Techno-economic assessment and optimization of the energy storage unit in the distribution network

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***Abstract*—The paper present results from the techno-economic assessment and optimization of an energy storage unit located in the mid-voltage distribution grid. The size and location of the unit are selected based on the predefined list of requirements and available locations. A second order cone programming optimization algorithm is applied to asses the installed capacity and all the results are validated against the voltage and loading limits with the power-flow calculations. The approach is described through a case-study example in which the potential benefits and optimal daily operation schedule are also shown in order to achieve additional welfare increase through the losses reduction and potential ancillary services provision.**

***Index Terms*—energy storage, distribution grid, second order cone programming**

I. Introduction

The environmental impacts the modern society is producing are being mitigated through an attempt to reduce the green house emissions [1] from all sources, namely power and energy and transport sectors. In the last decade the power and energy sector has been witnessing a big challenge with the massive penetration of the renewable energy sources (RES) [2]. This increase in decentralized production that is inherently stochastic and cannot be predicted perfectly is creating more requirements for the power systems to efficiently integrate these resources. This big paradigm shift from the centralized to the decentralized and smaller scale production of energy via RES is additionally followed by the fast development of electric vehicles that also have a significant stochastic element that needs to be accounted for [3] through different innovate approaches using the available benefits of energy storage on a large scale [4] or smaller scale [5], microgrids [6] and efficient utilization of current resources [7]. Many of the changes are happening in the distribution grid and the summed influence is then propagated even to the transmission system level. Therefore, solving the problem on the smaller scale, in the distribution system level, can yield benefits for the system as a whole. And as many of the energy storage technologies are gradually reaching wider integration maturity they are being considered for a range of potential benefits they can bring to the power system and its end users. Firstly, the electrical energy storage (EES) systems can ensure the N-1 criterion in the segments of the power system [8]. Secondly, the EES can provide contingency reserve as suggested by [9] or act as virtual synchronous machine to provide damping and system inertia [10]. Thirdly the voltage and secondary frequency regulation in addition to other market provided ancillary services can be provided by the energy storage [11]. The common approach is to observe and optimize the day-ahead market participation of an storage system (energy arbitrage) jointly with the reserve and balancing market participation [12]. This paper deals with finding the solution to the insufficient N-1 criterion considering and comparing the traditional solutions consisting of investment into new connection feeders and transmission lines and transformer capacities to the potential investment into the battery storage. It observes the advantages and disadvantages of all the different possible solution.

The main contribution of the paper is the application of the wholesome energy storage deployment process including the analysis of the input data to correctly identify the needs, determination of the location of the EES, optimization of the storage size and capacity through the second order cone optimization algorithm and finally accounting the power flow constraints (voltage and loading limits) and additional operational benefits of the EES.

The paper is structured as following. Introduction and motivation is given in the section I. Methodology description followed by the load flow and optimization problem formulation is done in the sections II and III respectively. The results of the case study are presented in the Section IV with the conclusions drawn in the final Section V.

II. Techno-economic Assessment Methodology

The results from the techno-economic assessment of the investment into electrical energy storage are presented. The paper shows the results from a case-study data-set coming from a segment of a medium voltage distribution grid. The methodology of the approach includes all the required steps to evaluate the EES investment project. The methodology uses the conclusions from the input data analysis paired with the mathematical confirmation of the results through the second order cone optimization algorithm. The main objective was to suggest the optimal EES parameters in order to ensure the N-1 criterion for the customers of the observed network. At

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the same time, the task was to analyze the potential additional benefits (voltage regulation, losses reduction, frequency reserve provision, increase of RES integration capacity) this investment into the energy storage can bring. As it can be seen from the Fig. 1 that shows the flow diagram of the process the initial step consists of the representative electrical model development including all the relevant parameters (transformer data, overhead line and cables data, consumption and peak load data etc.). This is done in specialized power system analysis software NEPLAN [13]. Once the detailed model is developed preliminary power flow analysis is performed based on the historical data consisting of the consumption profiles, voltage profiles and loading profiles. The critical networks scenarios are identified and are used in the later stages of the process through the optimization algorithm run developed in the optimisation environment of FICO Xpress [14]. Based on the optimization results optimal battery capacity and power are determined as well as the optimal daily operation plan to satisfy the power quality requirements. After that step the optimization results are compared to the historical analysis conclusions and final battery capacity and according cost are suggested.

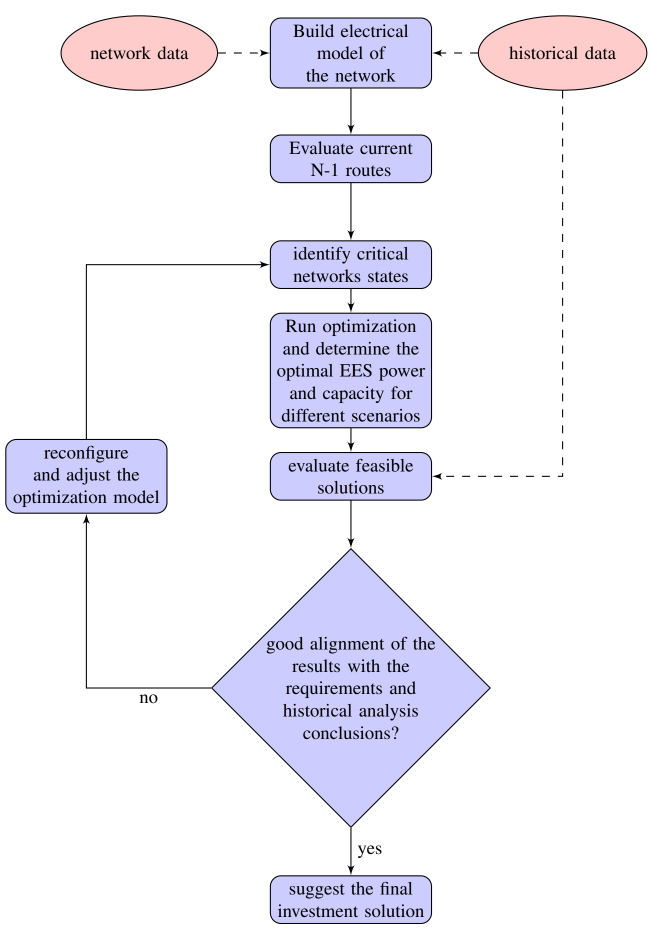

Fig. 1. Methodology flow diagram

III. Optimisation algorithm

A. Load flow formulation

As a part of the mentioned second order cone optimisation algorithm convex load flow formulation used in this paper that is based on *Distflow* branch equations [15], [16] which were relaxed to Second Order Cone Programming (SOCP) problem [17]. There are two main SOCP load flow formulations; Branch Flow Model (BFM) used in this paper and Bus Injection Model (BIM) derived from Semidefinite programming [18]. BFM is proven to be equivalent to BIM in [19] and both formulations are valid.

For two nodes i and j connected by line with impedance $Z_{ij} = R_{ij} + jX_{ij}$ on which flows power $S_{ij} = P_{ij} + jQ_{ij}$ following equations based on *Distflow* formulation can be written:

$$U_j^2 = U_i^2 - 2\left(P_{ij}R_{ij} + Q_{ij}X_{ij}\right) \tag{1}$$

$$I_{ij}^2 = \frac{1}{U_i^2}\left(P_{ij}^2 + Q_{ij}^2\right) \tag{2}$$

where U_i is line voltage magnitude of node i. Two approximations are used:

$$i_{ij} = I_{ij}^2 \tag{3}$$

$$v_i = U_i^2 \tag{4}$$

These approximations (3, 4), transform (1) to linear form:

$$v_j = v_i - 2\left(P_{ij}R_{ij} + Q_{ij}X_{ij}\right) \tag{5}$$

Equation (2) is second order cone which needs to be relaxed to inequality to form convex SOCP constraint:

$$i_{ij}v_i \geq P_{ij}^2 + Q_{ij}^2 \tag{6}$$

B. Optimization formulation

The optimization algorithm is applied on measurement data for one week period that includes the maximum load day (in the case for observed network it is a approximately the same for a cold summer day (February) and hot summer day (July)) and used to minimize EES size in all time periods t according to (7)

$$min \sum_t P_{ESS,t}^2 + Q_{ESS,t}^2 \tag{7}$$

s.t.

$$U_{min} \leq U_{i,t} \leq U_{max} \tag{8}$$

$$I_{i,j_t} \leq I_{i,j_{max}} \tag{9}$$

By using this optimization formulation algorithm provides feasible solutions with all voltages and currents complying to Grid code limitations in all simulated time periods (8, 9) and finds minimal ESS power to fit the constraints. ESS capacity is calculated a posteriori based on optimization results, simulated load levels and targeted autonomy level.

IV. Case study example

The objective of the techno-economic assessment is to evaluate different solutions that can ensure satisfactory N-1 criterion and continuous production of local distributed energy sources for the distribution network segment supplied from the transformer station TS 35/10 kV Cazma. The main goal is to assure the continuous supply strictly after the unexpected event utilizing the local distributed generation resources. Prerequisite for this is advancedly configured protection system than can compensate for the loss of the main power route. The electrical energy storage system of the carefully chosen characteristics would provide enough autonomy (e.g. 2 hours) during which time the distribution system operator (DSO) can carefully reconfigure and supply the different segments of the observed network from the alternative routes.

A. Current state

The Fig. 2 shows the modelled segment of the 10 kV network supplied from the corresponding 35/10 kV transformer stations. The peak load of the observed relevant network segment is approximately 4,5 MW in normal operating conditions and approximately 6,0 MW in case of various faults or network reconfiguration (transformer station reconstruction or unavailability, significant distributed generator maintenance (2 MW) or unavailability, 35 kV transmission line fault etc.). Under these conditions the majority of the customers in the observed segment of the network (primarily TS 35/10 kV Cazma supply area) cannot be supplied.

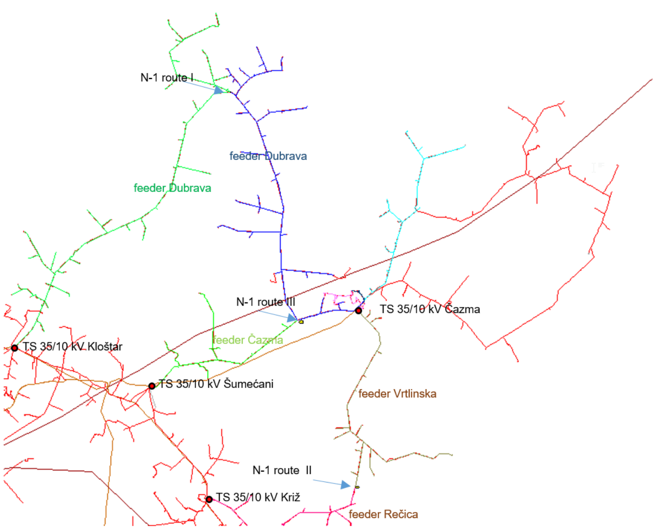

Fig. 2. Observed segment of the 10 kV network

The modelled case study networks represent the rural and semi-urban network but with significant number of larger and important customers that are specifically sensitive to potential loss of quality power supply.

The excerpt of the year of historical data is shown on Fig 3. It is important to note that all the customers with connected power greater than 50 kW are modelled with their exactly imported demand curves while the rest of the

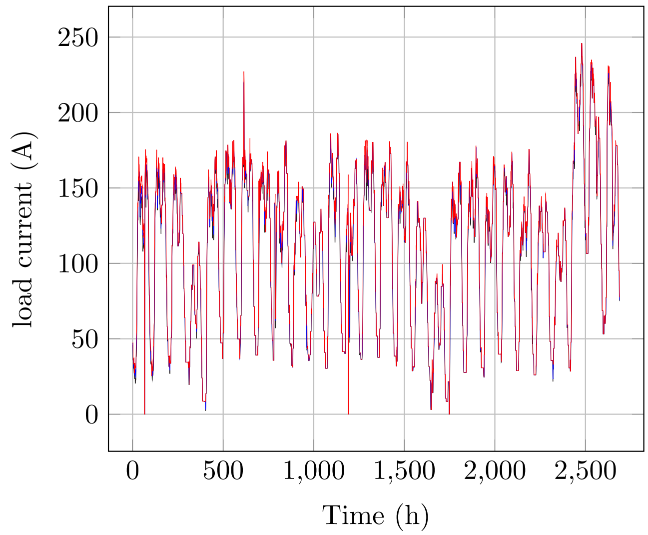

Fig. 3. Excerpt (Feb 2018) of the load measurements historical data (years 2017 and 2018) when max load was measured

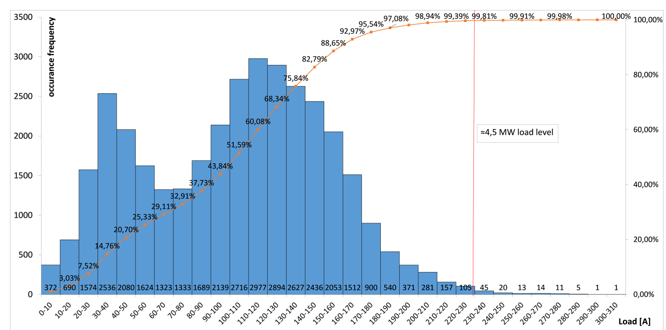

Fig. 4. Histogram of load occurrences of transformer station 35/10 Cazma for years 2017 and 2018 - maximum 15-min values

customers (approximately 30% of the total load) follow the load curve of the according supplying transformer station and characteristic curves of the main customer groups that are: public lighting, household, small entrepreneurship and small industry. Histogram of the load level occurrences is shown on Fig. 4.

The calculated capacities of the available different N-1 routes are shown in the table (Table I). Current N-1 routes cannot satisfy all the demand in case the usual supply route is not available. The best result assumes the reliability of 86% which means that approximately 15% of the time (load level) the route will not be sufficient to supply the customers which can incur significant costs.

An example of the voltage profile for the maximum load scenario of the segment of the observed network for the best available N-1 route shows that voltage drops and voltage levels are fairly out of allowed range even under the circumstances the distributed generation continues the production (Fig. 5 and Fig. 6) .

TABLE I
CALCULATED CAPACITIES OF THE N-1 ROUTES

N-1 route No.	Supply area	Supply capability		Max load level	Route reliability assessment[a]
	TS 35/10 kV	*DG production 2 MW*	*no DG production*		
Route I	TS 35/10 kV Klostar	0%	27%	2,4 MW	*61%*
Route II	TS 35/10 kV Sumecani	12%	45%	3,3 MW	*86%*
Route III	TS 35/10 kV Kriz	10%	35%	2,8 MW	*75%*

[a]Percent of time simulated load is lower than the N-1 route capacity

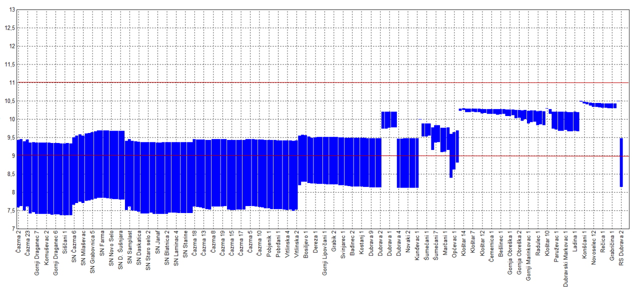

Fig. 5. Voltage profile throughout the busses of the observed network segment for the N-1 supply route II

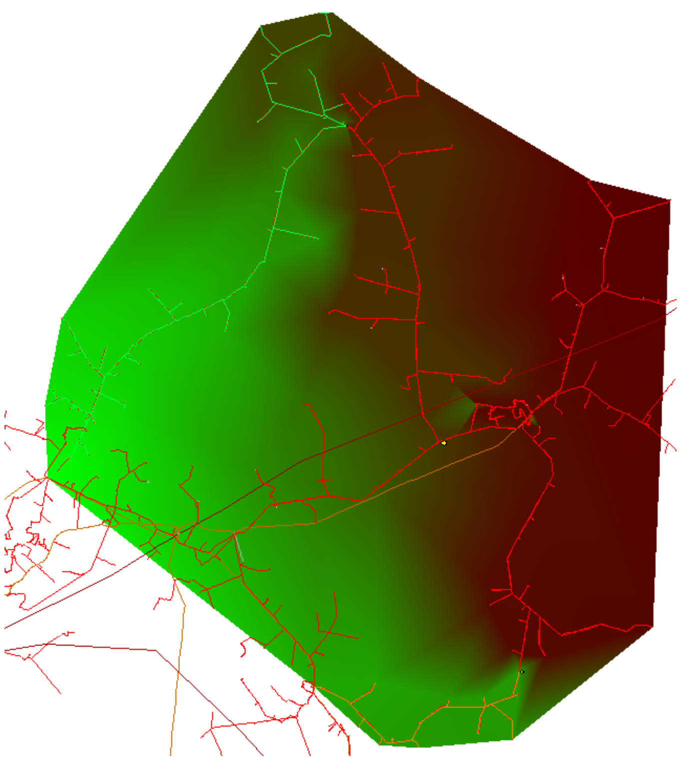

Fig. 6. Visualisation of the voltages out of range represented in red color for the N-1 supply route II

B. Optimisation results

The results of the optimization process that aimed to minimize the installed power of the battery energy storage, therefore minimizing the investment are shown in the table (Table II). The storage of the minimum rated power of 1,3 MVA and 3 MWh capacity can provide enough energy (in terms of active power) and reactive power voltage support for all the voltages on the observed network segment to stay within the boundaries (Fig. 7).

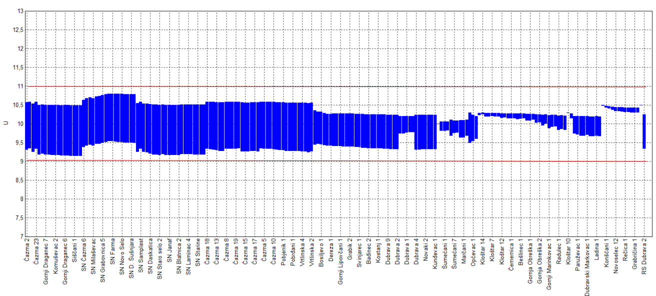

Fig. 7. Voltage profile throughout the busses of the observed network segment for the N-1 supply route II with the battery storage (1,3 MVA rated power and 3 MWh capacity)

The battery storage through the simulated period of the optimization process under the assumption the alternative route is used for an extended period of time provides significant amount of reactive power to support the voltage. The output power results of the optimisation process with the usage of battery storage for the supply though the route II and route III are shown on Fig. 8 and Fig. 9 respectively. It can easily be concluded that the route II requires significantly smaller battery size and can be selected as a preferred route to fulfill all the required actions and prerequisites regarding the protection system reconfiguration. In the current system the Croatian DSO is not penalized for not meeting the N-1 criterion (there are no system interruption penalties). It is expected that in the future the penalties will b introduced and the value of storage for ensuring the N-1 criterion will further increase. The detailed analysis of these potential cost avoidance will be part of the future work.

C. Alternatives comparison

The optimisation results of the battery storage parameters yielded two alternative solutions that were additionally compared cost-vise and advantage-vise to the traditional solutions. All considered alternatives are:

TABLE II

OPTIMAL BATTERY ENERGY STORAGE PARAMETERS

Solution variant	**Supply area (N-1)**	**Battery rated power**	**Battery storage capacity**[a]		
			1h autonomy	***2h autonomy***	***3h autonomy***
1.	TS 35/10 kV Sumecani (Route II)	1,3 MVA	2 MWh	3 MWh	3,5 MWh
2.	TS 35/10 kV Kriz (Route I)	1,8 MVA	2 MWh	3,5 MWh	5 MWh

[a]Autonomy to supply the full load through one N-1 route long enough to allow the DSO to reconfigure the network and maintain the supply via different routes for different parts of the networks

TABLE III

ALTERNATIVE INVESTMENT VARIANTS COMPARISON

Number	**Alternative description**	**Cost**[a]	**Advantages**	**Disadvantages**
1.	35 kV line Kriz-Cazma (13 km length)	0,95 mil EUR	- Ensures the N-1 criterion not only for the 10 kV voltage level network but also for 35 kV voltage level network	- Not compliant with the general development plan which aims to transfer the network to 110/20 kV system; - Complicated legal procedure to obtain the new corridor - Long completion period expected (5+ years)
2.	35 kV line Klostar-Cazma (19 km length)	1,35 mil EUR		
3.	Transition from 10 kV to 20 kV operational voltage level	1,65 mil EUR	- Increases significantly the potential of seamless integration of additional distributed energy and renewable energy resources from current 2 MW level to 5+ MW level - Technically the best long term solution solution and in accordance with long-term development plans of 110/20 kV system	- Very large number of elements that require the replacement or refurbishment (10 kV lines, transformers, transformer stations)
4.	Battery energy storage (N-1 route II) - power of 1,3 MVA and capacity 3,5 MWh	0,95 mil EUR	- Shortest expected completion period (less than 1 year) - scientific and research potential - Capability to use the battery energy storage for losses reduction and frequency reserve provision - Voltage and reactive power support - Increases the potential of distributed generation and renewable energy resources integration and adoption of new standards and technologies	- New technology without operational experience inside the Croatian DSO - Strict requirement on the protection system (parallel operation of 10 kV and 35 kV networks, breaker equipment replacement required) - Cost significantly increases for larger capacity and installed power
5.	Battery energy storage (N-1 route III) - power of 1,8 MVA and capacity 5,0 MWh	1,45 mil EUR		

[a]The total cost includes, if required, the protection system improvement implementation (approximately 0,15 mil EUR)

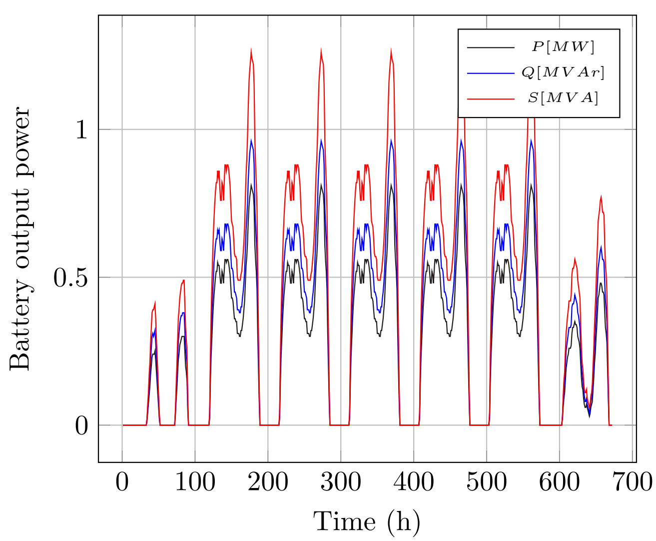

Fig. 8. The output of the optimisation process - power curve of the battery energy storage for the supply route III (TS 35/10 kV Sumecani)

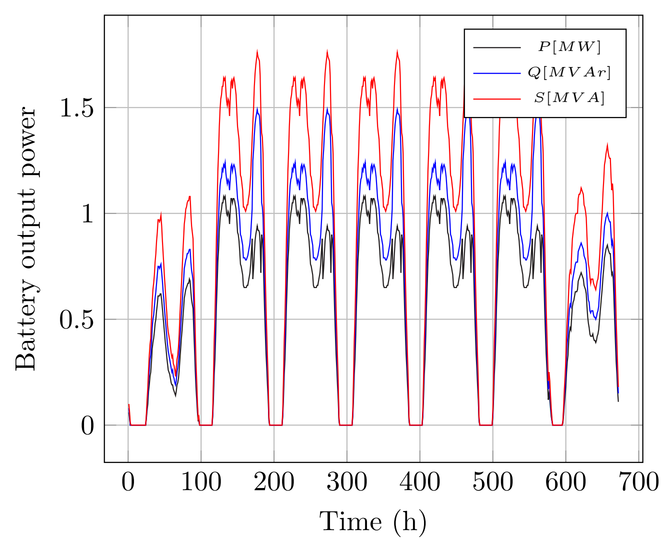

Fig. 9. The output of the optimisation process - power curve of the battery energy storage for the supply route II (TS 35/10 kV Kriz)

1) Investment into the 35 kV grid - new 35 kV supply route transmission line Kriz-Cazma (13 km in length);
2) Investment into the 35 kV grid - new 35 kV supply route transmission line Klostar-Cazma (19 km in length);
3) Investment into the 20 kV grid - transition of the supply area Cazma from the 10 kV to the 20 kV voltage;
4) Investment into the energy storage - battery energy storage to fully enable the N-1 route 2 (inverter power of 1,3 MVA and capacity of 3,5 MWh);
5) Investment into the energy storage - battery energy storage to fully enable the N-1 route I (inverter power of 1,8 MVA and capacity of 5,0 MWh).

Table III summarizes the comparison of the different investment options. It can be seen that from the technical aspect the best long term solution is the transition to the 20 kV voltage level. Solution that can be applied in the shortest time horizon and that can provide an array of additional long term benefits is the installation of battery energy storage. The 20 kV voltage level and battery storage solution are not mutually exclusive, meaning that they complement each other and increase the effectiveness of both solutions. Additionally it is important to note that the energy losses analysis could also add another beneficial effect of energy storage and transition of 20 kV and these analysis will be in the focus of the expansion of this work.

V. Conclusion

The paper presented the techno-economic assessment process that includes the optimization of an energy storage unit. The results from the case study that had the main aim of ensuring the N-1 criterion for a segment of the 10 kV distribution network are shown. The optimization of the energy storage parameters was conducted using the developed second order cone optimisation algorithm. The investment into battery energy storage was compared to alternative investment scenarios. The potential benefits and disadvantages of all the considered solutions were listed, specially for the battery energy storage which can help to reduce losses, provide the frequency reserve and support the voltage. Furthermore the paper has shown that the investment into the battery storage is technically satisfactory and has similar or lower cost compared to other capital investment solutions. The future work will include improvements of the techno-economic assessment methodology to consider more future trends such as integration of electric vehicles and in accordance improvements of the optimisation process and will include detailed analysis of the losses in the network for different scenarios.

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References

[1] O. Ogunrinde, E. Shittu, and K. K. Dhanda, "Investing in renewable energy: Reconciling regional policy with renewable energy growth," *IEEE Engineering Management Review*, vol. 46, no. 4, pp. 103–111, 2018.

[2] T. W. V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, "IPCC, 2018: Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global," World Meteorological Organization,, Geneva, Tech. Rep., 2018.

[3] I. Pavic, N. Holjevac, M. Zidar, I. Kuzle, and A. Neskovic, "Transportation and power system interdependency for urban fast charging and battery swapping stations in Croatia," in *2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 2017, pp. 1465–1470.

[4] "DOE Global Energy Storage Database," Sandia National Laboratories, USA, Tech. Rep., 2018, [Online] www.energystorageexchange.org/projects.

[5] M. Zidar, P. S. Georgilakis, N. D. Hatziargyriou, T. Capuder, and D. Skrlec, "Review of energy storage allocation in power distribution networks: applications, methods and future research," *IET Generation, Transmission Distribution*, vol. 10, no. 3, pp. 645–652, 2016.

[6] N. Holjevac, T. Capuder, N. Zhang, I. Kuzle, and C. Kang, "Corrective receding horizon scheduling of flexible distributed multi-energy microgrids," *Applied Energy*, vol. 207, pp. 176 – 194, 2017.

[7] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Transactions on Industrial Informatics*, vol. 7, no. 3, pp. 381–388, Aug 2011.

[8] Z. Zbunjak, H. Basic, H. Pandzic, and I. Kuzle, "Phase shifting autotransformer, transmission switching and battery energy storage systems to ensure n-1 criterion of stability," *Journal of Energy*, vol. 64, no. 3, pp. 285–298, 2016.

[9] V. Guerrero-Mestre, Y. Dvorkin, R. Fernández-Blanco, M. A. Ortega-Vazquez, and J. Contreras, "Incorporating energy storage into probabilistic security-constrained unit commitment," *IET Generation, Transmission & Distribution*, vol. 12, pp. 4206–4215, Oct. 2018.

[10] C. Yuan, C. Liu, T. Zhao, X. Xiao, and N. Tang, "Energy storage configuration strategy for virtual synchronous machine," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2016, pp. 1–6.

[11] A. S. Tsagkou, E. D. K. D. I. Doukas, D. P. Labridis, A. G. Marinopoulos, and T. Tengnér, "Stacking grid services with energy storage techno-economic analysis," in *2017 IEEE Manchester PowerTech*, June 2017, pp. 1–6.

[12] E. Drury, P. Denholm, and R. Sioshansi, "The value of compressed air energy storage in energy and reserve markets," *Energy*, vol. 36, no. 8, pp. 4959 – 4973, 2011.

[13] "Neplan," https://www.neplan.ch/, accessed: 2019-03-27.

[14] "Fico xpress optimisation," https://www.fico.com/en/products/fico-xpress-optimization, accessed: 2019-03-27.

[15] M. Baran and F. Wu, "Optimal capacitor placement on radial distribution systems," *Power Delivery, IEEE Transactions on*, vol. 4, no. 1, pp. 725–734, Jan 1989.

[16] M. E. Baran and F. F. Wu, "Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing," *IEEE Power Engineering Review*, vol. 9, no. 4, pp. 101–102, 1989.

[17] J. Taylor, "Conic Optimization of Electric Power Systems," Ph.D. dissertation, Massachusetts Institute of Technology, 2011.

[18] X. Bai, H. Wei, K. Fujisawa, and Y. Wang, "Semidefinite programming for optimal power flow problems," *International Journal of Electrical Power & Energy Systems*, vol. 30, no. 6-7, pp. 383–392, Jul 2008.

[19] S. H. Low, "Convex relaxation of optimal power flow - Part i: Formulations and equivalence," *IEEE Transactions on Control of Network Systems*, vol. 1, no. 1, pp. 15–27, 2014.