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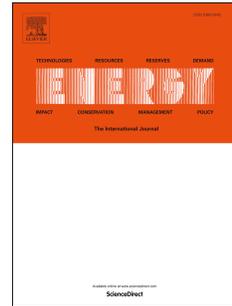
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Role of energy storage in ensuring transmission system adequacy and security

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Abstract

The main purpose of a Transmission System Operator is to ensure stable, reliable and efficient operation of its power system. Large-scale integration of renewable energy sources has introduced additional challenges to active control of transmission power systems. Traditionally, generation adequacy has been achieved through investments in generating units and transmission adequacy through investments in transmission lines. However, energy storage can be regarded as both the generation asset, as it reduces peak load and acts as a generator when injecting electricity into the network, and transmission asset, as it can move electricity in time thus reducing congestion and curtailment of renewable energy sources. This paper examines the role of energy storage in increasing power system adequacy and security. A method is proposed to define the charging/discharging schedule of energy storage after a contingency in order to preserve the system within the operating limits and to provide the system operator enough time to redispatch the system and relieve the overloaded lines. The method is applied to an actual part of the Croatian power system using scenarios that describe representative network states. The simulations are performed in a transmission operations and planning software using actual operating data. The results are analysed in details and conclusions on the role of the energy storage in providing transmission system adequacy and security is assessed.

Keywords: Energy Storage, Transmission System Adequacy, Transmission System Security, N-1 Contingency

1. Introduction

Power system reliability can be identified by considering two basic and functional aspects of the power system, adequacy and security. Adequacy is the ability of the power system to supply energy requirements to end users at all times, while the scheduled and expected unscheduled outages of the system elements are taken into account. Security, on the other hand, is the ability of the power system to resist impulsive disturbances, such as unexpected loss of system elements, e.g. generation units or transmission lines [1]. Ensuring adequacy and security in a power system is extremely important to the system operator (SO). The main activities of the SO are focused on the secure operation of the power system, ensuring availability of the transmission grid to satisfy the transmission requirements, contributing to security of supply by providing adequate transmission capacity and reliability of the transmission network, management of electricity flows in the transmission network by considering electricity exchanges with other interconnected networks and ensuring the availability of all necessary ancillary services. In fact, each SO has a role to transmit a high-quality power in

transmission grid in order to avoid interruptions and fulfill the criterion of stability and reliability.

An SO usually runs its power system from a national control centre, but there are also regional centres which act locally to maintain system stability and reliability. All commands are in the hands of dispatchers whose reaction and previous experience is essential in case of an unexpected event or a contingency. Contingency is defined as an unexpected failure or outage of a system device, such as a generator, transmission line, circuit breaker, switch, or other electrical element [1]. Every SO sets parameter limits within which the power system should stay stable after any possible contingency [2]. The SO has an obligation to conduct the following corrective interventions when appropriate (within 30 minutes after a contingency), and bring the power system back to the normal operation state [3]:

- generator re-dispatch
- voltage and/or power flow control on regulation transformers
- network re-configuration
- manual load shedding.

On the asset side, there have been major advances in energy storage technology resulting in demonstration projects where storage is used to provide corrective actions in case of a contingency as well. Techno-economic

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models have been developed for various types of energy storage (e.g. pumped storage system and compressed air energy storage system in [4]), and for different applications, e.g. energy and ancillary markets [5], reduction of wind power variability [6], and spatiotemporal energy arbitrage [7]. Possible energy storage applications depend on its type [8], which is generally divided in power-intensive and energy-intensive. To clarify, power-intensive energy storage can be (dis)charged in short time period, while energy-intensive storage takes several hours to (dis)charge.

This paper considers a power-intensive battery energy storage able to inject a large amount of power rapidly. Li-ion battery technology can provide such service. Moreover, its advantages include high energy density, power density [11], quick (dis)charging [12], cycling efficiency [13], low degradation [14], long lifetime [15], low operating and maintenance costs [16], as well as diverse applicability [17]. Applications of li-ion batteries, such as grid support, automotive and back-up power, are investigated in [18]. The authors show that li-ion batteries are suitable for these applications and they highlight the need to utilize batteries for several applications at the same time to increase their efficiency and justify the investment. In addition, li-ion batteries are useful for providing back-up power supply for a long-time period, as well as when performing a high number of partial charging/discharging cycles [19].

This paper analyses which capacity of battery energy storage and under which scenarios can assist the SO in a short time period, up to 15 minutes. This amount of time is sufficient for the SO to perform generator redispatch, reconfigure the network or perform any other action that will keep the system within the operating limits in a long run. The case study is performed on the Istrian peninsula – a part of the Croatian power system. This part is fairly isolated from the rest of the power system and experiences problems in case of a contingency. Also, there are significant differences in consumption and production which are represented through eight scenarios. The main objective of this paper is to use the proposed method to ensure security of the power system after a contingency using a battery energy storage system of an appropriate capacity. Besides the technical aspect, the market aspect is important as well. This means that the SO is responsible for enabling the generating units on the Istrian peninsula an access to the rest of the Croatian power system in order for them to sell their electricity in the market.

This paper is organized as follows: section 2 provides an overview of the research literature on this topic, section 3 formulates the proposed method, and section 4 presents results tested on the western part of the Croatian power system. Finally, the last section provides relevant conclusions.

2. Literature review and contributions

Contingencies in power system can be managed using preventive or corrective approach. Preventive approach means that no SO action is needed after a contingency to preserve the security of the power system, while corrective approach requires SO actions to preserve the security. Although the preventive approach is safer, it is usually much less economical than the corrective approach. In other words, running system closer to the security margin is beneficial from the technical aspect, but is cost ineffective. Authors in [20] introduce fast-response battery storage systems as part of an enhanced security constrained optimal power flow. This formulation is able to reduce power flows through overloaded lines in the first few minutes after a contingency. The base case generation costs are minimized in the first stage, while the short-term and long-term corrective actions are considered in the second stage. The results show that this approach reduces the long-term investments in additional transmission lines due to the effectiveness of energy storage in the post-contingency state. Our approach is similar to the one in [20] because battery energy storage is used to act as a fast responding facility in the post-contingency period to reduce overloaded power lines, while the generating units start ramping to increase or decrease power outputs. The contribution of this paper with respect to [20] are the real-world simulation scenarios and detailed power flow analysis using PSS@E (Power Transmission System Planning Software) grid model. This model is a full AC representation of the network, while the one in [20] uses a DC approximation thus ignoring voltage levels, reactive power and losses.

While the model presented in [20] considers a single optimal power flow instance in time, thus ignoring the intertemporal constraints, the model proposed in [21] considers the entire unit commitment scheduling procedure for an entire day. Due to computational complexity, the authors in [21] formulate a Benders' decomposition algorithm to obtain sufficient computational tractability. The results of the case study indicate that energy storage reduces the overall system cost through both, the corrective actions and energy arbitrage. However, this model again uses a DC representation of power flows, which might significantly differ from physical power flows.

Corrective actions are further investigated in [22]. A three-stage security unit commitment model is presented to reduce the re-dispatch costs in the contingency environment using an ac network representation. Due to complexity of the problem, the authors use a nested Benders decomposition approach that demonstrates good convergence properties. The proposed model is tested on the Spanish power system. Formulation of the frequency dynamics constrained unit commitment strategy supported by a fast-response large-scale battery, is proposed in [23]. The uncertainty of renewable generation is addressed by interval-based optimization and the batteries are utilized in order to minimize power imbalances. The model is

tested on both, six-bus system and the modified RTS-79 system, where the frequency security is provided. The results indicate that the overall system operating costs and wind curtailment are reduced.

In [24], the authors propose scheduling of energy storage operation in order to achieve reliability of the supply. Reliability is assessed for each hour and the minimum total operating cost is achieved using a cumulative transition matrix. The case study results show that the reliability constraint can be satisfied by procuring sufficient reserve capacity for achieving the minimum state of charge of energy storage. Storage degradation is minimized by operating the storage at reasonably low state of charge level and with minimum depth of discharge. Utilization of energy storage systems for congestion management is presented in [25]. The proposed method optimizes energy storage capacity and charging/discharging schedule in order to relieve line loadings. The model captures uncertainty related to wind and solar generation.

Energy storage operating model is used for providing flexibility in [26]. The model consists of three phases: i) day-ahead scheduling of generation and storage resources, ii) near-real time operation which utilizes flexibility of energy storage and iii) control actions performed by storage based on model predictive control in case of a contingency. The presented case study results in 2% cost savings when the proposed three-stage model is used when compared to the conventional operating practice. Blackout prevention techniques proposed in [27] are based on three schemes: traditional load shedding, the rate of change of frequency-based load shedding and separation of the grid. Their results indicate that if automated load shedding scheme cannot prevent disturbances, then separating the power system into islands helps. Another approach is considered in [28], where the authors obtain an islanding solution of the power system by introducing a spectral clustering method based on generator coherency grouping. Their analyses demonstrate the effectiveness of the proposed algorithm in blackout prevention on IEEE 9-bus and 118-bus systems. Authors in [29] present a smart protection scheme based on the synchronized measurement technology that contributes in mitigation of a partial or system-wide blackout. A study on grid-scale energy storage as an option to reduce wind curtailment in transmission network is presented in [30]. The results indicate that wind spillage can be reduced with energy storage costs as high as \$780/kW and ten hours of storage capacity. Generally, batteries with higher power ratings result in less overall wind curtailment in the system. The sensitivity analysis showed the most sensitive parameters are wind subsidies, cost of transmission expansion, battery degradation and battery life cycle.

A case study on integration of energy storage in Brazilian power system is conducted in [31]. This case study concludes that the minimum operating cost is achieved when energy storage is introduced in the Brazilian power system, as it reduces the wind curtailment in the high-

renewable scenario. Energy storage market potential in India is examined in [32]. Among many benefits of storage, the authors list voltage support, power reliability and network upgrade deferral, which is in the focus of this paper. A similar work, focused on energy storage industry in China, is presented in [33], while integration of energy storage in 100% renewable power system of Croatia is presented in [34]. As opposed to [31]-[34], which focus on the global picture within the listed countries, this paper focuses on the case study of Istria in Croatia and performs detailed analysis using a detailed representation of the network. The model in PSS@E has been widely tested and used by the Croatian TSO, making the obtained results relevant in both academic and technical sense.

The contribution of the paper are twofold:

1. A method for obtaining optimal energy storage capacity in an isolated power subsystem that keeps the system stability while the system operator reconfigures the network and redispatches the generation.
2. Valuation of energy storage investment in comparison with transmission lines for isolated power subsystems.

3. Method

The proposed method consists of the steps presented in Fig. 1. First, all input data, i.e. load, transmission network, energy storage, and generator data, are loaded into the PSS@E (Power Transmission System Planning Software) in order to create a grid model. Two characteristic network states are observed:

- Evacuation of power during maximum production and minimum demand,
- Supply of power during minimum production and maximum demand.

If a contingency is not removed, then the battery energy storage is optimized to the size that provides sufficient time to the dispatchers to perform corrective actions counteracting the contingency. Battery energy storage will inject or extract power according to the conditions in the power system. If the analyzed outage is corrected, the next simulation is performed. This is repeated until the final characteristic state, when the process is finished. The idea behind this paper is presented in Fig. 2a on a small power system with two buses, two generators, two lines, a load and an energy storage. Assume that generator G_1 is cheaper than G_2 and covers almost the entire load at bus 2. Accordingly, power flow is directed from bus 1 to bus 2. If line l_1 suffers an outage, the system should be able to continue its operation within the operational limits. System operator has to act quickly and perform generation re-dispatch. Fig. 2b shows power flow through the remaining line l_2 after a contingency has occurred. Power injection by energy storage is shown in Fig. 2c. At t_0 , when the contingency has occurred, power flow through

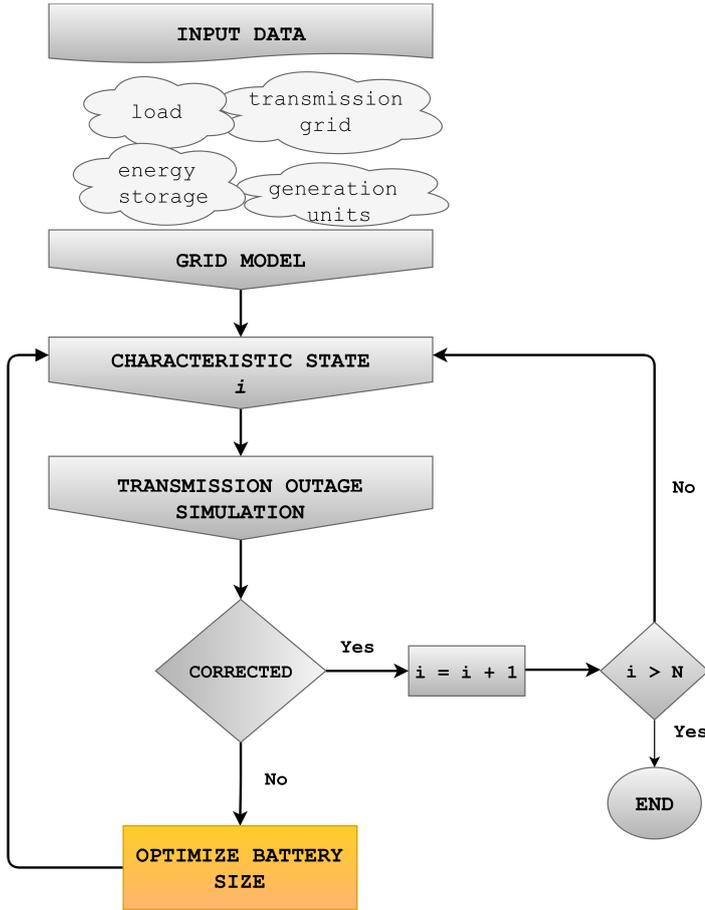
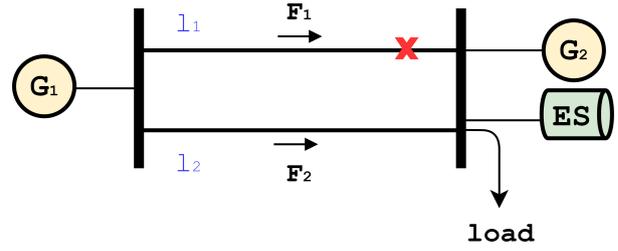


Fig. 1. Flow diagram of the proposed method.

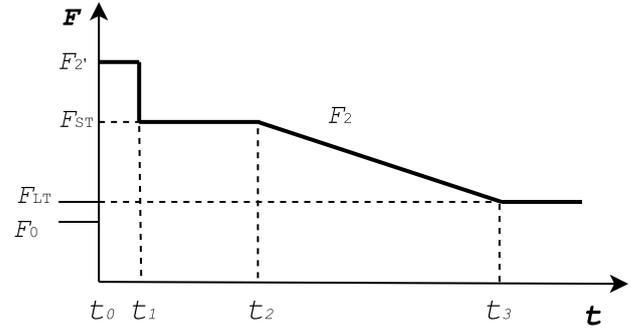
line l_2 increases to the line's short-term rating (this needs to be below the level at which the overcurrent relay trips). Very quickly, in period t_1 , energy storage at bus 2, because of its fast response, starts to inject power until period t_2 , when the generator units start ramping (G_1 ramps down and G_2 ramps up) and energy storage decreases its power until period t_3 . Power flow between t_1 and t_2 reaches the short-term emergency line rating, and it can stay at this level for a while before the line heats. After t_3 , power flow through line l_2 reaches its long-term continuous rating. After the disturbance is eliminated, the power system can return to its normal state, as well as the power flows through lines l_1 and l_2 .

4. Case study

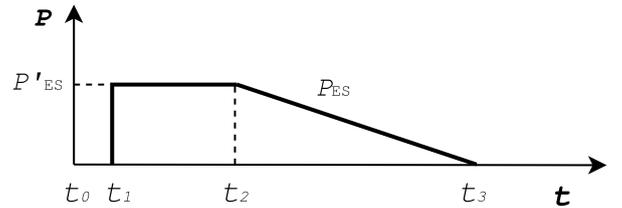
The method is tested at an isolated part of the Croatian power system, the peninsula of Istria. Croatian power system is experiencing a large growth of renewable energy sources. The north-western part of the system is supplying the Istrian peninsula, which is connected to the rest of the Croatian power system by one main and two auxiliary transmission lines, as shown in Fig. 3. This part of country is a relatively isolated part of the Croatian power system, although it supplies electricity to 100,000



a) Two-bus system



b) Flow in line l_2



c) Power injection by ES

Fig. 2. Corrective control approach.

people. However, this number is much higher during the summer season due to highly developed touristic sector. Total installed power generation capacity in Istria is 300 MW, while the consumption ranges from 80 to 230 MW. Transmission outages are analyzed in both system states. The transmission lines of great significance in those cases are:

- Line 220 kV Plomin – Pehlin – Melina (main),
- Line 110 kV Buje – Koper (aux 1),
- Line 110 kV Plomin – TS Lovran – TS Matulji – TS Pehlin (aux 2).

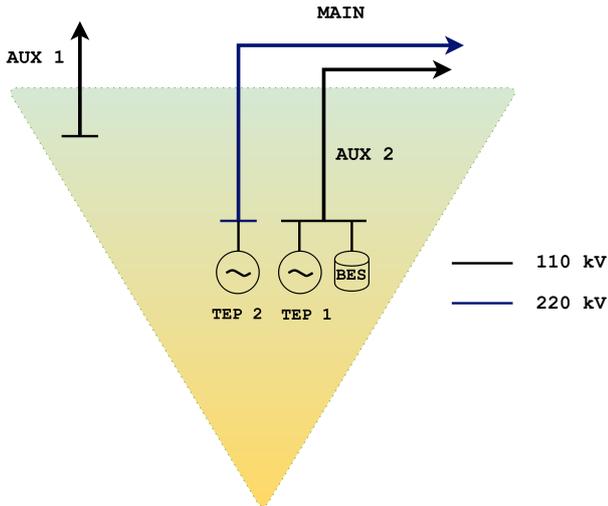
The main transmission line is the double-system 220 kV transmission line, connecting thermal power plant Plomin 2 (TEP 2) with the rest of the Croatian power system, i.e. TS Pehlin and TS Melina. The two 110 kV auxiliary transmission lines are limited to 70 MW (aux 1, towards Italy)

and 90 MW (aux 2, towards Croatia), due to restriction of the neighbouring power systems – Italian and Slovenian. An outage of the double-system transmission line 220 kV Plomin – Pehlin – Melina may overload these two auxiliary evacuation routes, which may result in a complete blackout of the Istrian peninsula. Therefore, in this case study we consider consequences of an outage of this line under eight scenarios. In the last ten years, the line 220 kV Plomin – Pehlin – Melina had five unexpected outages, resulting in the outage probability once in two years.

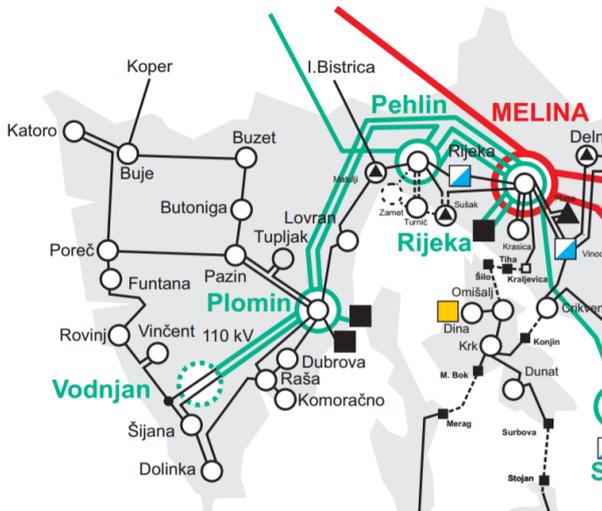
transient during an outage of thermal power plant Plomin (TEP 1 and TEP 2) or unavailability of the transmission lines, and to prevent a blackout of the Istrian peninsula.

4.1. Simulation results

All simulations are performed using Power Transmission System Planning Software (PSS®E) with input data from the Croatian TSO. Extreme cases are analysed: maximum production and minimum consumption and vice versa. Accordingly, the input data of interest for the simulations are outputs of TEP 1 and TEP 2 and load levels at each bus. The main double-system 220 kV transmission line is switched off in every simulation, thus simulating its outage. Therefore, two auxiliary lines and their maximum transmitted powers are analysed in the observed scenarios. After investigating historical data, eight scenarios are selected for detailed analysis. Table 1 contains data on thermal plants generation, load, overall injection/evacuation of electricity, status of battery energy storage, its size and the severance of the contingency. The critical state means that the power system is still in operation, but with increased power flows as compared to the normal operating conditions. Blackout indicates that there is no facility in operation mode in the power system network of Istria. Fig. 4 presents a simulation of the base case during the operation in the normal conditions. Fig. 5–12 show states from the PSS®E software for all eight scenarios. Red dashed circles denote the power flows at both auxiliary lines.



(a) Visual scheme



(b) Geographic position

Fig. 3. Visualization of the power system of Istrian peninsula.

For this reason, the installation of battery energy storage contributes to the security of supply of Istria, but also contributes to the preservation of production of the generating units (TEP 1 and TEP 2). If the blackout of the sub-system Istria occurs, these power plants cannot evacuate their production. Therefore, battery energy storage yields double benefit to the power system: to ensure a stable

4.1.1. Scenario I

Scenario I is represented in Fig. 5. Power outputs of thermal generators are at their maximum values: TEP 1 at 105 MW and TEP 2 at 210 MW, and the load is at its minimum, i.e. 85 MW. The difference between the production and the consumption in this state is 230 MW, which needs to be evacuated from the region. The outage of transmission line aux 2 is marked in orange, and the power flow is 118.7 MW, which is higher than the imposed flow limit (90 MW). After an outage of aux 2, the power flow at aux 1 increases to its power flow limit (70 MW), and immediately the Italian TSO switches off this line to ensure security in its power system. In this case, optimal BES capacity is 30 MW, allowing the dispatcher to react in under 30 minutes, and also to re-dispatch the generating units before the power system becomes unstable.

4.1.2. Scenario II

Scenario II, whose results are shown in Fig. 6, implies generator power outputs TEP 1 at 75 MW and TEP 2 at 120 MW, while the load is 85 MW. This scenario results in power difference 110 MW that needs to be evacuated from the Istrian peninsula. The power flows through lines aux 1 and aux 2 are 41.4 MW and 52.4 MW, respectively. If the increase in power flows would be up to 30 MW, the blackout could happen and accordingly, this state is

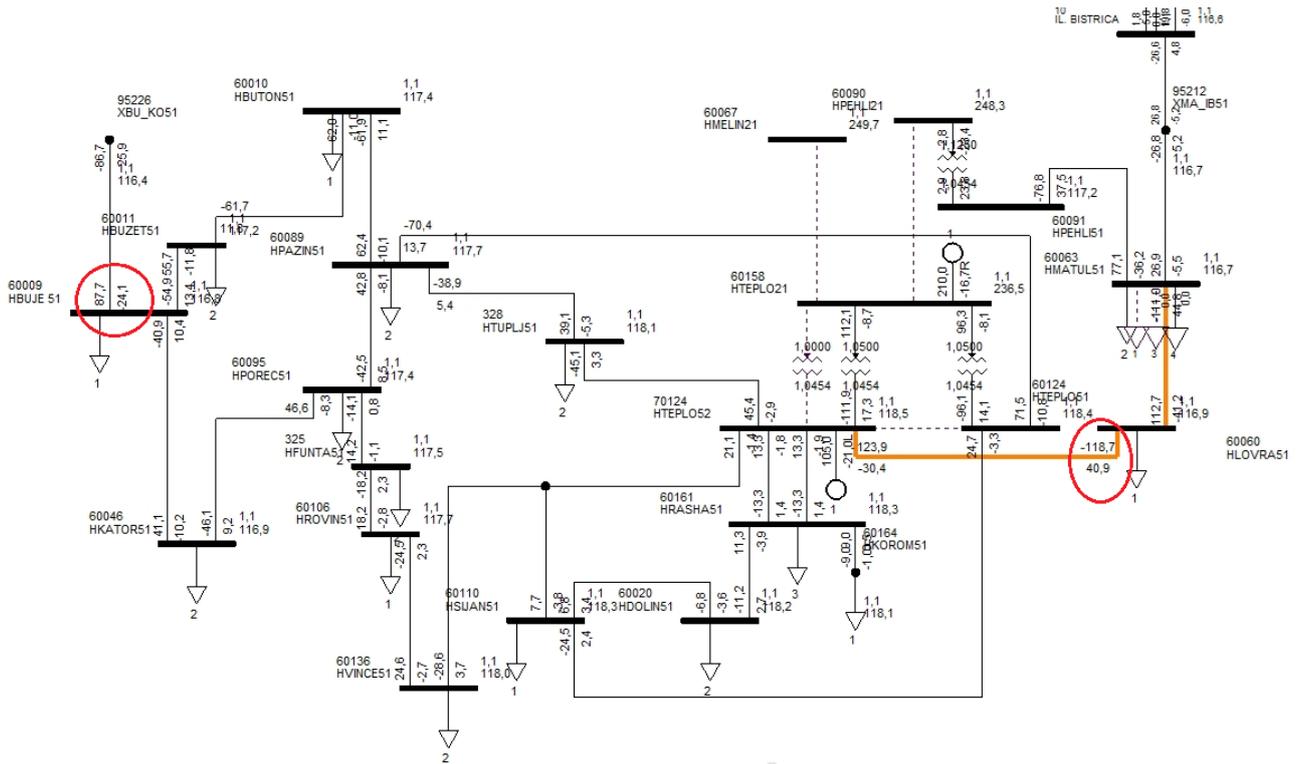


Fig. 5. State of network during scenario I.

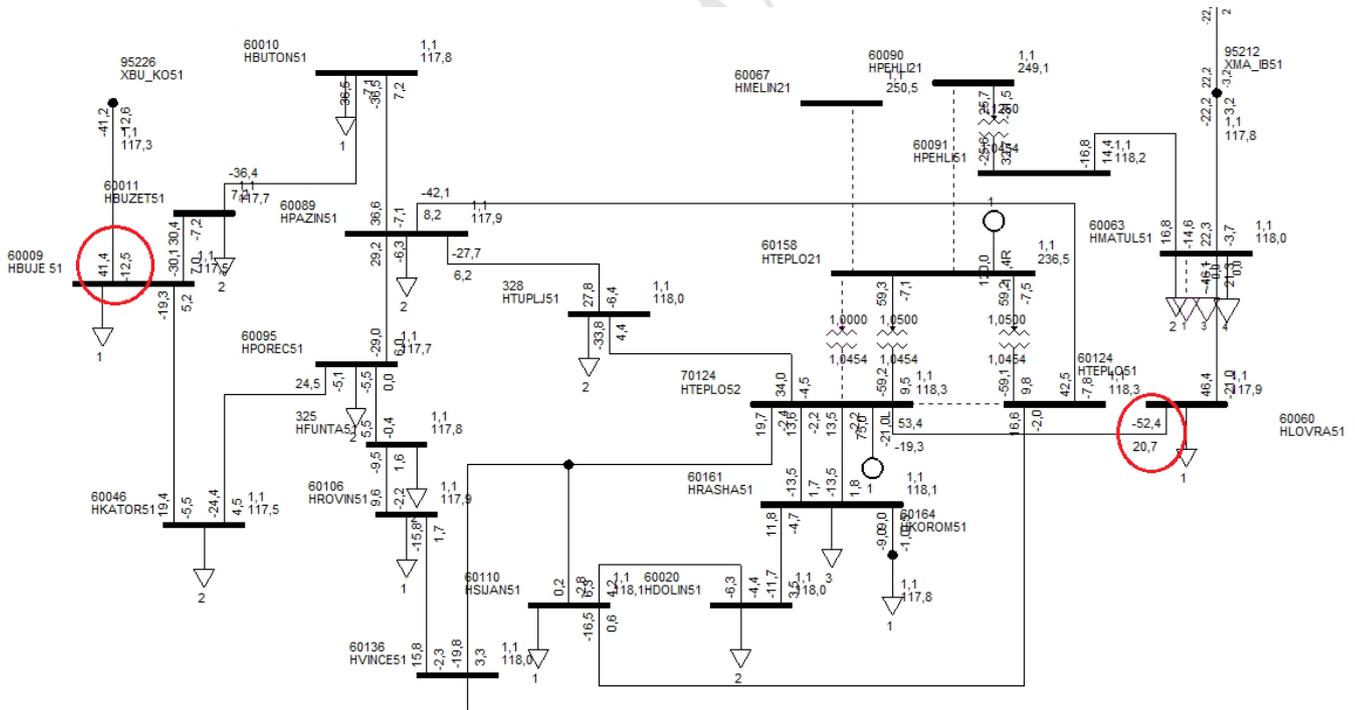


Fig. 6. State of network during scenario II.

4.1.5. Scenario V

Scenario V is shown in Fig. 9 and represents the worst possible case. Both thermal power plants are not in oper-

ation, while the consumption is at the maximum 230 MW. Both auxiliary lines are overloaded, and the blackout takes place. Thus, the whole demand needs to be supplied, and

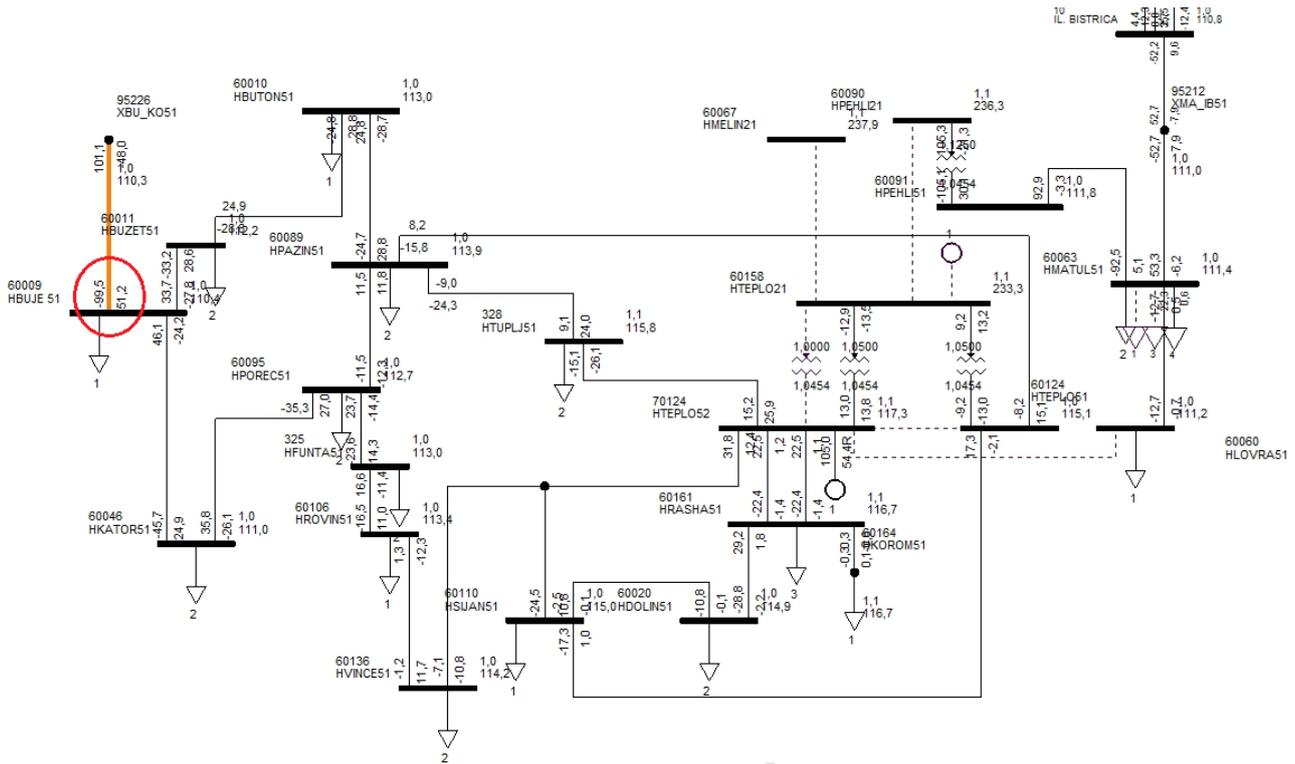


Fig. 9. State of network during scenario V.

4.1.6. Scenario VI

In scenario VI, presented in Fig. 10, the power output of generator TEP 2 is 120 MW, while TEP 1 is out of operation, and the consumption is at the maximum level, 230 MW. As a result, in this scenario 110 MW of power is needed to supply the demand. Both auxiliary lines are in operation, and power flows are 41.3 MW (aux 1) and 73.9 MW (aux 2). To prevent the occurrence of a blackout, installation of a 30 MW battery energy storage is needed. In this case, the battery would provide sufficient time for the dispatcher to react in this situation and for generators to re-dispatch their power outputs.

4.1.7. Scenario VII

Scenario VII is presented in Fig. 11. Power output of TEP 1 is 105 MW, TEP 2 does not operate, and consumption is again at maximum 230 MW. Power difference is 125 MW, and without any help, the blackout of the observed area occurs. The first auxiliary line has power flow 51.6 MW, while the second auxiliary line is switched off due to overload. Installation of a 20 MW battery energy storage would ensure secure operation of Istrian peninsula in this case.

4.1.8. Scenario VIII

The final scenario VIII is presented in Fig. 12. It considers the construction of a new 500 MW generation block at TEP Plomin instead of the existing fifty-year-old TEP1 generation block. This installation requires a new 400 kV substation Plomin to be integrated in the existing 400 kV

transmission line Melina - Divača (Slovenia). This scenario does not include any energy storage installation. The input data is modified as follows: generation block TEP 1 is decommissioned and the new one, TEPC500, is built. Joint operation of TEPC500 and TEP 2 results in 710 MW generation capability. The maximum demand in this scenario is 230 MW. This scenario considers a possible future project, which would spur the installation of a new 400 kV line. According to the current investment plans, installation of the new 400 kV line is strongly dependent on the construction of the new 500 kW generation block in Istria. The transmission capacity of the new 400 kV line is assumed at 1320 MVA. The power flows in Fig. 12 indicate that this scenario is resistant to the considered contingency and presents a secure solution for supply of Istrian peninsula.

4.2. Economic analysis

The results in Table 1 show the minimum installed battery storage capacity in order to avoid issues after a contingency of the main power line 220 kV Plomin – Pehlin – Melina in Istria. In scenarios I, II, IV and VI, installations of a 30 MW battery energy storage are sufficient to preserve system operation after a contingency. Scenario VII is the least harmful since it requires only 20 MW of storage capacity. However, scenarios III and V are critical. While in scenario III, the system can stay secure if a 100 MW battery energy storage is installed, scenario V results in a blackout even for higher energy storage capacity. Scenario VIII considers construction of a new 400 kV

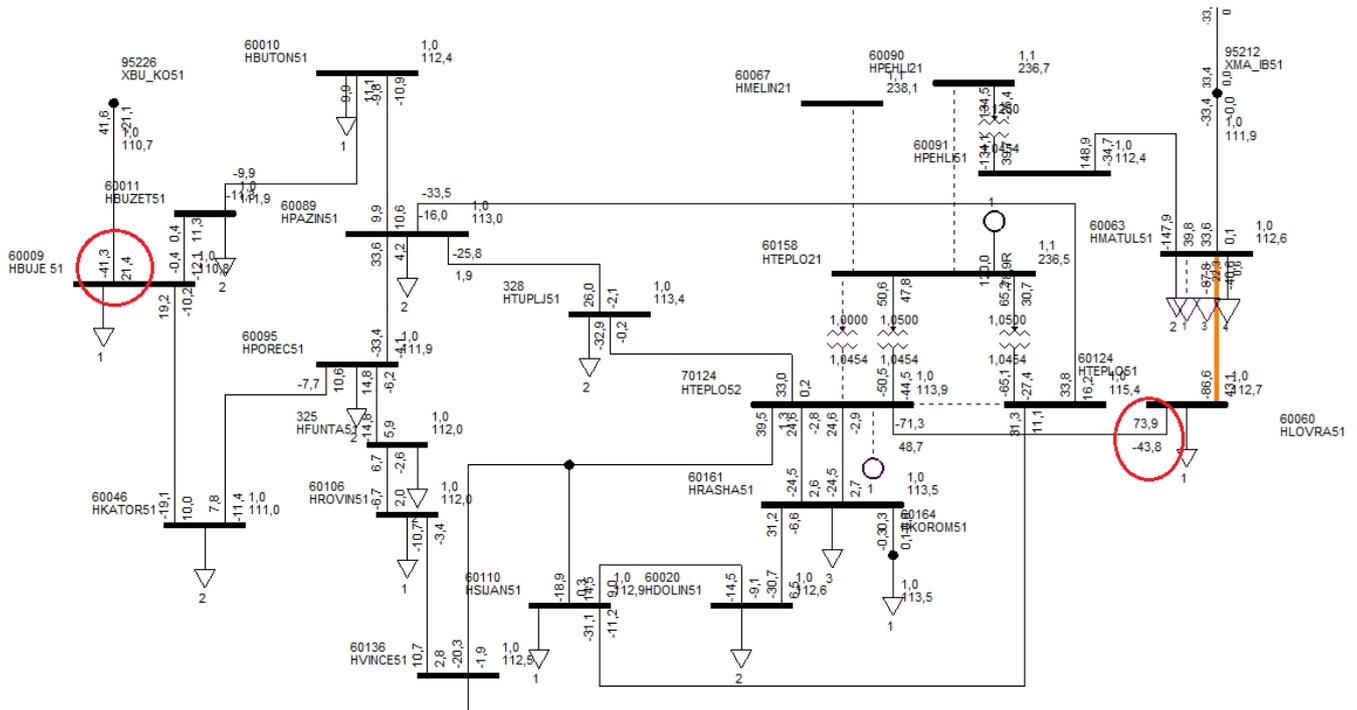


Fig. 10. State of network during scenario VI.

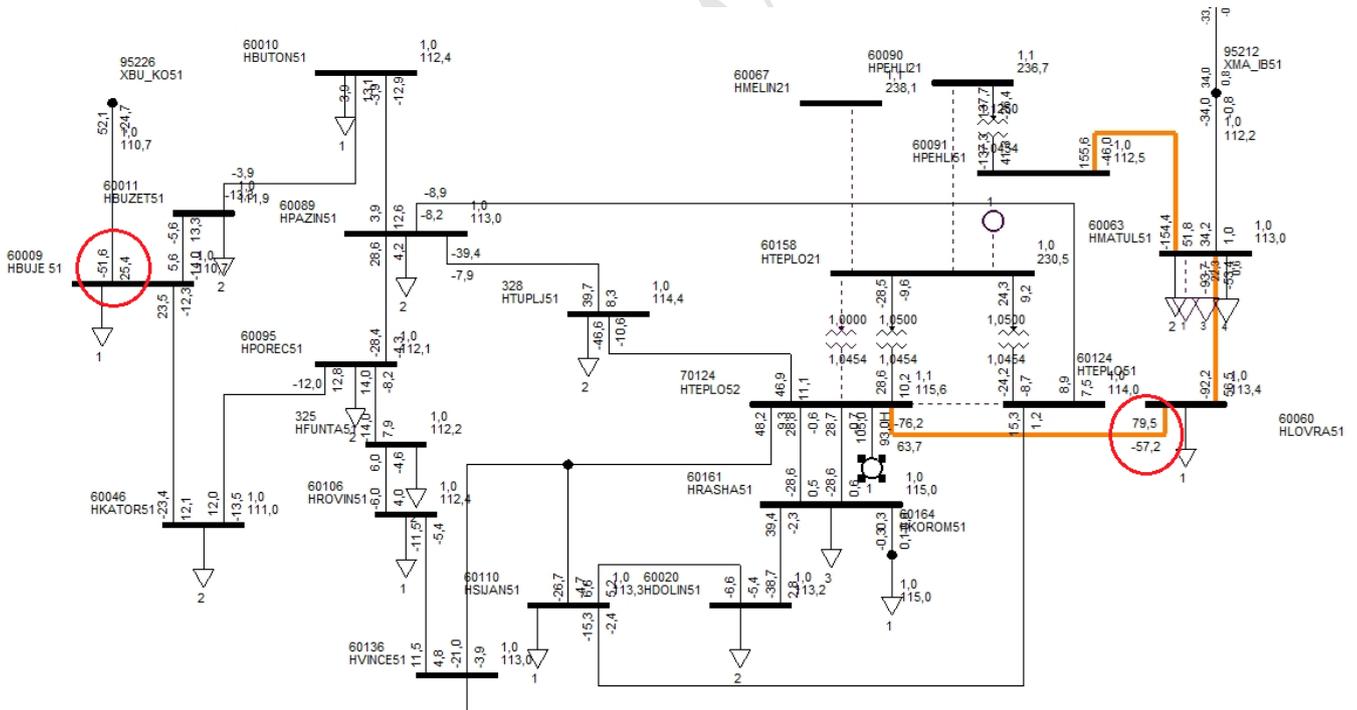


Fig. 11. State of network during scenario VII.

477 transmission line, which in theory would solve all the is-480
 478 sues in the Istrian subsystem. However, due to different481
 479 reasons, this construction is only considered in case a new

500 MW generation block is installed at thermal power
 plant Plomin.

It is assumed that battery energy system is priced at

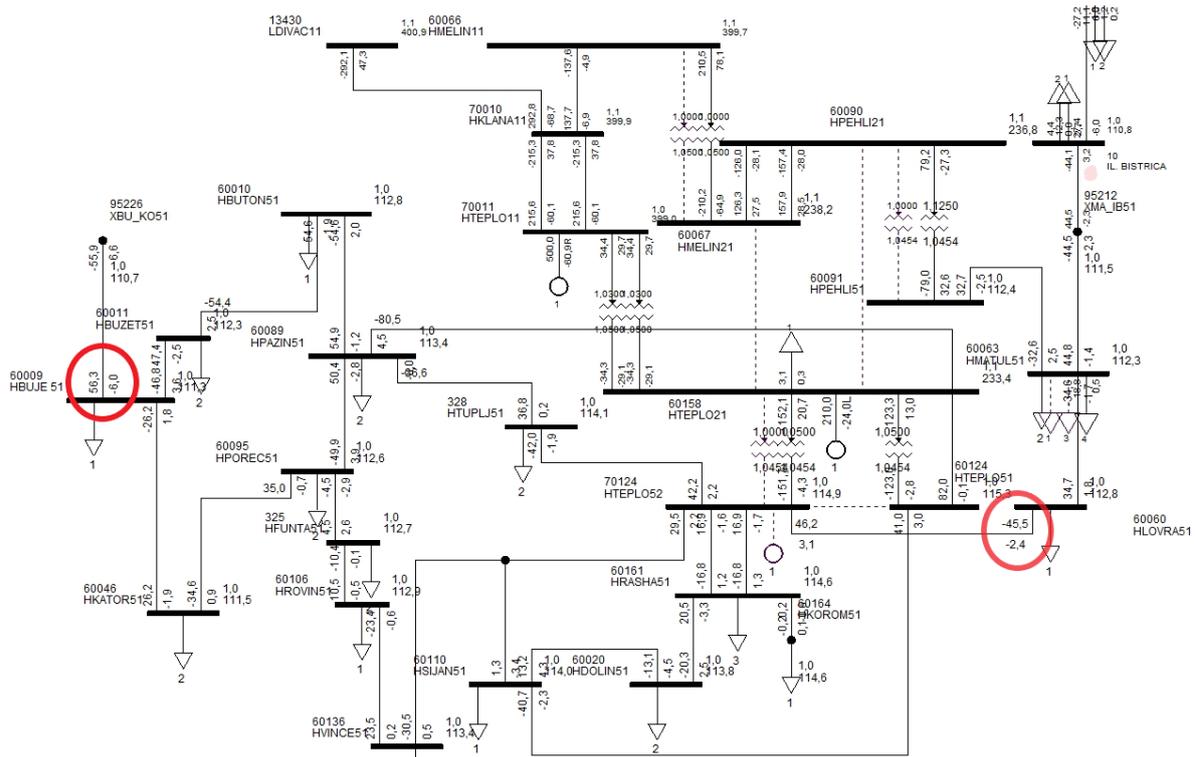


Fig. 12. State of network during scenario VIII.

450 €/kWh [35], which yields around 117 M€ installation⁵¹¹
 costs for 30 MW capacity, while 20 MW capacity costs⁵¹²
 around 78 M€. Estimated battery lifetime is 15 years.⁵¹³
 On the other hand, the cost of a 400 kV transmission line⁵¹⁴
 that would solve security issues in Istria is around 42 M€⁵¹⁵
 and its lifetime is 40 years. This would indicate that a
 new transmission line is still a more economical solution⁵¹⁶
 than energy storage. However, energy storage is a feasible
 option due to following reasons:

- Construction of a new transmission line is time consuming, usually taking at least 5-6 years to finish, and in some cases conditioned by other projects (in the presented case study this is the installation of a new 500 MW generation block at thermal power plant Plomin).
- In this regards, battery energy storage can be considered as a temporary solution, until the new transmission line is constructed.
- As opposed to transmission lines, which can only move⁵²⁹ electricity in space, battery energy storage can be additionally used to provide other services, such as voltage support, reserve provision and energy arbitrage.⁵³² However, there are regulatory issues related to this,⁵³³ since merchant-owned energy storage should not take⁵³⁴ part in regulated activities and vice versa. This issue is elaborated in details in [36]. For instance, if⁵³⁶ battery energy storage is used for reserve provision⁵³⁷ at 7 €/(MW/h) throughout the 15-year life time, the⁵³⁸

20 MW storage unit would generate 18.4 M€ income, while the 30 MW storage unit would generate 27.6 M€ income. In both cases, the income obtained through provision of reserves is 24% of battery energy storage capital cost.

5. Conclusion

Eight scenarios are investigated in details and battery energy storage integration is proposed to prevent to black-outs of the Istrian peninsula after a contingency, at least until the network is upgraded with a new 500 MW generation block at thermal power plant Plomin and a new 400 kV transmission line towards Divača (Slovenia). The selected scenarios represent worst-case system states which can occur after a contingency of the backbone 220 kV can occur. Installation of a battery energy storage system would ensure a more secure operation of the observed area in six scenarios, while in the worst-case scenario the only feasible solution to prevent blackouts is to construct a new transmission line. Having in mind a new power plant with installed capacity of 500 MW planned for the next decade, the best long-term solution would be to construct a new 400 kV transmission line. However, since construction of a new transmission line is a lengthy project and might not even be possible due to steep terrain and/or legal issues, battery storage solution would fit the current needs for security of the Istrian power system. Furthermore, battery storage can be installed to increase security until the new transmission line is constructed, after which

the battery storage can be relocated to other parts of the power network where necessary.

The future work will focus on interaction of energy storage and demand response on ensuring system security. Also, the role of energy storage in ensuring the N-1 criterion on radially connected islands will be analyzed.

Acknowledgement

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- Transmission lines are cost effective, but difficult to construct
- Battery energy storage is a solution for preserving security of a power system
- Battery energy storage enables the system operator to redispatch the lines
- By providing reserves, battery energy storage can retrieve 24% of its investment

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