

Role of Energy Storage in Ensuring Transmission System Adequacy and Security

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ABSTRACT

The main purpose of Transmission System Operators (TSOs) is to ensure stable, reliable and efficient operation of a power system. Large-scale integration of renewable energy sources has introduced additional challenges to active control of transmission power system.

Energy Storage (ES) is modelled and integrated within Croatian area using seven scenarios describing those states in the network: i) maximum generation and minimum load; ii) minimum generation and maximum load; iii) no generation; and assessing the size of battery ES which would prevent cascade outages. All simulations are performed in Power Transmission System Planning Software (PSS®E). The results are analysed in detail and conclusions on the role of ESS in providing transmission system adequacy and security is assessed.

KEYWORDS

Energy Storage, Transmission System Security

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 the end users at all times, while the scheduled and reasonably expected unscheduled outages of the system elements are taken into account. Security is the ability of the power system to resist impulsive disturbances, such as unexpected loss of system elements, e.g. generation units of transmission lines [1].

Ensuring adequacy and security in power system is extremely important to the system operator (SO). The main activities of the SO are secure operation of the power system, ensuring the availability of the transmission grid to satisfy 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 changes with other interconnected networks and ensuring the availability of all necessary ancillary services. In fact, the SO has a role to transmit a high-quality power in transmission grid in order to avoid interruptions and fulfil the criterion of stability and reliability.

SO usually runs its power system from a national control centre, but there are also regional centres which participate to maintain system stability and reliability. All commands are in the hands of dispatchers whose reaction and previous experiences are essential in presence of 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 limit in transmission network in which the power system should stay stable while following any possible contingency [2]. SO has an obligation to provide the following corrective interventions when appropriate (within 30 minutes after a contingency), and to bring the power system back to the normal operation state [3]:

- Generator re-dispatching,
- Usage of voltage and/or power flow control on regulation transformers,
- Network re-configuration,
- Manual load shedding.

On the technology side, there have been major advances in energy storage technology resulting in research demonstration projects where storage is used to provide corrective actions in case of a contingency as well. Possible energy storage applications depend on its type [4], which is generally divided in power-intense and energy-intense energy storage. To clarify, power-intense energy storage usually can be discharged in very short time period, while energy-intense storage can be discharged within several hours.

This article considers a power-intense battery energy storage which would be able to inject a large amount of power needed in short-term periods, within seconds or minutes. Li-ion battery belongs to this type of batteries since it can quickly respond to the necessary requirements of the power system [5]. Moreover, their advantages include high energy density and efficiency, long lifetime, low operation and maintenance costs, as well as diverse applicability. To help power operators when a disturbance occurs, this paper analyses which capacity of battery energy storage can assist them in very short time period, up to 15 minutes. Case study is represented on Istrian peninsula – a part of the Croatian power system. This part is fairly isolated from the rest of the power system and experiences problems with quick response in case of a contingency. Also, there are significant differences in consumption and production which are represented through seven scenarios while the main transmission power line is not in operation. The main effort of this paper is to ensure that power system stays stable after a contingency using the appropriate capacity of battery energy storage system, as well to ensure that power generating plants can sell their electricity in the market.

This paper is organized as follows: section Literature review provides an overview of research articles on this topic, section Method describes a formulation of the used method, and section Case study presents results tested on the western part of the Croatian power system. Finally, last section provides relevant conclusions.

LITERATURE REVIEW

Contingencies in power system can be managed using preventive or corrective approach. Preventive approach means that no SO operation is needed to preserve the security of the power system, while corrective approach requires SO operations 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 [6] introduce a problem formulation of fast – response battery storage systems as a part of an enhanced security constrained optimal power flow. This formulation is able to reduce flows in overloaded power lines in 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 power lines presenting the effectiveness of this model in the post – contingency approach. Similarity of our approach such is that battery storage system is used to act as a fast responding facility in post – contingency period to reduce overloaded power lines while the generating units start ramping to increase or decrease power outputs. However, the main contribution of this paper are the real-world simulation scenarios and using a detailed PSS®E (Power Transmission System Planning Software) grid model.

Authors in [7] present a smart protection scheme based on the synchronized measurement technology that contributes in a mitigation of a partial or system-wide blackout. Two system states are analyzed, low and high consumption. The difference is in the using other power system devices, such as batteries in our case, while similarity is the program tool in which the model is analysed.

Different blackout prevention techniques are proposed in [8], 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 auto load shedding scheme cannot prevent disturbances, then separating power system into islands helps. Another approach is modelled in [9] where authors obtain an islanding solution of the power system by introducing a spectral clustering method based on generator coherency grouping. Their analyses demonstrate the efficiency of the proposed algorithm in prevention of blackouts on IEEE 9-bus and 118-bus system. This model is quite different than ours, because our approach does not allow losing connection to neighbouring parts of the power system.

Using utility-scale battery energy storage when performing corrective measures along with generator re-dispatching is proposed in [10]. The model of energy storage system is included in security-constrained unit commitment. When a contingency occurs, battery is discharged and the power is injected into the network. This ensures minimum necessary time in which generators are re-dispatched, in other words to buys time for slow ramping generators to act. The authors show that energy storage reduces the overall system cost through both, the corrective actions and energy arbitrage.

Corrective actions are further investigated in [11]. 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 nested Benders decomposition approach that demonstrates good convergence properties. The proposed model is tested on Spanish power system. We also use real-world power system, but implement the model in a state-of-the-art simulation software.

In [12], the authors propose a two-stage model in which a generating company maximizes its profit in the master problem, while the bidding strategy is verified in the subproblem. In case corrections, i.e. re-dispatch, is need due to congestion, a Benders cut is added to the master problem.

In distribution level model presented in [13], energy storage is modelled to ensure optimal values of active and reactive power at different prices by performing different applications, e.g. arbitrage, reserve and frequency response. The results show that providing such applications jointly could be more beneficial for energy storage owners as well as for distribution system operators due to better utilization of the network. This paper deals with few applications of energy storage, while our approach is to introduce only one application and examine it in more details.

Authors in [14] examine the effect of energy storage on the number of outages in distribution power system. Results show significant reduction in outage duration, while on the other hand frequency of outages is increased slightly by introduction of energy storage devices as additional elements in the power grid.

Formulation of the frequency dynamics constrained unit commitment strategy supported by a fast-response large-scale battery, is proposed in [15], very like to our paper approach. The uncertainty of renewable generation is addressed by interval-based optimization and the purpose of batteries is 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, and the power system costs and wind curtailment are reduced.

Applications of li-ion batteries, such as grid support, automotive and back-up power are investigated in [16]. 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 to that, providing back-up power supply for a long-time period, as well as a high number of partial charging or discharging cycles of li-ion batteries, are proven in [17].

METHOD

The method consists of the steps presented in Fig. 1. First, all input data are loaded into a PSS@E (Power Transmission System Planning Software) grid model: load parameters, transmission network parameters, energy storage data, and generator data. We observe two characteristic network states:

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

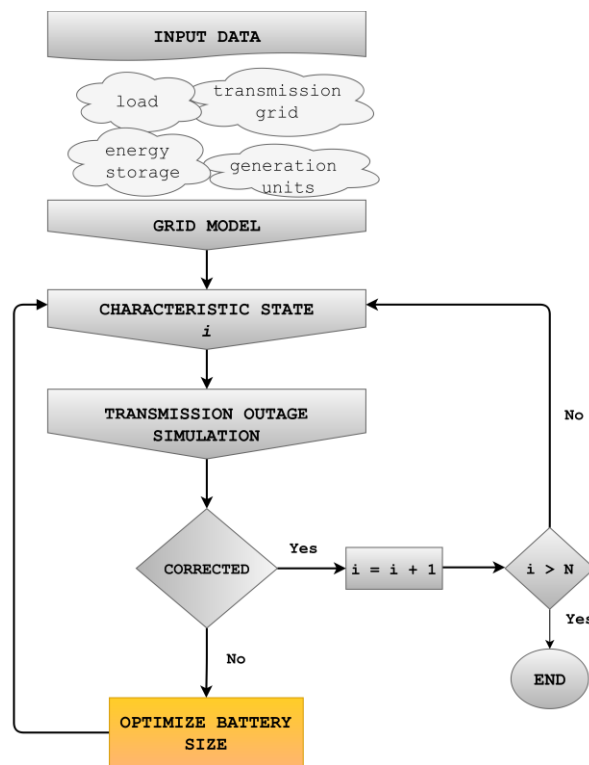


Figure 1. Flow diagram of the proposed method

If a contingency is not removed, then the battery energy storage is optimized to the size that provides sufficient time to the dispatchers and allows them to perform corrective actions which are appropriate for the contingency. Battery energy storage will inject or extract power according to the conditions in the power system. If the analysed 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 Figure 2a, on a small power system with two generators, two lines, a load and an energy storage. Assume that generator G1 is cheaper than G2 and covers almost the entire load at bus 2. Accordingly, power flow is directed from bus 1 to bus 2. If line l1 suffers an outage, the system should be able to continue operating within the operational limits. System operator must act quickly and perform generator re-dispatch. Figure 2b shows power flow through the remaining line l2 after a contingency has occurred. Power injection by energy storage is shown in Figure 2c. At t_0 , when the contingency has occurred, power flow through line l2 increases to the line's upper short-term rating (this needs to be below the level at which 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 generator units start ramping and energy storage device decreases its power until period t_3 . Power flow between t_1 and t_2 reaches its short-term emergency rating, and it can be in that state for few minutes. G1 ramps down to decrease power output, while G2 ramps up to increase its power output. After t_3 , power flow through line l2 reaches its long-term continuous rating. When the disturbance is eliminated, the power system can return in normal state, as well as the power flows through lines l1 and l2.

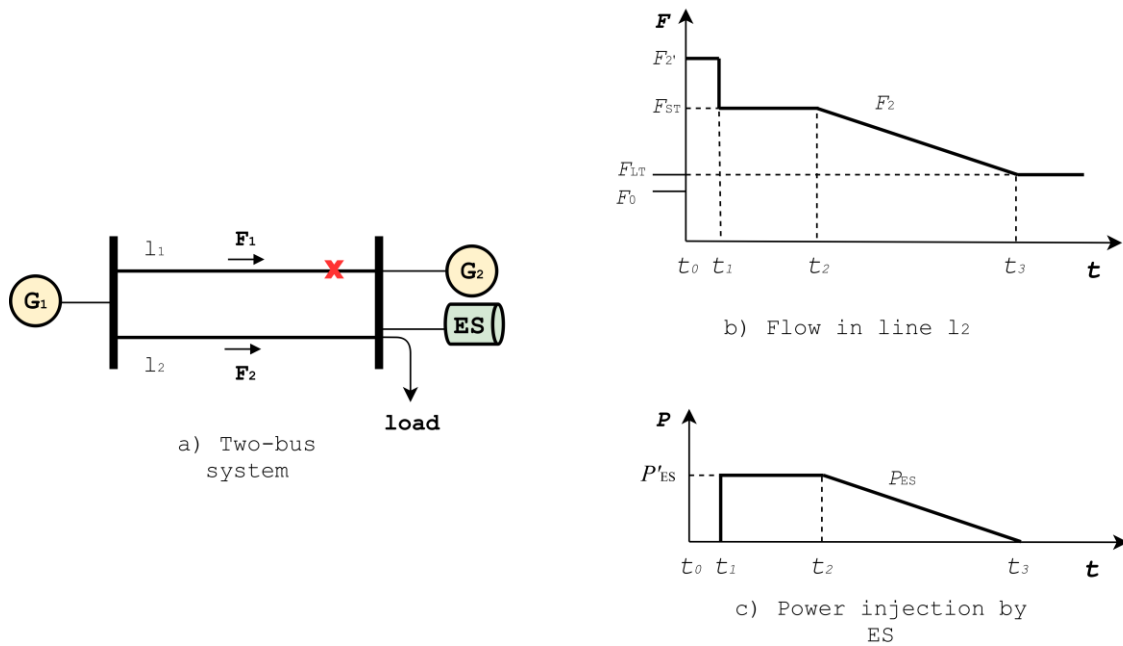


Figure 2. Corrective control approach

CASE STUDY

Description of Croatian power system

Croatian power system is experiencing large growth of renewable sources. The northwestern part of the system is supplying Istrian peninsula, which is connected to the rest of the Croatian power system by one main and two auxiliary transmission lines, as shown in Figure 3. This part of country is considered as a relatively isolated part of the Croatian power system, although it supplies with electricity about 100,000 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 analysed in both system states. The transmission lines of great significance in those cases are:

- a) Line 220 kV Plomin – Pehlin – Melina – the main,
- b) Line 110 kV Buje – Koper – aux 1,
- c) 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. Other 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, and these two auxiliary evacuation routes may result in a complete blackout of Istrian peninsula.

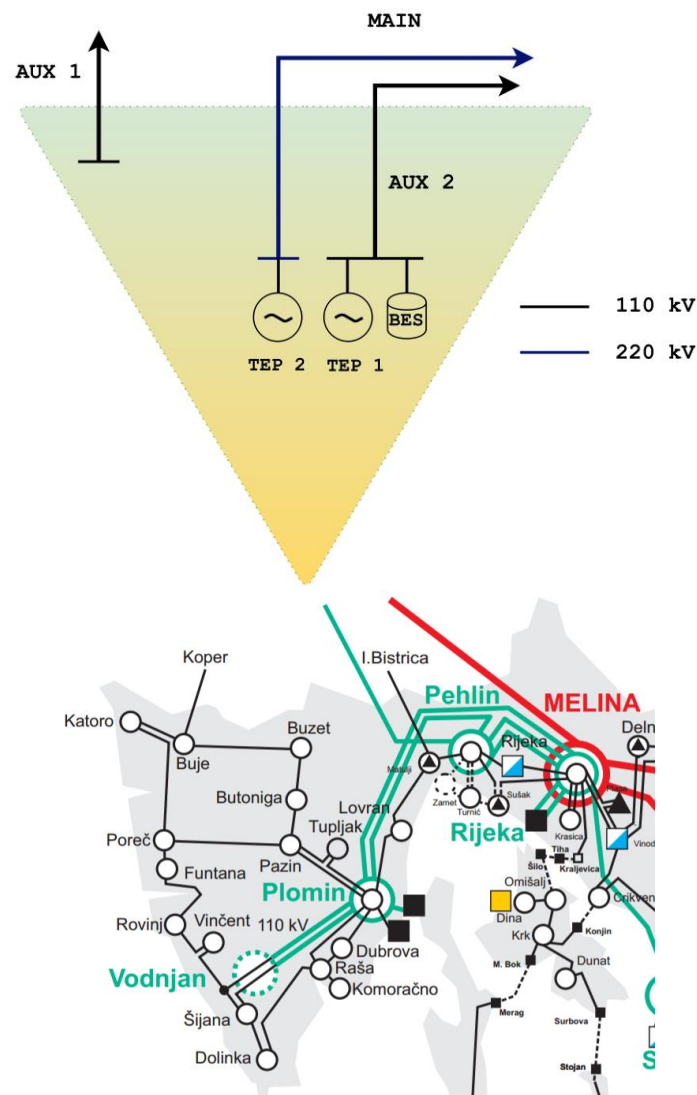


Figure 3 Visualization of the power system of Istrian peninsula.

For this reason, the installation of battery ES, 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 subsystem Istria occurs, the power plants cannot evacuate their production. Therefore, battery energy storage yields double benefit to the power system: to help ensuring a stable transient during an outage of thermal power plant Plomin (TEP 1 and

TEP 2) or unavailability of the transmission lines, and to prevent the blackout of the Istrian peninsula.

Simulation results

All simulations are performed using Power Transmission System Planning Software (PSS®E) with input data from the Croatian TSO. Extremes cases are analysed: maximum production and minimum consumption and vice versa. Accordingly, 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. We therefore analyse two auxiliary lines and their maximum transmitted powers in the analysed scenarios. After investigating twelve possible scenarios, seven are selected for detailed description.

In Table 1, after summation of production and consumption, the fifth column presents the needed injection/evacuation power in/from Istrian peninsula. The sixth column provides an information if the battery energy storage should charge or discharge in this scenario and the seventh column shows optimal BES capacity to be connected to the network. The final column provides information if the state of the power system is critical or a blackout has occurred. 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 of the power system indicates that there is no any facility under operation mode in the power system network (they are out of the operation).

Figures 4–10 represent static states from PSS for all seven scenarios. Red dash circles denote the amount of power flow at both auxiliary lines.

Table 1. All scenarios generated by PSS

Scenarios	TEP 1 (MW)	TEP 2 (MW)	Load (MW)	Injection (+) / Evacuation (-)	BES	BES size (MW)	Critic/Blackout
I	105	210	85	-230	Charging	30	Blackout
II	75	120	85	-110	Charging	30	Critic
III	105	0	230	125	Discharging	100	Blackout
IV	0	210	85	-125	Charging	30	Critic
V	0	0	230	230	Discharging	>120	Blackout
VI	0	120	230	110	Discharging	20	Blackout
VII	105	0	230	125	Discharging	20	Blackout

Scenario I

Scenario I is represented by Figure 4. Power outputs of thermal generators are at their maximum values: TEP 1 is 105 MW and TEP 2 is 210 MW, and 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 insure security level in its power system. In this case, optimal BES capacity is 30 MW, allowing the dispatcher to react in under 30 minutes, and also the generator units would have enough time to re-dispatch their power output before the power system becomes unstable.

Scenario II

Scenario II, whose results are shown in Figure 5, implies generator power outputs TEP 1 at 75 MW and TEP 2 at 120 MW, while the load is at 85 MW. This scenario results in power difference up to 110 MW that need to be evacuated from 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 named critic.

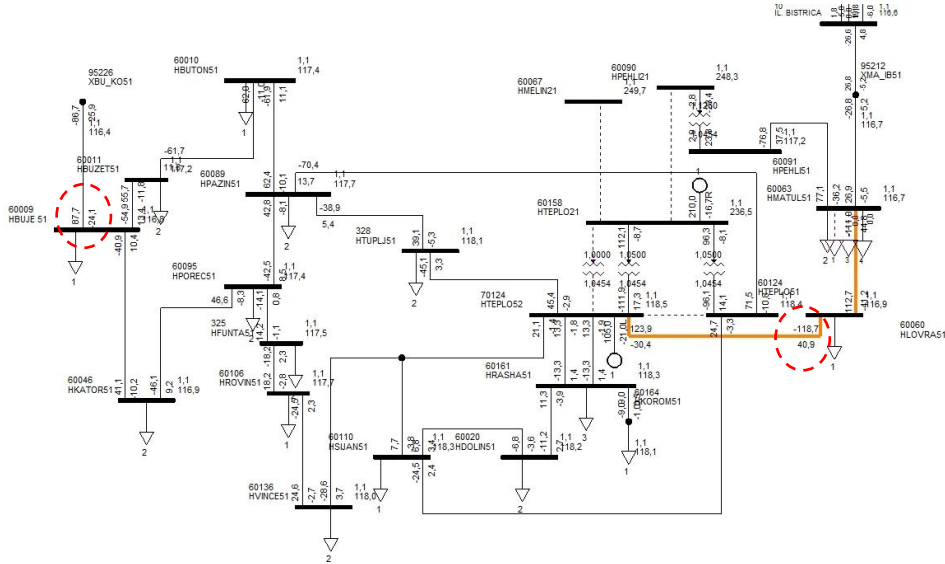


Figure 4. State of network during scenario I

Moreover, this state could be additionally alleviated because the power flows in this part of Europe have a direction from Southeast Europe to Northwest Europe, especially during the period with higher production of hydro power plants in the south part of Croatia. Thus, an installation of BES with capacity of 30 MW would ensure higher level of security in observed area.

Scenario III

The resulting power flows of scenario III are shown in Figure 6. Generator output of TEP 1 is 105 MW, TEP 2 is not in operation, and maximum consumption is 230 MW. Power difference in this state is 125 MW, and this amount of power needs to be injected into the power system. However, both auxiliary transmission lines, aux 1 and aux 2, are above their permitted values, i.e. 94.8 MW and 147.9 MW, respectively. This state results in a complete blackout of the observed area. On the other hand, to prevent this failure and provide normal operation of the power system, installation of 100 MW capacity of power-intensive BES is required.

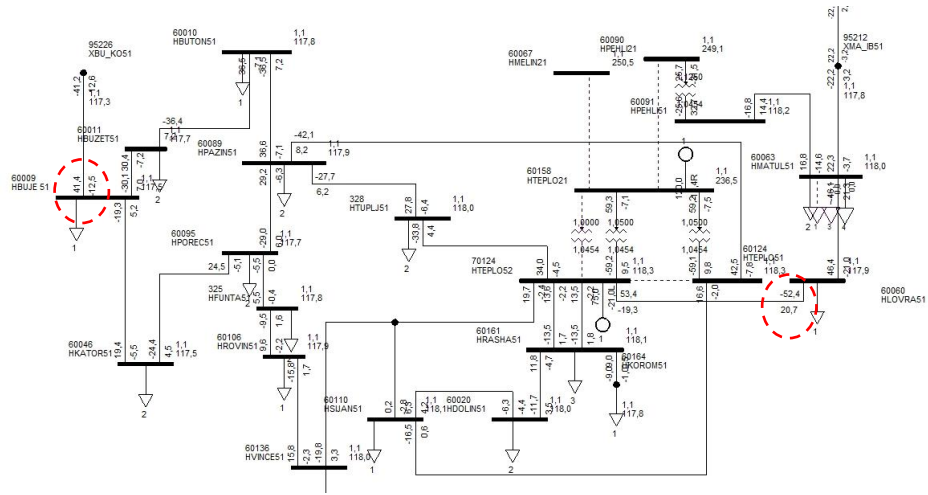


Figure 5. State of network during scenario II

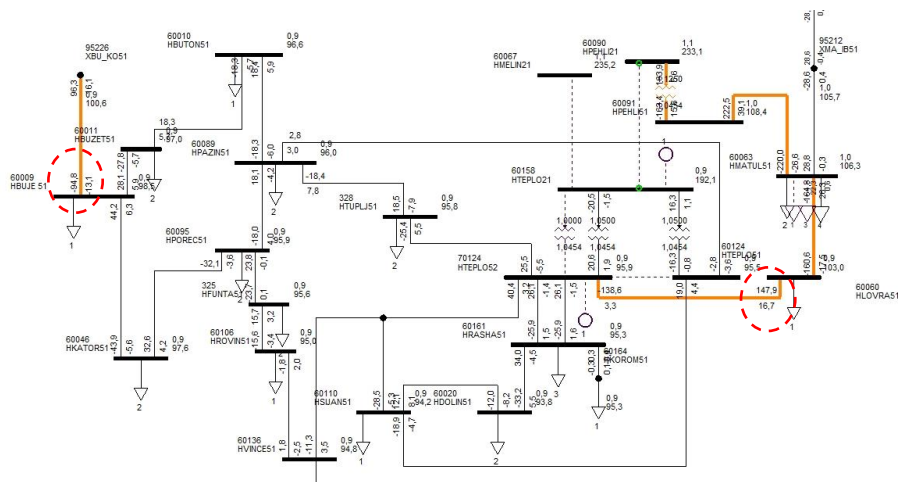


Figure 6. State of network during scenario III

Scenario IV

Figure 7 presents static state of the analyzed power system during scenario IV. Thermal power plant TEP 1 is out of operation, while TEP 2 produces at the maximum production level, 210 MW. Consumption is at its minimum, 85 MW. The needed evacuation capacity is 125 MW. Auxiliary transmission lines are both operating very close to their maximum permitted values, aux 1 is at 49.8 MW and aux 2 is at 58.1 MW. Similarly, to scenario II, this state is called critic, and installation of 30 MW of BES would increase the security during operation.

Scenario V

Scenario V is shown in Figure 8 and represents the worst possible case. Both thermal power plants are not in operation, 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 the installation of BES of any kind is not sufficient to help the power system. The best solution for this case is building a new transmission line.

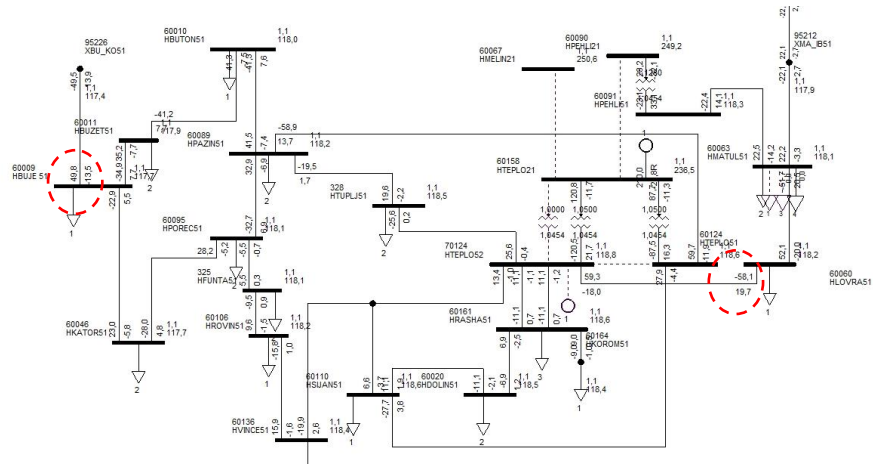


Figure 7. State of network during scenario IV

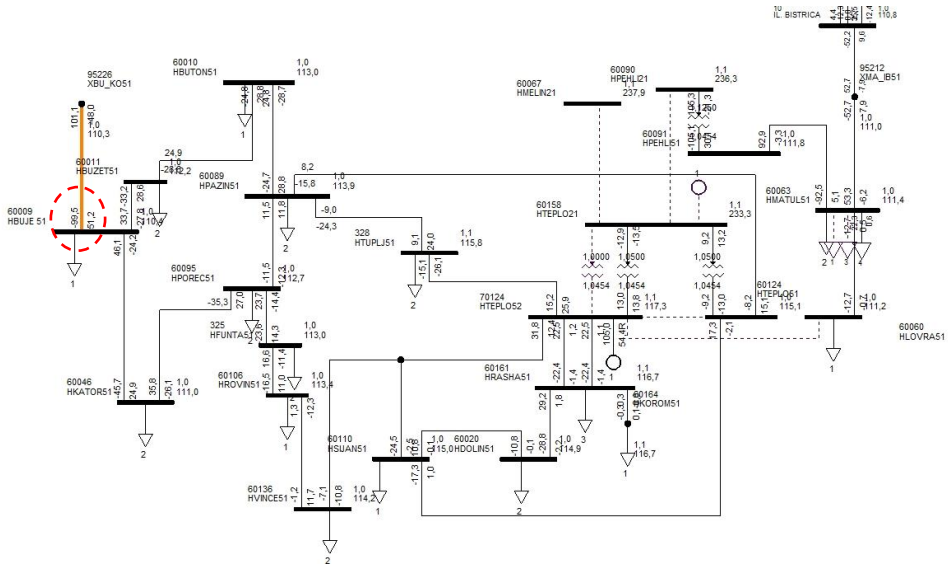


Figure 8. State of network during scenario V

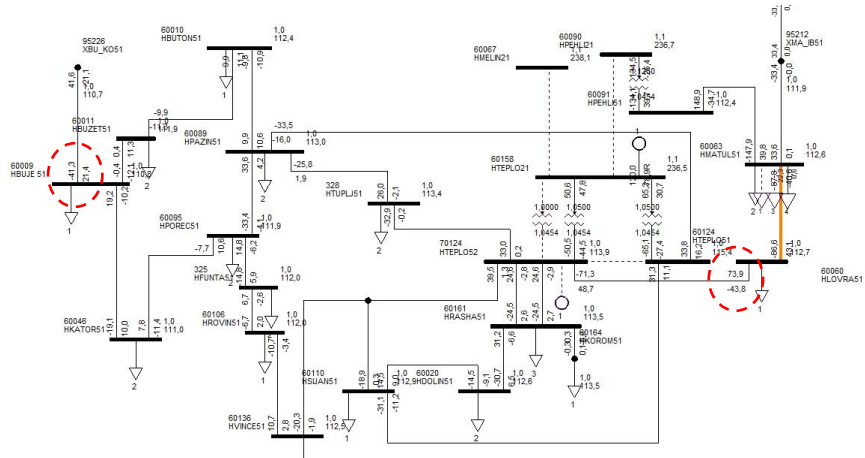


Figure 9. State of network during scenario VI

Scenario VI

In scenario VI, presented in Figure 9, 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 injected power is needed to supply the demand. Both auxiliary lines are under operation, and power flows are 41.3 MW (aux 1) and 73.9 MW (aux 2). To prevent occurrence of a blackout, the installation of a BES with 20 MW capacity would help to preserve the power system stability. In this case, the battery would provide sufficient time for a dispatcher to react in this situation and for generators to re-dispatch their power outputs.

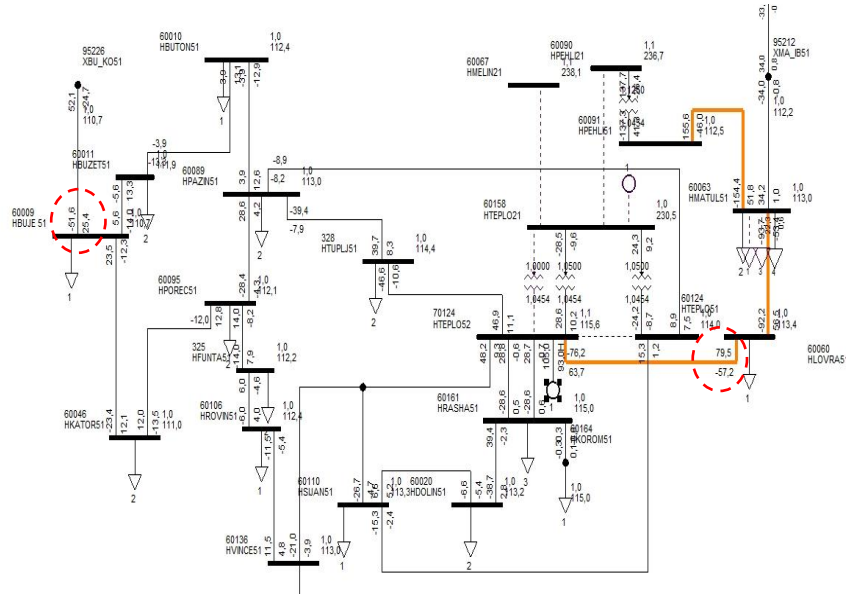


Figure 10. State of network during the scenario VII

Scenario VII

Finally, the last scenario VII is presented in Figure 10. 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 BSS would ensure secure operation of Istrian peninsula in this case.

Economic analysis

We assume that battery energy system is priced at 399 €/kWh [18], which yields around 97 M€ installation costs for 30 MW capacity (25 blocks), while 20 MW capacity (17 blocks) costs around 66 M€. Estimated battery lifetime is around 15 years. The lifetime of transmission line is 40 years. A new 110 kV transmission line with power capacity 123 MVA would be enough if there is no any new power plant. The cost of 110 kV transmission line is around 6.5 M€, double 220 kV transmission line is around 16 M€, while 400 kV transmission line costs around 18 M€. So, the optimal solution can be to build a new 110 kV line if there would not be a new power plant, or on the other hand, a new double 220 kV transmission line, if the power plant would be installed. Even if the building period is included, and losses (value of loss of load) are around 12 M€ in six years (with the probability around 200 MWh/year), indicates that new transmission line is still a more economic solution for this case study when the battery storage system is not used to provide any other services. But, in

case when TSO needs to avoid losses and to ensure transmission system adequacy and security in short period, the battery system can be a suitable solution.

CONCLUSION

Seven scenarios are investigated in details and BES integration is proposed to prevent to blackouts of the Istrian peninsula after a contingency. The selected scenarios represent possible worst-case system states during which a contingency of the backbone 220 kV can occur. Installation of a BES system would ensure better 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. After economic analyses, it is obvious that new 110 kV transmission line is still a more economic solution for this case study when the battery storage system is not used to provide any other services. But, in case when TSO needs to avoid losses and to ensure transmission system adequacy and security in short period, the battery system can be a suitable solution.

ACKNOWLEDGE

This work has been supported in part by Croatian Science Foundation and Croatian Transmission System Operator (HOPS) under the project Smart Integration of RENewables (I-2583-2015).

REFERENCES

1. UCTE, Operational Handbook, June 2004
2. UCTE, Emergency Operations, May 2006
3. Grid Management Committes, Implementing Single Outage Contingency (N-1) Operational Criterion
4. Geurin, S. O., Barnes, A. K. and Balda, J. C., Smart Grid Applications of Selected Energy Storage Technologies, IEEE PES, Conference Publications, pp 1 – 8, 2012
5. Brown, R. E., Network Reconfiguration for Improving Reliability in Distribution Systems, IEEE Power Engineering Society General Meeting, pp 1 – 6, July 2003
6. Wen, Y., Guo, C., Kirschen, D. S., Dong, S., Enhanced Security-Constrained OPF With Distributed Battery Energy Storage, IEEE Transactions on Power Systems, Vol. 30, No.1, pp 98 – 108, January 2015
7. Mikac, E., Kirinčić, V. and Skok S., Smart Protection Scheme for the Power Subsystem of Istria Region, International Journal of Contemporary ENERGY, Vol. 1, No. 1, pp 13 – 23, February 2015
8. Yusuf, J., Sakib, F. and Ahsan, Q., Study of Blackout Prevention of a Power System, 9th International Conference on Electrical and Computer Engineering, pp 1-4, December 2016
9. Esmailian, A. and Kezunovic, M., Prevention of Power Grid Blackouts Using Intentional Islanding Scheme, IEEE Transactions on Industry Applications, Vol. 53, No. 1, pp 622 – 629, January 2017
10. Wen, Y., Guo, C., Pandžić, H. and Kirschen, D. S. Enhanced Security-Constrained Unit Commitment With Emerging Utility-Scale Energy Storage, IEEE Transactions on Power Systems, Vol. 31, No. 1, pp 652 – 662, January 2016
11. Martineu-Crespo, J., Usaola, J. and Fernandez, L., Security-Constrained Optimal Generation Scheduling in Large-Scale Power Systems, IEEE Transactions on Power Systems, Vol. 21, No. 1, pp 321–332, February 2006

12. Yamin, H., Al-Sgtash, S. and Shahidehpour, M., Security-Constrained Optimal Generation Scheduling for GENCOs, *IEEE Transactions on Power Systems*, Vol. 19, No. 3, pp 1365–1372, August 2004
13. Moreira, R., Moreno, R and Strbac, G., Value of Corrective Network Security for Distributed Energy Storage Applications, *IET Generation, Transmission & Distribution*, Vol. 10, No. 7, pp. 1758–1767, 2016
14. Raihan, M. I. A., Impact of Energy Storage Devices on Reliability of Distribution System, 2nd International Conference on Electrical, Computer & Telecommunication Engineering (ICECTE), pp 1–4, December 2016
15. Wen, Y., Li, W., Huang, G. and Liu X., Frequency Dynamics Constrained Unit Commitment With Battery Energy Storage, Vol 31, No. 6, pp 5115–5125, 2016
16. Stan, A.-I., Świerczyński, M., Stroe, D.-I., Teodorescu, R. and Andreasen, S. J., Lithium ion battery chemistries from renewable energy storage to automotive and back-up power applications — An overview, 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp 713–720, 2014
17. Hiroshi, H. and Ippei, H., Evaluation and Application Technology of New Batteries in UPS Procedure, *Fuji Electric Review*, Vol. 58, No. 4, pp 191–196, 2012.
18. Available at: <https://www.greentechmedia.com/articles/read/energy-storage-costs-lcos-lazard-lithium-ion-flow-batteries>