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Enhancing resilience of low-inertia power systems through a novel load shedding method with synchronous condenser power control

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Abstract
This study explores the challenges posed by the transition to large-scale deployment of renewable energy sources, which lead to a significant reduction in the inertia of power systems. It focuses on enhancing resilience and frequency stability in response to sudden disturbances, such as generator failures or transmission line disconnections. The paper critically evaluates the limitations of conventional under-frequency load shedding (UFLS) methods and advances a novel Rapid Load Shedding (RLS) approach. The RLS method harnesses the active power response of synchronous condensers (SCs) to enable faster load shedding, thereby improving system stability and addressing operational constraints from a reliability perspective. The study demonstrates the feasibility of implementing new control systems using the proposed structure of a special protection scheme. It also examines the economic benefits of enhancing the allowable transfer capacity in the Baltic Power System (BPS) through this method. The findings highlight how the RLS approach can enable higher transfer capacities whilst maintaining system resilience. Additionally, the results indicate that the RLS method can significantly mitigate frequency deviations and enhance system stability, offering a promising solution for low-inertia power systems with high levels of renewable energy integration.

Keywords Power system inertia · Resilience assessment · Load shedding · Frequency stability · Synchronous condensers · Feasibility study

Abbreviations

BPS	Baltic power system
CHPP	Combined heat and power plant
DFT	Discrete Fourier transform
HP	Hydropower plant
PMU	Phasor measurement units
PS	Power systems
PSHP	Pumped storage hydropower plant
RES	Renewable energy sources
RLS	Rapid load shedding
RoCoF	Rates of change of frequency
SC	Synchronous condenser
SCCT	Synchronous condenser control terminal
SPP	Solar power plant
SPS	Special protection scheme
UFLS	Under-frequency load shedding
UPS	Unified power system of Russia
WAMS	Wide area measurement system
WPP	Wind power plant

1 Introduction

1.1 Energy transition challenges: reduction in power system inertia

The European Union's 2030 Climate & Energy Framework and its 2050 targets for climate neutrality outline a transformative shift towards renewable energy sources (RES), improved efficiency, and smart, flexible grids (EC 2014), (EC 2021). Whilst essential for decarbonization, this transition challenges power system (PS) stability by replacing conventional synchronous generators with non-synchronous RES, which provide little or no rotational inertia. (Prabhakar et al. 2022), (ERCOT 2018). This shift reduces system inertia and complicates frequency regulation, increasing the rate of change of frequency (RoCoF) and the risk of blackouts due to weakened frequency and angular stability (Castillo 2014), (Zalostiba 2013), (Hatziargyriou et al.

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2021). Ensuring energy security and operational resilience in this new paradigm requires innovations in system design and regulation (Johnson et al. 2020), (Ratnam et al. 2020).

1.2 Challenges of low-inertia systems

Low inertia complicates the PS management during unforeseen but inevitable events, such as short circuits, faults, or damage to transmission lines or generators. According to the widely used N-1 security criterion, operators must ensure the functionality of the power system even during the sudden failure or disconnection of any critical component (Zbunjak et al. 2015). Transient processes triggered by such events can cause significant deviations from nominal system parameters, potentially leading to further faults and equipment damage. In the low-inertia systems, the transient processes occur more rapidly, making it increasingly difficult for automated systems to operate effectively. The swing equation illustrates the relationship between system inertia and frequency dynamics (Kundur et al. 1994), (Machowski et al. 2012):

$$\frac{d\omega}{dt} = \Delta P(t)\frac{\omega_{syn}}{2H_{tot}}, \tag{1}$$

where ΔP is the difference between mechanical input power and electrical output power (per unit), ω_{syn} is the synchronous (angular) speed (radians/seconds), H_{tot} is the total system inertia (seconds).

Equation (1) demonstrates that lower system inertia leads to higher rates of change and faster frequency drops for the same power imbalance, weakening power system resilience. To diminish the risk of severe disturbances the following strategies can be employed:

- **Increasing system inertia** (H_{tot}): incorporating additional synchronous machines, such as synchronous condensers (Luo et al. 2021), (Soleimani et al. 2024), (Hadavi et al. 2021); introducing synthetic inertia from advanced inverter-based technologies; or connecting independent power systems through transmission lines (Nguyen et al. 2019), (Roux et al. 2022);
- **Reducing power imbalance** (ΔP): limiting power output from sources in operation, however, this may reduce economic efficiency (Ali et al. 2006), (Ratnam et al. 2020).
- **Rapidly addressing imbalances**: employing advanced automation and measurement tools to detect disruptions and quantify imbalances; deploying corrective actions like adjusting generator output or load to quickly restore power balance (Ørum et al. 2015), (Guzs et al. 2022).

Under-frequency load shedding is commonly used to stop frequency drop; however, additional measures should be taken since the load shedding setting thresholds are reached more quickly in the case of low-inertia system. The reduction in system inertia due to large-scale RES integration underscores the need for innovative solutions to enhance resilience and security. Amongst the mentioned, synchronous condenser (SC) technology has shown significant potential for enhancing system inertia (Roux et al. 2022), (Zhou et al. 2019) and improving frequency control during generation loss events (Guzs et al. 2022).

1.3 Under-frequency load shedding

Unexpected power deficiencies decelerate synchronously rotating machines. To prevent a frequency drop, the balance must be restored. When frequency reserves are insufficient, under-frequency load shedding (UFLS) is typically activated. Conventional multi-step UFLS gradually disconnects load only after frequency thresholds are crossed. Lower inertia levels lead to faster frequency drop for the same power imbalance, potentially undermining the effectiveness of traditional UFLS and compromising system resilience. The introduction of faster UFLS triggering would therefore be beneficial, especially for medium and small size PSs.

To improve UFLS, various semi-adaptive and adaptive schemes have been proposed. Some use fixed frequency and RoCoF thresholds (Delfino et al. 2001) and (Ben Kilani et al. 2017), whilst others use a dynamic combination of frequency and RoCoF as a triggering method (Rudež and Mihalič, 2011), (Ben Kilani et al. 2017), and (Rudež and Mihalič, 2017). More advanced methods estimate inertia or total power imbalance to refine shedding triggers (Zare et al. 2019), with some also factoring in bus voltage (Jianjun et al. 2018). Despite methodological differences, all rely on frequency-based measurements in one way or another.

Whilst adaptive UFLS schemes offer significant advantages over traditional ones, their application as system-wide protection is limited. This is due to the complexity of real power systems and the challenges of ensuring fast and accurate measurements of frequency and RoCoF, as well as the availability of frequency and inertia data for various generators (Rudež and Mihalič, 2017). Consequently, a predictive approach to UFLS, as described, e.g., by (Rudež and Mihalič, 2017), could represent the next step in the development of UFLS.

To address the identified challenges, (Sauhats et al. 2021) proposed a novel Rapid Load Shedding (RLS) method that leverages the response of synchronous condensers to sudden power imbalances, aiming to enhance power system stability. The SC power response to frequency changes can be described as follows (derived from the swing Eq. (1)):

$$\Delta P_{sc}(t) = \frac{2H_{tot}}{\omega_{syn}} \bullet \frac{\mathrm{d}\omega_{sc}}{\mathrm{dt}}, \quad (2)$$

This method utilises the measurement of active power injections from the SCs into the grid ΔP_{sc} as an indicator of power system imbalance magnitude and serves as a trigger for UFLS and Special Protection Scheme (SPS) activations. The proposed approach seeks to improve the capacity of critical power system components, such as large generators and major transmission lines, which are often constrained by stability or resilience requirements under the N-1 criterion. The focus is particularly on addressing the challenges associated with low-inertia systems characterized by a high penetration of renewable energy sources. The method shows particular promise in systems, whether large or small, where synchronous condensers serve as the dominant source of inertia. The results of simulations and testing, as outlined in (Sauhats et al. 2021), and (Sauhats et al. 2023b), demonstrate that this RLS approach significantly improves post-contingency frequency response and enhances the overall resilience of small power systems connected to larger grids via DC and AC lines. These studies underscore the method's potential to mitigate frequency nadirs or increase the allowable generator capacity in island mode operations, a scenario that arises when the AC connection line is disconnected — a relatively rare but plausible event. However, the impact of this approach on the operational dynamics of AC power lines that maintain reserve capacity remains unexamined. Additionally, the economic viability of deploying the specialized measurement devices required by this method, as well as their integration into existing infrastructure, has yet to be assessed. This article seeks to address these gaps by exploring the broader implications for control strategies and evaluating the practical and economic feasibility of implementing the RLS approach.

1.4 The main contributions

The main contributions of this study are as follows:

1. Enhanced Transmission Capacity: The study identifies opportunities to increase the maximum allowable capacity of interconnection transmission power lines. This is achieved through advanced protection schemes that:

- Swiftly respond to large disturbances.
- Disconnect loads insensitive to short power outages.
- Seamlessly integrate reserve generators.Collectively, these measures significantly enhance the system's economic efficiency and stability.

2. Feasibility of Rapid Power Measurements: The research establishes the practicality of rapid active power measurements, enabled by specially developed and rigorously tested digital measurement units. These units are characterized by their simplicity, cost-effectiveness, and strong potential for widespread adoption across diverse power systems.
3. Improved Transfer Capacity Utilization: By leveraging real-world data and insights from the Nord Pool electricity market, the study demonstrates significant improvements in transfer capacity utilization. The approach's economic viability and effectiveness are illustrated through a case study of the Baltic power system, particularly after its synchronization with the Central Europe grid.
4. Extension and Validation of a Load Shedding Method: This paper extends our previously proposed load shedding method (Sauhats et al. 2021) by applying and validating it in a significantly more complex, realistic, and operationally relevant scenario. Unlike the earlier case study of an islanded power system, the current work focuses on an interconnected, high-renewable grid. This extension demonstrates the method's robustness, scalability, and adaptability under practical system constraints.

1.5 Structure of the paper

The remainder of this paper is structured as follows: Sect. 2 outlines the fundamentals of the proposed control and measurement method, providing a detailed explanation of its operational mode. Section 3 presents case studies to demonstrate the economic viability of the proposed strategy. Finally, Sect. 4 concludes the paper with a summary of key findings and insights.

2 Methodological approach

2.1 The principle and structure of the RLS and SC control scheme

Let us consider an unexpected large generator outage in a power system comprising the following components: synchronous generators, synchronous condensers, renewable energy sources, loads powered by electric motors, and high-voltage grid tie lines. A generator outage in such a system results in a transition to a new state. Specifically, the rotation frequency of synchronous machines changes. In the process of decelerating rotating masses, the kinetic energy accumulated in them is converted into electric energy and injected into the power grid (Kundur et al. 1994). Within a few seconds delay after disturbance, the generator's governors respond to the frequency decline, attempting to restore the system to its nominal frequency (by activating primary frequency control). Simultaneously, the drop in frequency leads to a reduction in power consumption for frequency-dependent loads. However, during the initial phase of the transient process, the system dynamics are predominantly influenced by the loss of active power of the disconnected generator and the system's inertia. At this early stage, the effects of primary frequency control and load power reduction can be neglected. Consequently, we can assert that the volume of the disconnected power ΔP at the very beginning of the process prior to primary frequency control is compensated by the injection of the active power by each element of the power system possessing inertia (Sauhats et al. 2021):

$$\Delta P = \sum_{a=1}^{S} \Delta P_{SC\_a} + \sum_{b=1}^{G} \Delta P_{G\_b} + \sum_{c=1}^{L} \Delta P_{L\_c}, \qquad (3)$$

where ΔP_{SC_a}, ΔP_{G_b}, ΔP_{L_c} are the active power injections of every synchronous condenser, synchronous generator and frequency-dependent load (for example, electric motors) present in the PS; *S, G, L* are the total numbers of these condensers, generators and frequency-dependent loads. To stop the frequency change, it is sufficient to restore the balance between generation and consumption, e.g., by disconnecting a load equal to ΔP. Whilst the load volume could theoretically be estimated by measuring all ΔP values included in (3), this approach is complex and impractical in real power systems due to the vast number of components. However, in power systems where inertia is predominantly contributed by a small number of inertial sources, the problem can be simplified by expressing (3) as:

$$\Delta P = \left(1 + \frac{\sum_{b=1}^{G} \Delta P_{G\_b} + \sum_{c=1}^{L} \Delta P_{L\_c}}{\sum_{a=1}^{S} \Delta P_{SC\_a}}\right) \sum_{a=1}^{S} \Delta P_{SC\_a} = K_r \bullet \sum_{a=1}^{S} \Delta P_{SC\_a} \qquad (4)$$

In practice, the coefficient K_r is not constant; its value is always greater than 1 and varies depending on the operating mode, PS topology and the total system inertia. However, it can be asserted that the measured SC active power injections can serve as a reliable basis for load shedding aimed at frequency stabilization, particularly when synchronous condensers are the primary source of inertia.

In such a power system, the initial power change (ΔP_{SC_a}) across all SCs approximately equals the amount of lost generation. When SCs provide most of the system's rotational inertia, their aggregated active power injection can serve as a robust basis for initiating load shedding to stabilize frequency. This situation typically occurs in low-inertia power systems – for example, those with very high penetration of inverter-based and few conventional synchronous generators online (Roux et al. 2022), (Wang et al. 2023). Under such conditions (often seen in isolated networks or grids that have decommissioned many thermal plants), system operators install synchronous condensers specifically to supply inertia and maintain system strength. Thus, the SCs become the primary source of stored kinetic energy (inertia) in the grid. Following a sudden loss of generation in this kind of system, the kinetic energy from the SC rotors is immediately released as active power – an inertial response – to counter the power deficit. In fact, this initial surge of power from the SCs will approximately equal the lost generation because the condensers are virtually the only elements contributing significant inertia. This close correspondence means that by monitoring, one can effectively estimate the size of a generation loss disturbance in real time. As a result, using the measured SC power injection as a trigger for UFLS is well justified: shedding at least an equivalent amount of load (scaled by $K_r > 1$ to provide a margin) will counterbalance the loss and help arrest the frequency decline.

Thus, by measuring the real power injection of the SCs, it is possible to estimate the approximate amount of load to shed promptly, not waiting for standard UFLS operation. This forms the core principle of the proposed RLS: monitoring of the SC active power injections provides real-time information about instantaneous generation loss and expected frequency drop, enabling RLS activation within 100–200 ms from the moment of the contingency without relying on frequency or RoCoF measurements. This faster response substantially reduces the frequency fall and the value of the frequency nadir, lowering the risk of frequency limit violations.

The typical power injection waveform of a synchronous condenser, in response to a generation loss event in a power system with traditional UFLS, was modelled using power system transient stability programme ETAP and is shown in Fig. 1. Up to the 0.5-s mark, the system remained balanced, and the real power on the synchronous condensers was 0 MW. Then, at 0.5 s, a generator disconnection occurred. All elements with inertia absorbed the power surge, with 250 MW being taken on by the SCs. As the transition processes unfolded, the frequency-dependent element behaviour caused the power deficit to redistribute, leading the SCs to take on additional power. Subsequently, generator regulators operated, and standard UFLS was activated. It can be observed that after the three stages of UFLS operation, the curve passed through 0, indicating a near-balanced state. However, due to overcompensation, an additional stage was triggered, and the process stabilized at—200 MW. If the load

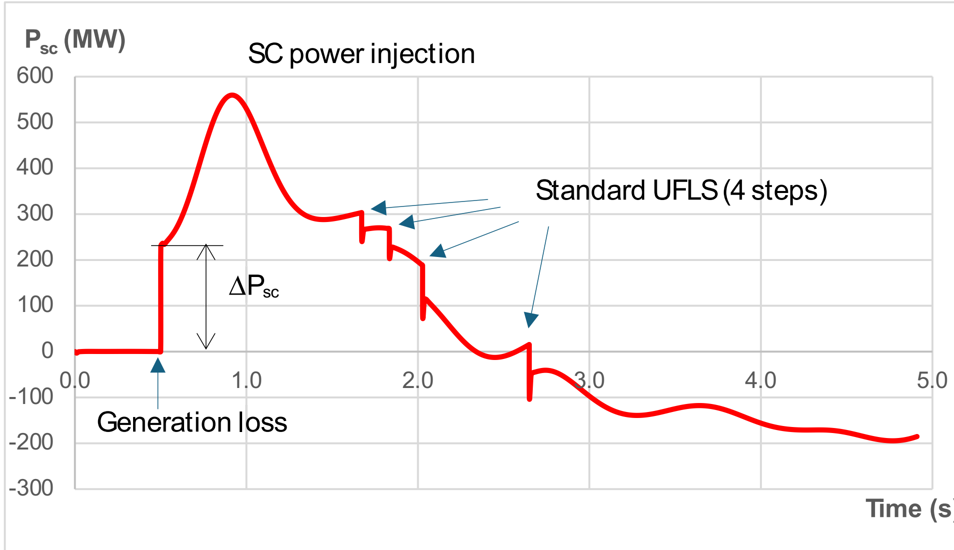


Fig. 1 SCs' real power injection after loss of a generation event

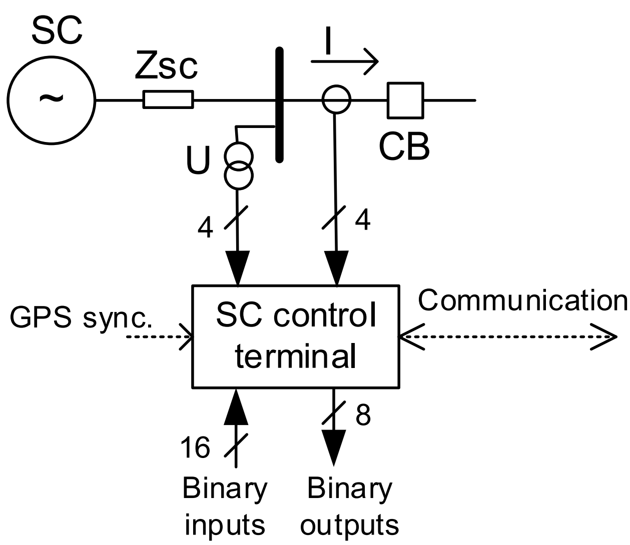


Fig. 2 SC control terminal connection

had been shed immediately, the process would have stabilized faster, and traditional UFLS operation would not have been necessary (more details can be found in (Guzs 2023)).

Implementing this concept requires the use of a Wide Area Measurement System (WAMS) and/or dedicated measurement units or terminals. To control the SCs' power injection, (Sauhats et al. 2023b) proposed using a dedicated SC control terminal (SCCT). The SCCT measures SC currents and voltages and estimates the real power of the SCs (Fig. 2, (Sauhats et al. 2023b)).

Two options of the RLS operating principle are possible:

1. The SCCTs continuously measure SC voltages and currents, estimate phasors and active power, and transmit this data to a control and monitoring centre. The real power of all SCs is estimated, a decision on the amount of load to shed is made in real time, and trip commands are sent from the control centre (see Fig. 3). This centralised approach implies a high-speed communication network and measurements synchronisation.
2. If the active power value, exceeding which load shedding action becomes unavoidable, is predefined (through power system contingency simulation), then decentralised approach can be used. The SCCT estimates the SC's real power, and if the power injection exceeds the predefined setting (ΔPsc), the terminal sends a binary command to a predefined frequency relay to disconnect a fixed load amount.

As noted in (Sauhats et al. 2023b), implementing the centralized emergency automation method is feasible using Phasor Measurement Units (PMUs) available in the electrical equipment market. However, to reduce the requirements for communication channels and block terminals in non-symmetric modes and/or in case of network failure, the decision to develop a dedicated terminal has been taken. The complexity and costs of this terminal are expected to be comparable to those of commonly used protection relay terminals.

The evaluation of ΔPsc enables restoration of balance in the power system. To achieve this, it is necessary to disconnect a corresponding load volume. It is advisable to prioritise disconnecting loads that are not sensitive to short-term power supply interruptions, such as heating systems, battery charging systems, or pumps of hydroelectric storage plants. Disconnecting these loads is intended to halt the development of the emergency process. Simultaneously, reserve capacities of hydro units can be activated, after which the disconnected load can be reconnected.

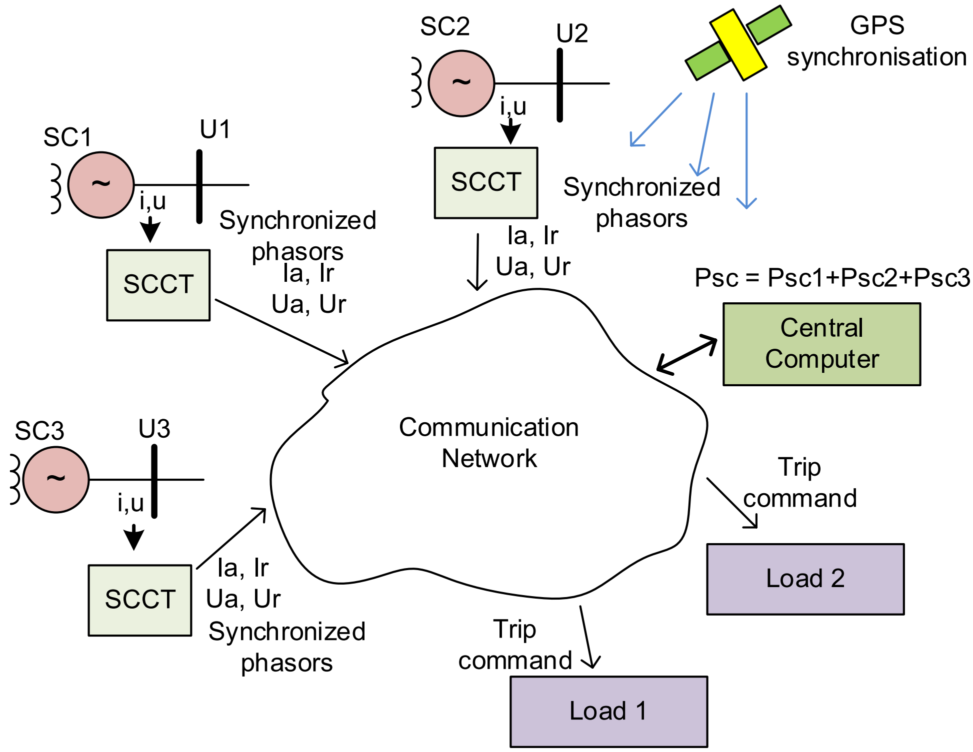


Fig. 3 Centralised SCs control scheme

2.2 SCs control terminal

The estimation of real power in this study follows the phasor measurement approach outlined in (Phadke et al. 1994), (Sauhats et al. 2023b), where complex power is computed using voltage and current phasors. These phasors are derived from sampled waveforms via a full-cycle Discrete Fourier Transform (DFT), producing real and imaginary components used to calculate active power (Phadke et al. 1994), (Noroozian and Andersson 1993).

With a 1 ms sampling interval and 20 ms estimation window, active power and the rate of change of frequency (RoCoF) can be determined every 20 ms using only basic arithmetic operations, since sines and cosines can be calculated in advance and entered in the form of coefficients.

The proposed hardware architecture of the synchronous condenser control terminal (SCCT) follows a standard intelligent electronic device (IED) design for power systems.

The SCCT continuously measures currents and voltages of the SC, calculates active power and compares the averaged values with terminal settings.

As soon as active power injection exceeds the terminal triggering setting, the terminal activates appropriate binary output which sends a signal to frequency relay to shed predefined amount of load. To avoid false triggering during short circuits and other abnormal regimes of the network, terminal continuously monitors the balanced state of the currents and voltages.

The SCCT is equipped with a disturbance recording function, which provides records of the instantaneous waveform of the controlled signals, the value of estimated active power and the state of the binary inputs/outputs (Fig. 4).

The portable Omicron Protection Test Set and Calibrator (Omicron 2025) was employed to test a prototype of the RLS automation terminal in the laboratory. The Calibrator generates highly precise test signals for calibrating measurement devices such as energy meters and protective relaying devices. These signals can be digitally configured and designed to vary over time, ensuring comprehensive testing capabilities.

Examples of the test results evaluating the functionality of the developed prototype and the suitability of the applied signal processing algorithms are presented in Fig. 4.

In Fig. 4, the test input signals applied to SCCT prototype are intended to emulate the SC power injection response. The angle between the currents and voltages was set to zero, thereby emulating only the real power response of the SC. Currents ramp emulates the delay of SC power injection, and Pa, Pb, Pc represent the power calculated by SCCT prototype (as shown in Fig. 4). The terminal compares the calculated active power with the device settings and activates the appropriate binary outputs to shed the prescribed amount of load (P > Pn in Fig. 4).

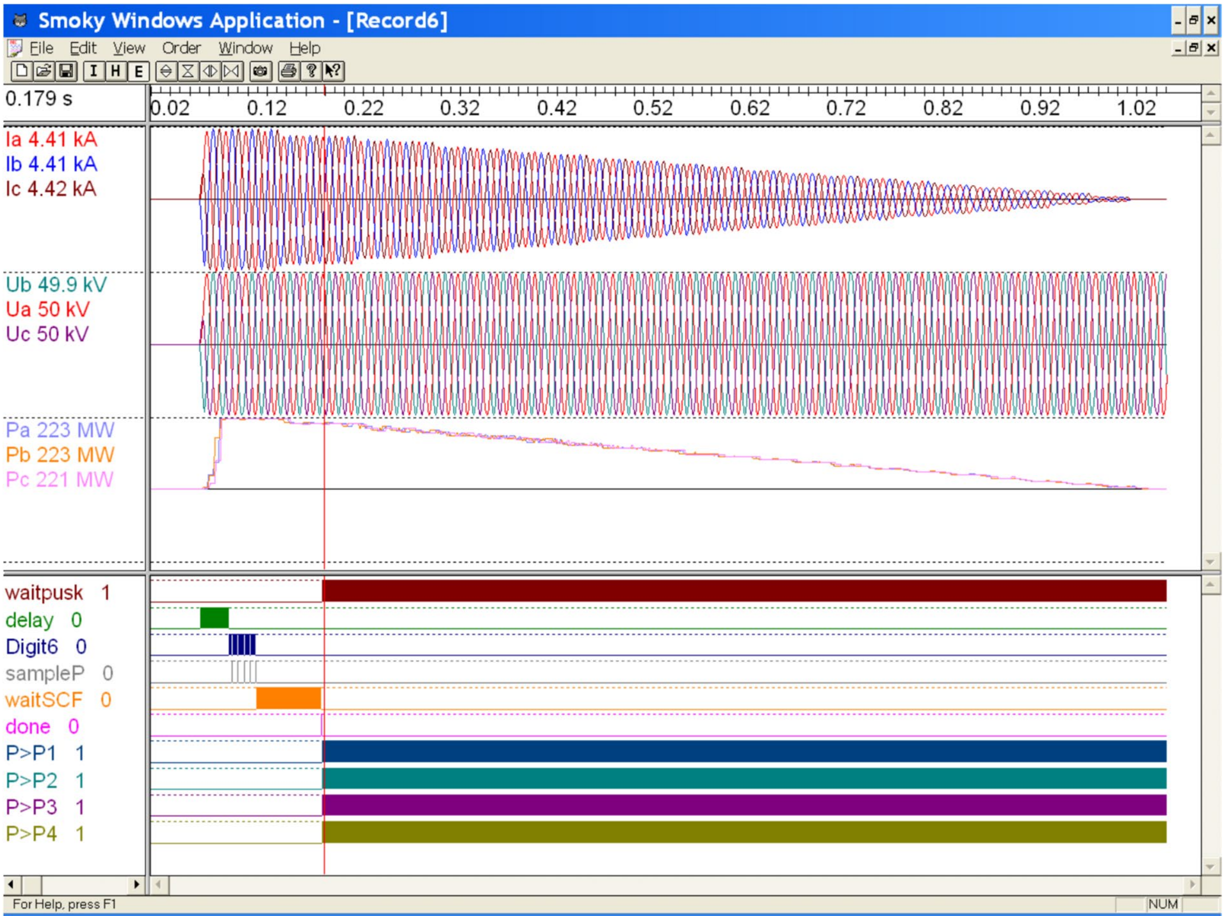


Fig. 4 SCCT record of emulation of a SC active power injection event

3 Application case studies

3.1 The Baltic power system

The Baltic power system (BPS), consisting of Estonia, Latvia, and Lithuania, has been chosen as the case study to demonstrate the feasibility of the proposed rapid load shedding approach. The BPS is a relatively small system with a peak load of 4 683 MW (ENTSO-E, 2024), and it serves as an ideal example of a low-inertia power system. The simplified structure is shown in Fig. 5, which includes pumped storage hydropower plants (PSHP), combined heat and power plants (CHPP), hydropower plants (HPP), solar power plants (SPP), wind power plants (WPP), synchronous condensers (SC) and DC and AC interconnections.

In early 2025, the total installed capacity in the BPS is 11.5 GW. Latvia's primary energy sources are the Daugava Cascade Hydropower plants (1558 MW) and natural gas CHPs (1025 MW). Estonia relies heavily on oil shale (1330 MW), which, despite its high CO_2 emissions, is set to phase out by 2030. Lithuania's energy mix includes natural gas plants (1503 MW) and the Kruonis PSHP (900 MW). The share of renewables is growing (total installed capacity of solar is 3411 MW and wind 2501 MW), however, the BPS still faces power supply deficits.

Historically, the BPS operated synchronously with the Unified Power System of Russia (UPS), which provided substantial frequency and angular stability, along with significant inertia reserves. To improve energy independence of the BPS and to ensure integration in the European energy market, the transmission infrastructure has been modernized (EC, n.d.), including the development of new AC and DC interconnections: two HVDC interconnections between Estonia and Finland (Estlink 1 and Estlink 2, the total capacity is 1.05 GW) (in 2024), an HVDC link (NordBalt) between Lithuania and Sweden with maximum capacity of 700 MW and the LitPol AC transmission line (maximum capacity 500 MW), connecting Lithuania to Poland. The largest power source is a natural gas-fired power plant with a capacity of around 800 MW. These sources met the security requirements under the N-1 criterion when the BPS was synchronized with the UPS. However, disconnecting from

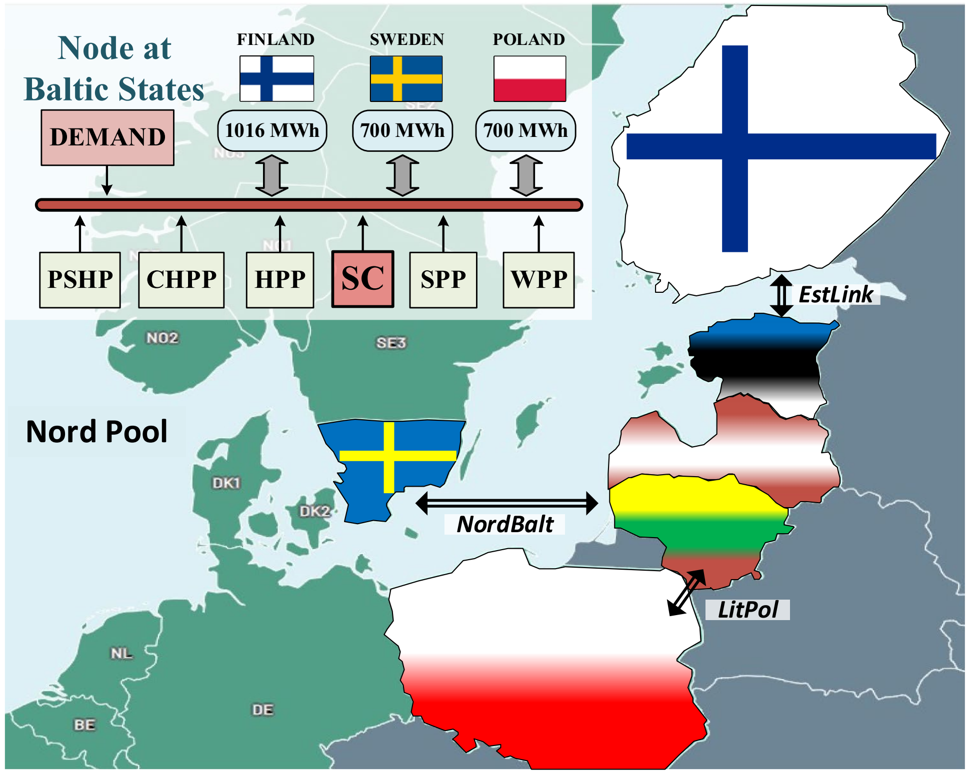


Fig. 5 Map of the Baltic power system and model structure

the UPS results in the loss of inertia, introducing new operational constraints.

With the reduced system inertia, the maximum allowable capacity of existing energy sources decreases. To compensate for this, nine synchronous condensers, each with a nominal capacity of approximately 100 MVA, have been installed in 2024/2025 (EC, n.d.). Despite these upgrades, the allowable transfer capacity (for commercial flows) remains limited to approximately 300–400 MW. As the result the constructed transmission lines are not fully utilised, particularly LitPol interconnection, where commercial flows are limited to 100–150 MW (a thermal limit capacity of 2000 MW). Any planned or unplanned outages of this AC interconnection will result in the operation of the Baltic PS in an island mode (Guzs et al. 2022), relying solely on its own inertia reserves, which are notably lower than current inertia provided by the UPS. Operating in island mode poses significant challenges to the frequency stability of the BPS. The feasibility of addressing these challenges is analysed in (Sauhats et al. 2021). We put forward that implementing the suggested automation system could enable operation with a higher allowable transfer capacity, potentially reaching up to 700 MW—the level maintained prior to disconnection from the UPS. To achieve this, it is critical to rapidly detect the onset of a frequency drop, temporarily disconnect a sufficient amount of load to restore balance and promptly activate reserve generation. The load to be disconnected must be economically resilient to short-term interruptions. Suitable candidates for this purpose include powerful pumps at pumped storage hydropower plants (Sauhats et al. 2024), batteries of storage systems (Baltputnis et al. 2024), electrical boilers (Gicevskis and Linkevics 2023), and electric vehicle charging stations, all of which can facilitate the restoration process effectively.

3.2 Estimation of economic benefit

Using dynamic PS models and the Nord Pool electricity market model, an assessment of the economic benefits of the proposed solution was conducted. This assessment was based on the Baltic PS case study and involved addressing the following sub-tasks:

- **Evaluating the maximum allowable transfer capacity of interconnections in two scenarios**: using traditional UFLS and implementing a new SPS. In both scenarios, the N-1 criterion must be satisfied, requiring restrictions on the transmission capacities of interconnection power lines. Although determining exact NTC values is outside the scope of this study, we estimate – based on operational constraints and prior simulation work (Sauhats et al. 2021), (Guzs 2023) – that the proposed automation scheme could allow for an increase of the allowable transfer capacity from the current 300–500 MW range up to approximately 700 MW. This is primarily due to the enhanced ability to manage the critical N-1 contingency: the unexpected outage of the Sweden–Lithuania interconnector (700 MW). Under current conditions, such an event risks overloading the Lithuania–Poland interconnection and requires rapid disconnection of ~ 400 MW of load. The proposed automation system leverages fast-acting, controllable loads, including the 1000 MW pumping capacity of the Kruonis PSP, electric boilers, and battery storage (totalling ~ 300 MW), to shed sufficient load within tenths of a second. This capability ensures safe post-contingency operation, potentially reaching the nominal capacity of the interconnector (700 MW).

- **Calculating the economic benefits in monetary terms.** To quantify the economic benefits in monetary terms, we evaluate the advantages of a power system with a 700 MW interconnection transfer capacity. This assessment is conducted relative to systems with more constrained transfer capacities of 0 MW, 300 MW, or 500 MW. The ability of the power system to withstand the loss of a 700 MW generator, utilizing RLS, has been demonstrated in previous paper (Sauhats et al. 2021).

In general, cross-border transfer capacity is determined by accounting for the unique characteristics and technical limitations of the power grid, such as thermal constraints and stability concerns. The implementation of advanced automation technologies can enhance stability limits and mitigate the impacts of emergency processes. The proposed RLS method allows for significantly faster load shedding activation, bypassing the need for frequency and/or RoCoF measurements, instead relying on the active power injection from synchronous condensers as the triggering criterion.

The frequency response demonstrates that faster load shedding activation has a profound impact on the frequency nadir for the same amount of disconnected load. In the context of the Baltic power system, simulations and calculations (Sauhats et al. 2021), (Guzs 2023) indicate that cross-border transfer capacity can be maintained at current levels following disconnection from the UPS, provided RLS triggering occurs within 0.1–0.5 s after the contingency moment.

To assess the economic benefits in monetary terms, we forecast electricity prices across the Baltic power system and neighbouring countries (Sweden, Finland, Poland). This analysis involves defining the generation portfolio and consumption profiles, and simulating the operation of interconnected PS based on the rules of the Nord Pool electricity market (more details on the methodology and electricity market model are provided in (Sauhats et al. 2021), (Petrichenko et al. 2021), (Sauhats et al. 2023a)).

The BPS is modelled as a low-inertia system for the year 2050, following its disconnection from the UPS and reflecting a high penetration of RES. In this scenario, the installed generation capacity includes solar power at 2800 MW and wind power at 9000 MW. We analyse the impact on the electricity market prices and evaluate potential benefits under varying allowable transfer capacities of the NordBalt line (0, 300, 500 and 700 MW). The inclusion of the 0 MW capacity scenario serves the purpose of model validation. To balance the BPS, reserve gas-fired power plants are utilized. Given the high penetration of RES in the BPS, the reserve power plants ensure energy generation during shortages. The bidding costs of the reserve power plants depend on gas prices, which are subject to uncertainty, and multiple options are modelled to account for this variability (100, 200, and 300 EUR/MWh).

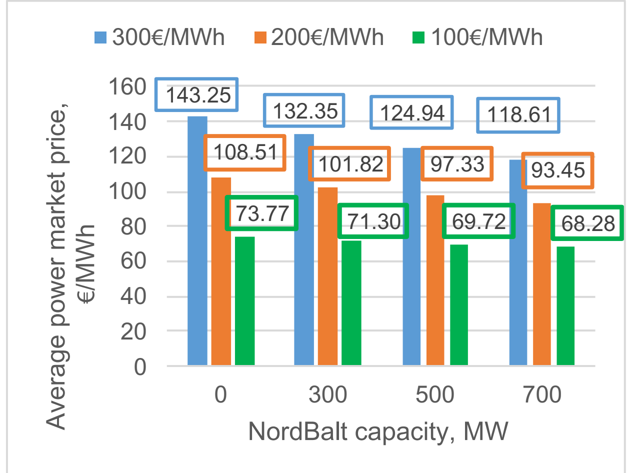


Fig. 6 Average market electricity price depending on allowable transfer capacity and reserve bidding costs

Figure 6 shows the impact of allowable transfer capacity of the NordBalt line on the average annual electricity prices in the Baltic price area. Moreover, the bidding costs of reserve power plants significantly affect average electricity market prices, underscoring their role in the overall cost structure. The results highlight the potential for achieving significant economic benefits by increasing allowable transfer capacity, thereby enhancing total welfare.

As depicted in Fig. 7, the increase in allowable transfer capacity results in higher annual incomes from energy exports, rising from 202.96 million euros (MEUR) to 322.86 MEUR (or 119.9 MEUR). Conversely, the decrease in allowable transfer capacity leads to significantly higher import costs, driven by the resulting increase in electricity prices. For instance, at bidding costs of 100 EUR/MWh, the additional expenses amount to 49 MEUR. However, this figure escalates dramatically – more than eightfold – to 413 MEUR when the bidding costs reach 300 EUR/MWh.

It should be noted (see Fig. 8), that the allowable transfer capacity has a significant impact on the annual power surplus. The power surplus refers to the energy that could be generated by renewable sources under

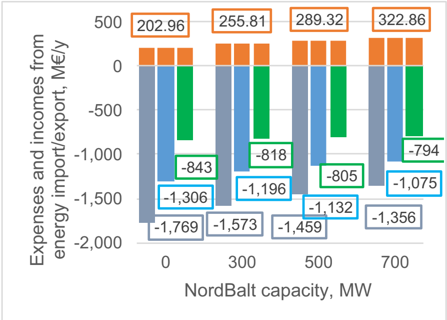


Fig. 7 Annual expenses and incomes from electricity import and export depending on NordBalt link allowable transfer capacity and reserve bidding costs (300€/MWh, 200€/MWh, 100€/MWh)

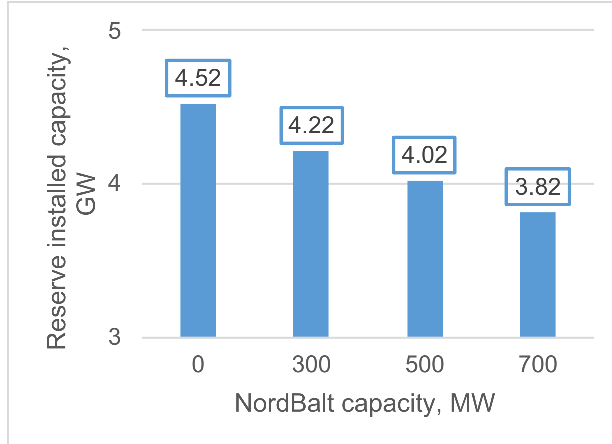


Fig. 9 Capacity of additional reserve needed to eliminate power deficiency

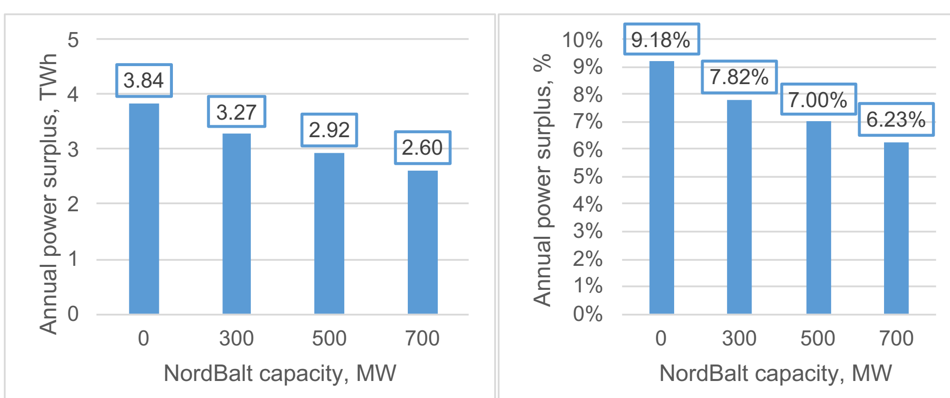
favourable meteorological conditions but cannot be consumed or exported due to insufficient demand or interconnection constraints. In such scenarios, when utilizing or transferring the generated energy becomes impossible, the power system is compelled to curtail production. In the considered scenarios the surplus difference amounts to 1.24 TWh, representing nearly 3% of the total energy.

In the case of intermittent generation, another challenge arises when an energy deficit occurs. This deficit refers to the inability to generate sufficient power to meet demand due to interconnection constraints limiting energy imports and unfavourable meteorological conditions. To address this issue, additional reserves are required, as illustrated in Fig. 9. For instance, a reduction in allowable transfer capacity by 200 MW could require the construction of a power plant with equivalent capacity. Building a gas-fired plant of this size would cost approximately 200 MEUR, based on an estimated total capital cost of 1,000 EUR/kW (Lazard LCOE, 2024). However, implementing the proposed automation system could effectively eliminate the need for this expense.

Let us compare the calculation results with real data of the forced disconnection in the BPS. For instance, the NordBalt line was disconnected from 2023–09-04 till 2023–09-23. Prior to and after the disconnection, the power exchange over the NordBalt line (to Lithuania) operated at full capacity (700 MW). Figure 10 illustrates the Nord Pool the day average of day-ahead prices in the Lithuania and Sweden price zones. The average 10-day price before the disconnection was 62.42 EUR/MW·h in Sweden and 114.39 EUR/MW·h in the Baltic States. During the 20 days disconnection period, the electricity price difference widened, with average prices reaching 51.32 EUR/MWh in Sweden and 131.07 EUR/MWh in Baltics. If the NordBalt line had been operational, an energy amount of 16,800 MW·h could be transferred to Lithuania daily. Considering the difference between two price zones, the economic effect could have been approximately 26.8 MEUR for the entire period (from 2023–09-04 till 2023–09-23), or 1.34 MEUR per day.

When comparing the presented example with the simulation results shown in Figs. 6 and 7, the annual average price in the BPS increases from 118.61 EUR/MWh to 143.25 EUR/MWh, representing a significant price difference of 24.64 EUR/MWh when the allowable capacity is reduced to zero, compared to 16.68 EUR/MWh in the previous example. However, the annual import cost difference

Fig. 8 Annual power surplus in TWh and percents



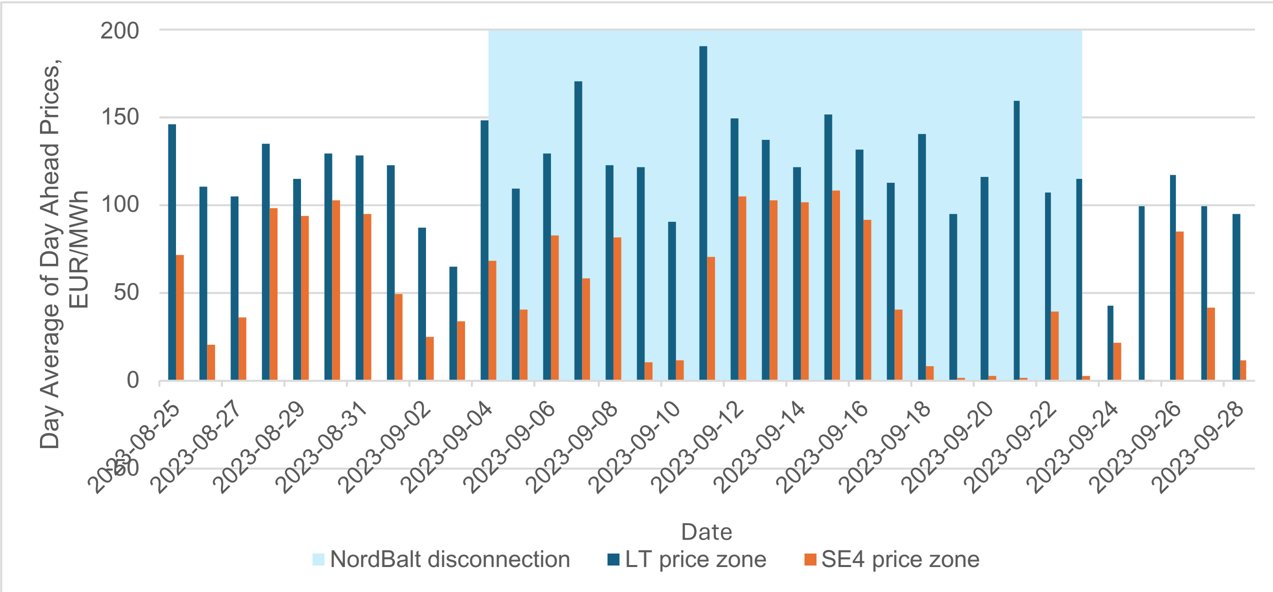


Fig. 10 Day average of day-ahead prices

of 413 MEUR, or approximately 1.13 MEUR per day on average, is lower than the 1.34 MEUR per day calculated in the earlier example. Despite these differences, both examples clearly demonstrate the potential for economic benefits through the optimal use of interconnection capacity enabled by the proposed automation. The error in the difference estimation is around 16%. However, considering that the simulation was performed for anticipated PS parameters, which differ significantly from those used in the second example, we conclude that the results are reasonable and can be validated.

4 Future perspectives and conclusions

The replacement of thermal power plants using fossil fuels with renewable energy sources leads to a reduction in the inertia of the power system. This process may intensify restrictions on the permissible capacity of elements within the power system that are subject to failure and necessitate the use of synchronous condensers. The proposed Rapid Load Shedding method, which uses active power measurements from synchronous condensers, offers a more efficient solution for maintaining frequency stability and for mitigating the operational and stability constraints imposed by the N-1 security criterion – particularly those concerning allowable transfer capacity and contingency planning. Whilst the RLS approach shows significant promise, it requires the deployment of specialized measurement devices and a robust communication infrastructure for real-time data processing and decision-making. All necessary measurements can be performed using algorithms and hardware similar to those employed in Phasor Measurement Units. This approach facilitates the cost-effective integration of renewable energy sources and synchronous condensers, reducing the need for stringent transfer capacity limitations traditionally imposed for stability during low-probability disturbances. The analysed enhancements could enable more efficient utilization of existing transmission infrastructure. Implementing RLS technology in the Baltic Power System demonstrates the potential to significantly increase allowable transfer capacity—from the current 300–400 MW to approximately 700 MW—without compromising system stability. This improvement could result in additional profits on the scale of hundreds of millions of euros and enhance the integration of renewable energy sources.

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Data Availability The data presented in this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

References

Ali MH, Murata T, Tamura J (2006) Effect of coordination of optimal reclosing and fuzzy controlled braking resistor on transient stability during unsuccessful reclosing. IEEE Trans Power Syst 21:1321–1330. https://doi.org/10.1109/TPWRS.2006.876670

Baltputnis K, Broka Z, Cingels G, Sīlis A, Junghāns G (2024) Robust market-based battery energy storage management strategy for operation in European balancing markets. J Energy Storage 102:114082. https://doi.org/10.1016/j.est.2024.114082

Ben Kilani, K., Elleuch, M., Haj Hamida, A., 2017. Dynamic under Frequency Load Shedding in Power Systems, in: 14th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, pp. 377–382. https://doi.org/10.1109/SSD.2017.8166970

Castillo A (2014) Risk analysis and management in power outage and restoration: A literature survey. Electr Power Syst Res 107:9–15. https://doi.org/10.1016/j.epsr.2013.09.002

Delfino, B., Massucco, S., Morini, A., Silvestro, S.F., 2001. Implementation and Comparison of Different under Frequency Load-Shedding Schemes, in: 2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262). IEEE, pp. 307–312. https://doi.org/10.1109/PESS.2001.970031

EC, 2014. 2030 Climate and Energy Policy Framework EUCO 169/14.

EC, 2021. Delivering the European Green Deal [WWW Document]. Eur. Comm. URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.

EC, n.d. Baltic Energy Market Interconnection Plan [WWW Document]. Eur. Comm. URL https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/baltic-energy-market-interconnection-plan_en (Accessed 5.15.24).

ENTSO-E, 2024. Transparency Platform [WWW Document]. Entso-E Transpar. Platf. URL https://transparency.entsoe.eu/dashboard/show.

ERCOT, 2018. Inertia: Basic Concepts and Impacts on the ERCOT Grid.

Gicevskis K, Linkevics O (2023) The role of decentralized electrode boiler in ancillary services and district heating: a feasibility assessment. Latv J Phys Tech Sci 60:32–42. https://doi.org/10.2478/lpts-2023-0029

Guzs D, Utans A, Sauhats A, Junghans G, Silinevics J (2022) Resilience of the baltic power system when operating in island mode. IEEE Trans Ind Appl 58:3175–3183. https://doi.org/10.1109/TIA.2022.3152714

Guzs, D., 2023. Cost effective, innovative solution for transmission capacity management in low-inertia weakly interconnected power systems (Doctoral Thesis). RTU.

Hadavi S, Mansour MZ, Bahrani B (2021) Optimal allocation and sizing of synchronous condensers in weak grids with increased penetration of wind and solar farms. IEEE J Emerg Sel Top Circuits Syst 11:199–209. https://doi.org/10.1109/JETCAS.2021.3053554

Hatziargyriou N, Milanovic J, Rahmann C, Ajjarapu V, Canizares C, Erlich I, Hill D, Hiskens I, Kamwa I, Pal B, Pourbeik P, Sanchez-Gasca J, Stankovic A, Van Cutsem T, Vittal V, Vournas C (2021) Definition and classification of power system stability—revisited & extended. IEEE Trans Power Syst 36:3271–3281. https://doi.org/10.1109/TPWRS.2020.3041774

Jianjun, Z., Dong, Z., Yang, G., Zhihong, Y., 2018. Load shedding control strategy for power system based on the system frequency and voltage stability(Apr 2018), in: China International Conference on Electricity Distribution, CICED. IEEE, pp. 1352–1356. https://doi.org/10.1109/CICED.2018.8592262

Johnson SC, Rhodes JD, Webber ME (2020) Understanding the impact of non-synchronous wind and solar generation on grid stability and identifying mitigation pathways. Appl Energy 262:114492. https://doi.org/10.1016/j.apenergy.2020.114492

Kundur, P., Balu, N.J., Lauby, M.G., 1994. Power system stability and control, The EPRI power system engineering series. McGraw-Hill, New York San Francisco Washington [etc.].

Lazard LCOE, 2024. Levelized costs of energy analysis (Executive summary No. Version 17.0). Lazard LCOE.

Luo X, Li F, Fan L, Niu T, Li B, Tian L, Yu H (2021) Influence of synchronous condensers on operation characteristics of double-infeed LCC-HVDCs. Processes 9:1704. https://doi.org/10.3390/pr9101704

Machowski, J., Bialek, J.W., Bumby, J.R., 2012. Power system dynamics. Stability and Control, Power System Stability and Control, Third Edition. John Wiley & Sons, Ltd.

Nguyen HT, Yang G, Nielsen AH, Jensen PH (2019) Combination of synchronous condenser and synthetic inertia for frequency stability enhancement in low-inertia systems. IEEE Trans Sustain Energy 10:997–1005. https://doi.org/10.1109/TSTE.2018.2856938

Noroozian M, Andersson G (1993) Power flow control by use of controllable series components. IEEE Trans Power Deliv 8:1420–1429. https://doi.org/10.1109/61.252669

Omicron, 2025. Omicron [WWW Document]. Omicron. URL https://www.omicronenergy.com (Accessed 1.24.25).

Ørum, E., Kuivaniemi, M., Laasonen, M., Bruseth, A.I., Jansson, E.A., Danell, A., Elkington, K., Modig, N., 2015. ENTSO Report - Future System Inertia. ENTSO-E.

Petrichenko L, Petrichenko R, Sauhats A, Baltputnis K, Broka Z (2021) Modelling the future of the baltic energy systems: a green scenario. Latv J Phys Tech Sci. https://doi.org/10.2478/lpts-2021-0016

Phadke AG, Pickett B, Adamiak M, Begovic M, Benmouyal G, Burnett RO, Cease TW, Goossens J, Hansen DJ, Kezunovic M, Mankoff LL, McLaren PG, Michel G, Murphy RJ, Nordstrom J, Sachdev MS, Smith HS, Thorp JS, Trotignon M, Wang TC, Xavier MA (1994) Synchronized sampling and phasor measurements for relaying and control. IEEE Trans Power Deliv 9:442–452. https://doi.org/10.1109/61.277716

Prabhakar K, Jain SK, Padhy PK (2022) Inertia estimation in modern power system: A comprehensive review. Electr Power Syst Res 211:108–222. https://doi.org/10.1016/j.epsr.2022.108222

Ratnam KS, Palanisamy K, Yang G (2020) Future low-inertia power systems: Requirements, issues, and solutions—A review. Renew Sustain Energy Rev. https://doi.org/10.1016/j.rser.2020.109773

Roux A, Bekker B, Dalton A (2022) Synchronous condensers as a viable inertia support mechanism on the future South African grid. Energy Sustain Dev 69:192–201. https://doi.org/10.1016/j.esd.2022.06.010

Rudež, U., Mihalič, R., 2011. Comparison of Adaptive UFLS Schemes in Modern Power Systems, in: 2011 IEEE Electrical Power and Energy Conference : IEEE EPEC 2011. IEEE, pp. 233–238. https://doi.org/10.1109/EPEC.2011.6070202

Rudež, U., Mihalič, R., 2017. Trends in WAMS-based Under-Frequency Load Shedding Protection, in: IEEE EUROCON 2017 : 17th International Conference on Smart Technologies : Conference Proceedings : 6–8 July 2017, Ohrid, Mcedonia. pp. 782–787. https://doi.org/10.1109/EUROCON.2017.8011217

Sauhats A, Utans A, Silinevics J, Junghans G, Guzs D (2021) Enhancing power system frequency with a novel load shedding method including monitoring of synchronous condensers' power injections. Energies. https://doi.org/10.3390/en14051490

Sauhats A, Petrichenko R, Zima-Bockarjova M (2023a) A pragmatic approach to the economic assessment of green synthetic methane power in the baltics. Energies 16:7479. https://doi.org/10.3390/en16227479

Sauhats A, Utāns A, Žalostība D (2024) Leveraging pumped storage power plants for innovative stability enhancement of weakly interconnected power systems. Energies 17:3754. https://doi.org/10.3390/en17153754

Sauhats, A., Utans, A., Zalostiba, D., Mutule, A., Grigals, O., Guzs, D., 2023b. Feasibility Study : Improving Low-inertia Power System Resilience By Novel Load Shedding Method Including Control of Synchronous Condensers' Power Injections, in: 63rd ESReDA Seminar "Resilience Assessment: Methodological Challenges and Applications to Critical Infrastructures": Proceedings. ESReDA | Joint Research Centre, Ispra, Italy, pp. 1–10. https://doi.org/10.2760/2808748

Soleimani H, Habibi D, Ghahramani M, Aziz A (2024) Strengthening power systems for net zero: a review of the role of synchronous condensers and emerging challenges. Energies 17:3291. https://doi.org/10.3390/en17133291

Wang Z, Li Q, Kong S, Li W, Luo J, Huang T (2023) Analysis of renewable energy consumption and economy considering the joint optimal allocation of "renewable energy + energy storage + synchronous condenser." Sci Rep 13:20376. https://doi.org/10.1038/s41598-023-47401-4

Zalostiba, D., 2013. Power system blackout prevention by dangerous overload elimination and fast self-restoration, in: 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe. IEEE. https://doi.org/10.1109/ISGTEurope.2013.6695371

Zare, F., Ranjbar, A., Faghihi, F., 2019. Intelligent topology-oriented load shedding scheme in power systems, in: ICEE 2019 : 27th Iranian Conference on Electrical Engineering. IEEE, pp. 652–656. https://doi.org/10.1109/IranianCEE.2019.8786519

Zbunjak Z, Bašić H, Pandžić H, Kuzle I (2015) Phase shifting autotransformer, transmission switching and battery energy storage systems to ensure n-1 criterion of stability. J Energy - Energ 64:285–298. https://doi.org/10.37798/2015641-4157

Zhou G, Wang D, Atallah A, McElvain F, Nath R, Jontry J, Bolton C, Lin H, Haselbauer A (2019) Synchronous condenser applications: under significant resource portfolio changes. IEEE Power Energy Mag 17:35–46. https://doi.org/10.1109/MPE.2019.2909005

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