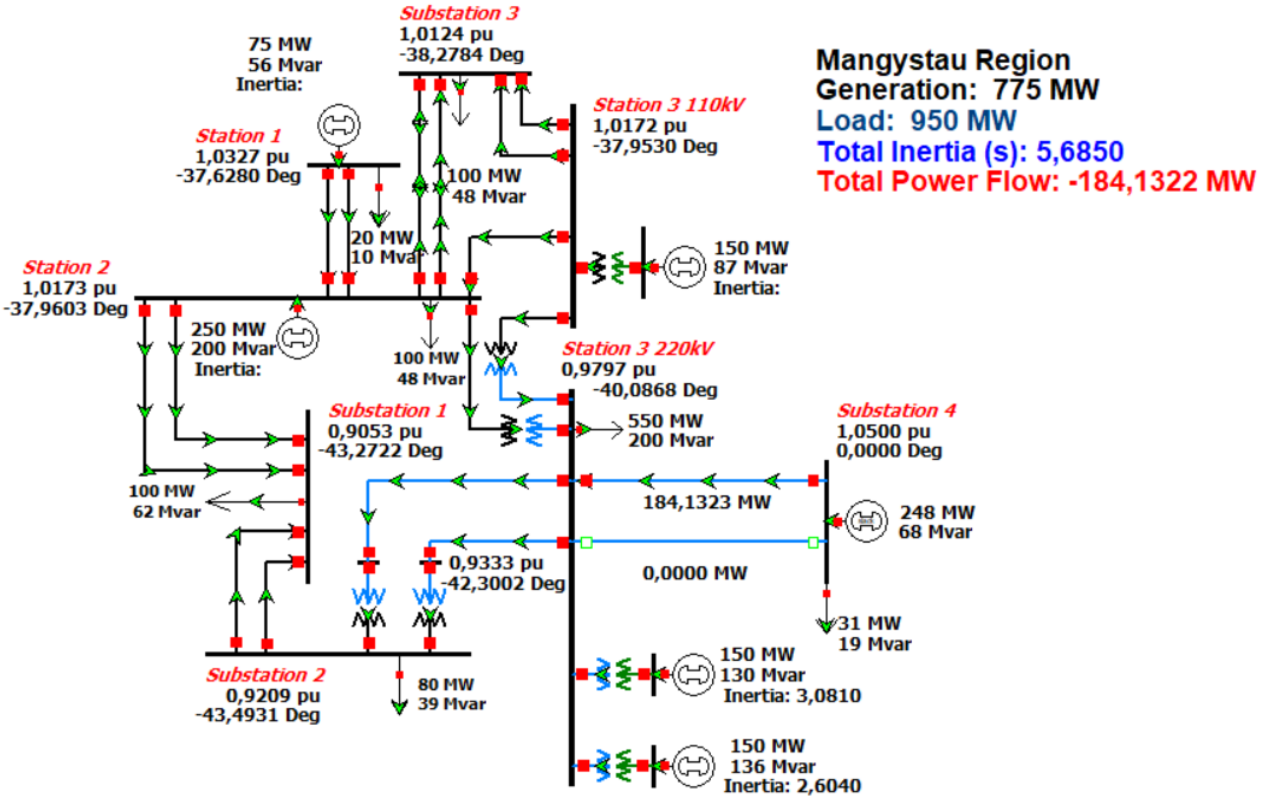


Figure 2. Post-emergency mode after disconnection of one of the 220 kV interconnect lines

Control actions are formed using an emergency automation system that includes automatic dosing of control actions. The registration of the fact of disconnection of the 220 kV line and the value of the voltage angle δ are accepted as the starting element. If, during an emergency shutdown of the 220 kV line, the value of the voltage angle δ exceeds the critical value calculated by the SMMS, the load from the SLSA is disconnected by an amount sufficient to maintain stability. In this paper, the load shutdown values of 250 and 300 MW are considered.

Results and discussion

Figure 5 shows the characteristics of changing the voltage angle with an inertia constant of 5.68 s under conditions of impaired transient stability, as well as during the implementation of emergency automation measures that turn off the 250 and 300 MW loads by 1.62 s. The plots show that turning off the 250 MW load was insufficient to compensate for the excess kinetic energy accumulated in the generator rotors in short-circuit mode short circuits. As a result, the voltage angle continues to increase, reaching 180°, which indicates that the system is switching to asynchronous mode. Switching off the 300 MW load, on the contrary, provides the necessary energy balance: the braking area of the generator in the transient process exceeds the area of its acceleration. This allows you to maintain the transient stability of the system, while the voltage angle stabilizes and smoothly transitions to a new stable state.

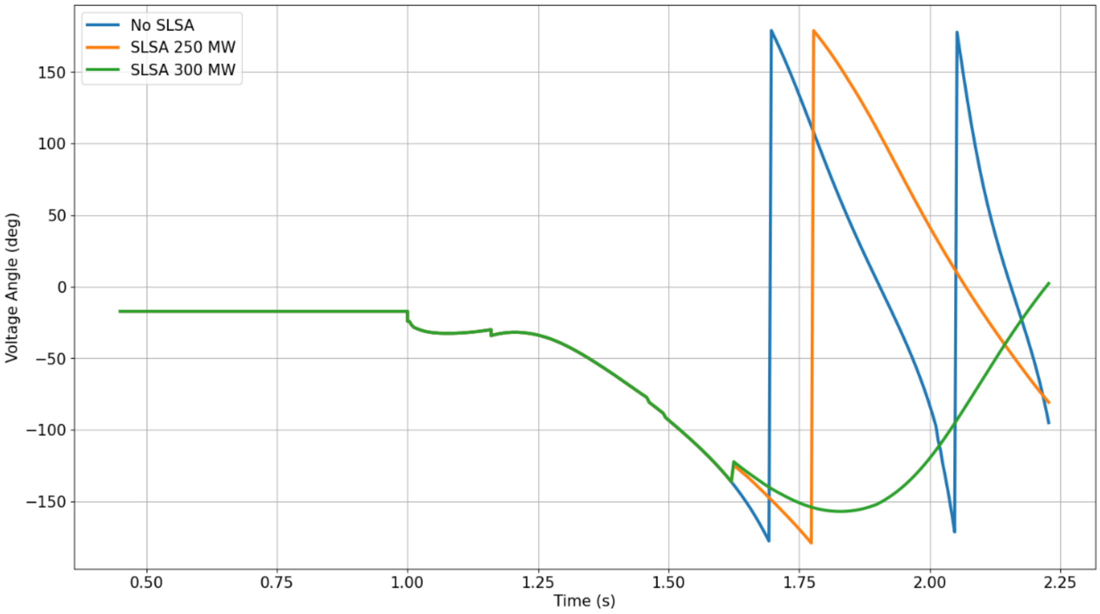
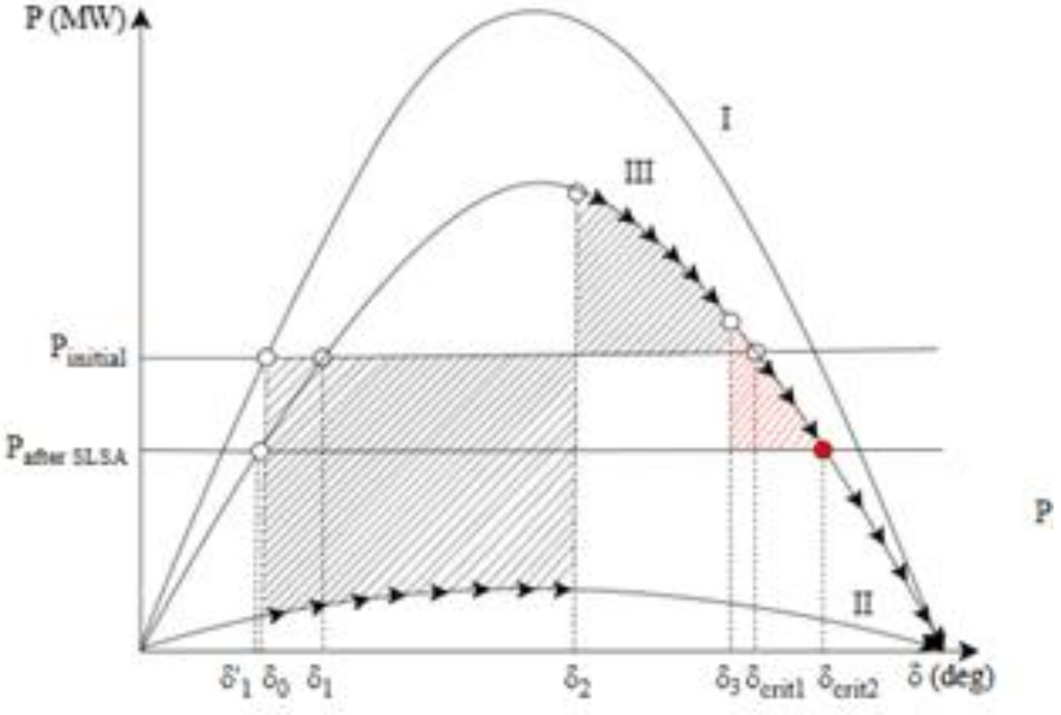
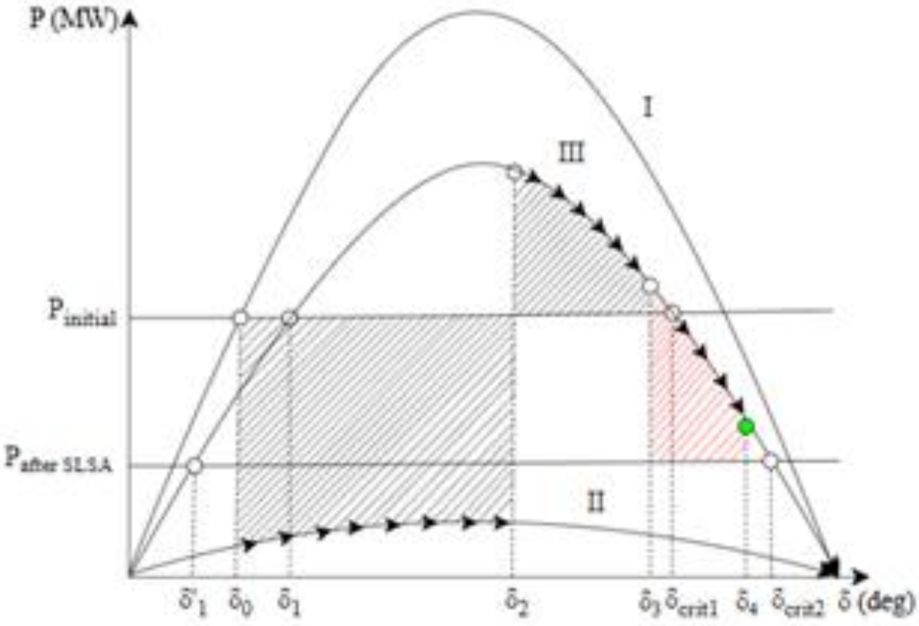


Figure 5. Voltage angle fluctuations with and without control actions

The simulation results are demonstrated in the angular characteristics of the power transmission network shown on Figure 7.



(a) Inertia 5.68 s. SLSA amount 250 MW.
Transient stability is violated



(b)Inertia 5.68 s. SLSA amount 300 MW.
Transient stability is maintained

Figure 7. Angular characteristics (P vs. δ) for aggregated interconnect lines for 2 scenarios

Figure (a) applies a control exposure that disconnects a fixed amount of load via special load shedding automation with 250 MW value. The essence of this example is the insufficient volume of SLSA and the inevitable occurrence of asynchronous mode. When using SLSA, the straight line $P_{initial}$ decreases to $P_{after\ SLSA}$, thereby increasing the critical value of the angle according to the criterion of transient stability. The key point is that the SLSA is applied as δ_3 approaches the first critical angle value. However, the stored kinetic energy of acceleration of the generators is so high that the volume of SLSA load shedding is not sufficient and the angle δ_3 still exceeds the new value δ_{crit2}.

Figure 7 (b) illustrates the application of 300 MW load shedding from the emergency automatics. In this case, the transient process up to the angle δ_3 is identical to the previous variants with instability. However, at the moment δ_3, a large load is disconnected, and thus $P_{after\ SLSA}$ drops much lower, thereby increasing the critical value of the transient stability angle. The angle increases to the value δ_4, which does not reach the critical value, and, after several periods of oscillations, returns to the steady state. The area limited by δ_3, δ_4, angular characteristic III and $P_{after\ SLSA}$ is an additional decelerating area of synchronous generators, which is superimposed on the previous decelerating area limited by δ_2, δ_3, angular characteristic III and $P_{initial}$, and their sum begins to exceed the acceleration area of the generators during a short circuit.

According to the scenario in Figure 7 (b) shows the possibility of using SMMS to identify critical angles for transient stability, taking into account all the regime-balance conditions, the composition of the generators and their inertia, and applying the results of these calculations in the triggering organs of emergency automation, which allows the power system to maintain stability and avoid cascade shutdowns and blackouts.

Conclusion

With the rapid growth of inertia-less renewable energy sources, maintaining transient stability in power systems has become increasingly critical. This study emphasizes the need for new emergency control methods, as traditional schemes with fixed thresholds no longer ensure adequate reliability under reduced system inertia.

The research introduces an adaptive emergency control algorithm based on real-time SMMS data. By determining critical voltage angles during post-fault conditions, the proposed method enables fast, situation-dependent adjustment of control actions that reflect the current system state and inertia level.

The practical value of the approach is demonstrated through transient simulations of the Mangystau power grid. The adaptive scheme—metered load shedding of 300 MW triggered by critical-angle detection—successfully restores stability and prevents asynchronous operation. A smaller shedding volume (250 MW) proved insufficient, emphasizing the need for precise tuning based on dynamic monitoring.

The concept, however, also presents several risks that must be addressed:

1. SCADA or WAMS malfunctions may cause incorrect SMMS calculations and improper actions.
2. Determining the correct magnitude of control actions is challenging and depends on operating conditions.
3. Automatic reclosers may either enhance or worsen stability if the fault is not fully cleared.
4. Excessive load shedding can cause power flow reversal, potentially compromising steady-state stability; in such cases, generation tripping may also be required.

Overall, the proposed method reduces the likelihood of unnecessary load disconnection and enhances the efficiency and reliability of modern power systems. Integrating real-time monitoring, stability-margin assessment, and adaptive emergency control provides a robust and practical framework for maintaining transient stability in grids with high renewable penetration and for preventing cascading failures.

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АВТОМАТИЧЕСКОЕ ПРЕДОТВРАЩЕНИЕ НАРУШЕНИЯ ПЕРЕХОДНОЙ УСТОЙЧИВОСТИ НА ОСНОВЕ РЕЗУЛЬТАТОВ РАСЧЕТОВ СИСТЕМЫ КОНТРОЛЯ ЗАПАСА УСТОЙЧИВОСТИ

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Аннотация. Растущая доля возобновляемых источников энергии (ВИЭ) и вывод из эксплуатации синхронных генераторов значительно снижают инерционность энергосистемы, что делает обеспечение устойчивости в переходных процессах критически важной задачей для современных энергосистем. Традиционная противоаварийная автоматика с фиксированными пороговыми значениями в этих условиях уже неэффективна. В данном исследовании обосновывается необходимость перехода от статических к адаптивным методам управления с использованием мониторинга в реальном времени. Предлагаемый подход основан на системе мониторинга запаса устойчивости (SMMS), которая рассчитывает критические углы напряжения между узлами, используя данные WAMS и SCADA. Это позволяет динамически корректировать параметры аварийного управления в зависимости от фактического состояния сети и уровня инерционности. Данный подход продемонстрирован на примере моделирования переходных процессов в Мангистауской энергосистеме (Казахстан). Результаты показывают, что снижение инерционности приводит к потере синхронизма, но адаптивное управление с целенаправленным сбросом нагрузки (например, 300 МВт) восстанавливает устойчивость, в то время как меньшие объемы оказываются недостаточными. Это подчеркивает важность точного выбора управляющих воздействий. Метод позволяет избежать чрезмерных отключений и повышает надежность и эффективность малоинерционных систем. Несмотря на такие риски, как сбои телеметрии, адаптивное управление предлагает современный инструмент для предотвращения каскадных отключений в сетях с высоким уровнем проникновения ВИЭ.

Ключевые слова: стационарная устойчивость, переходная устойчивость, система контроля запаса устойчивости, противоаварийная автоматика, постоянная инерции, инверторные ресурсы.

ТҰРАҚТЫЛЫҚ ЖАҒДАЙЫН БАҚЫЛАУ ЖҮЙЕСІНІҢ ЕСЕПТІЛЕРІНІҢ НӘТИЖЕЛЕРІ НЕГІЗІНДЕ ӨТПЕЛІ ТҰРАҚТЫЛЫҚ БҰЗУЫНЫҢ АВТОМАТТЫ АЛДЫН АЛУ

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Андатпа: Жаңартылатын энергия көздерінің (ЖЭК) өсіп келе жатқан үлесі және синхронды генераторларды пайдаланудан шығару электр жүйесінің инерциясын айтарлықтай төмендетеді, бұл өтпелі тұрақтылықты қазіргі заманғы электр желілері үшін маңызды міндетке айналдырады. Бекітілген шекті параметрлері бар дәстүрлі апаттық автоматтандыру бұл жағдайларда енді тиімді емес. Бұл зерттеу нақты уақыт режиміндегі бақылауды пайдалана отырып, статикалық басқару әдістерінен адаптивті басқару әдістеріне ауысуды дәлелдейді. Ұсынылған тәсіл WAMS және SCADA деректерін пайдаланып түйіндер арасындағы кернеудің сыни бұрыштарын есептейтін Тұрақтылық маржасын бақылау жүйесіне (SMMS) негізделген. Бұл нақты тор күйі мен инерция деңгейіне негізделген төтенше жағдайды басқару параметрлерін динамикалық реттеуге мүмкіндік береді. Тәсіл Қазақстандағы Маңғыстау энергетикалық жүйесінің өтпелі модельдеуінде көрсетілген. Нәтижелер азайған инерция синхронизмнің жоғалуына әкелетінін көрсетеді, бірақ мақсатты жүктемені азайту арқылы адаптивті басқару (мысалы, 300 МВт) тұрақтылықты қалпына келтіреді, ал кішірек көлемдер жеткіліксіз. Бұл бақылау әрекеттерін дәл таңдаудың маңыздылығын көрсетеді. Әдіс шамадан тыс ажыратуларды болдырмауға көмектеседі және төмен инерциялық жүйелердің сенімділігі мен тиімділігін арттырады. Телеметриялық ақаулар сияқты тәуекелдерге қарамастан, адаптивті басқару ЖЭК енуі жоғары желілерде каскадты үзілістердің алдын алудың заманауи құралын ұсынады.

Түйін сөздер: тұрақты күйдегі тұрақтылық, өтпелі тұрақтылық, тұрақтылық маржасын бақылау жүйесі, апаттық автоматика, инерция тұрақтысы, инвертор негізіндегі ресурстар.