Assessment of N-1 Criteria Using Energy Storage

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***Abstract*—The goal of the Transmission System Operator is to run its power system in a reliable manner, incurring the lowest possible values of SAIDI and SAIFI indices to its consumers. This is achieved by using meshed networks, where after an outage of a line power flows through the remaining lines still satisfy all the technical constraints. However, in some cases it is difficult and costly to ensure parallel lines, which automatically voids the N-1 criterion.**

This paper examines generalized cases in which an energy storage system is used to increase security of supply. Specifically, energy storage is used to provide N-1 security reserve for a limited amount of time at locations where installation of additional transmission lines is difficult and costly, e.g., remote islands. Besides providing theoretical results, the paper presents a case study based on an Adriatic island within the Croatian power system.

***Index Terms*—transmission planning, energy storage, N-1 criterion**

I. Introduction

Power systems are generally operated by Transmission System Operators (TSO) in a reliable and safe manner. This means that a preventive N-1 security criterion should be satisfied at all time periods during normal operation. This should ensure that in presence of a contingency, e.g. trip of a power line, the transmission network should be able to continue supplying all the loads without interruption. To ensure this, the worst possible cases are simulated during the operation planning procedure.

This paper presents an analysis of different scenarios used to assess the role of an energy storage system (ESS) in increasing the security of supply of parts of transmission network where ensuring N-1 is difficult and/or costly, e.g. islands. An example of such case is represented in Fig. 1. The island subsystem is connected by two radial submarine cables, a 110 kV transmission cable and a 20 kV distribution cable, represented by purple and green colours. Radial distribution network contains 20/0.4 kV substations to supply the end users, which is marked by green-orange circles. In normal operation, the entire load is supplied from the radial 110 kV line via a 110/20 kV transformer. It is important to note that in the case described in Fig. 1 the transmission network does not satisfy the N-1 criterion, while the distribution network does, because the load can be supplied using the 20 kV distribution submarine cable, which is open in normal operation. Therefore, if the 110 kV line trips, the island load can only be supplied through distribution network (if voltage and thermal limits allow). However, in case of an ESS at the island 110/20 kV substation, the ESS could ensure N-1 security criterion for a limited amount of time, depending on the storage capacity.

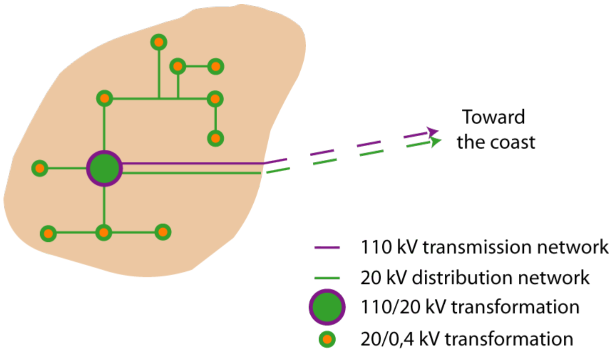

Fig. 1. An example of an island network

The scope of this paper is assessment of economic and technical effectiveness of investment in ESS using SAIDI and SAIFI indices [1]. System Average Interruption Frequency Index (SAIFI) is the average number of interruptions that an end user experiences during one year, while System Average Interruption Duration Index (SAIDI) is the average outage duration for each served end user. Both parameters are calculated as shown in equations (1)–(2).

$$SAIFI = \frac{\sum_{i=1}^{I} f_i \cdot C_i}{C_T} \tag{1}$$

$$SAIDI = \frac{\sum_{i=1}^{I} U_i \cdot C_i}{C_T} \tag{2}$$

where C_i is number of end users at location i, C_T is total number of end users, f_i is total failure rate at location i, and U_i is annual outage time at location i. These indices are usually averaged over one-year intervals.

This paper is organized as follows. The remainder of this Section provides a literature overview of the topic, Section II describes the proposed method, and Section III presents results of applying the proposed method to the Croatian power system, including a comparison of installation of ESS and transmission line in order to secure N-1 security criterion. Finally, Section IV provides relevant conclusions.

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A. Literature review

We review the relevant research documents on ESS applications and transmission expansion. Generally, ESS has been demonstrated as an effective way of dealing with the uncertainty and volatility of intermittent renewable resources, as well as in providing other auxiliary services, while the purpose of transmission expansion is to ensure transmission adequacy and disable market participants to exercise market power.

1) Storage operation and applications:

Many studies address the benefit of an ESS performing arbitrage. ESS operation differs depending on the environment. In a vertically integrated system, ESS is operated in a way to reduce the overall operating costs, while in a market-based power system, independently owned ESS is operated with a goal of maximizing its profit, consequently improving the social welfare [2]. An economic evaluation of ESS in both energy and ancillary services is investigated in [3]. The model is compared for three different market products: i) day-ahead market, ii) intraday market and iii) regulation market. It is concluded that ancillary services bring more profit to an ESS than arbitrage. Although storage operation brings income to its owner during exploitation, it is still questionable if ESS investment is economically sound having in mind the current market prices and ESS investment costs.

In [4], the authors use a bilevel structure to optimize both locations and size of ESS investment in order to provide energy arbitrage and reduce congestion in the transmission network. ESS investment costs are considered within the cost minimization of the overall power system operation in order to ensure the desired level of profitability to the investor.

In [5] and [6] the voltage support by energy storage is investigated. Both papers show that compensation used with both active and reactive battery power enables stability of the voltage profile than in the case when only reactive power is used.

The authors in [7] present several projects in which the energy storage applications are investigated, such as energy dispatching and arbitrage, power reliability and quality, islanding operations and grid frequency regulations. Moreover, they propose a useful method on battery ESS operation in power system.

In a similar paper to ours, but at the distribution level, the authors in [8] propose a model with ESS connected at critical buses of the distribution network. The role of energy storage is to supply costumers up to 2 hours in case of a disturbance. Furthermore, the authors obtain optimal size of battery storage, but concluded that such risk mitigation of not satisfying the N-1 criterion can not justify its installation.

2) Transmission expansion planning:

Transmission system expansion has been an ongoing research topic for many years. This topic gained on importance with integration of renewable generation, bringing additional uncertainty in the planning procedure. The authors in [9] modelled a DC optimal transmission network expansion using the N-1 security criterion with a genetic algorithm.

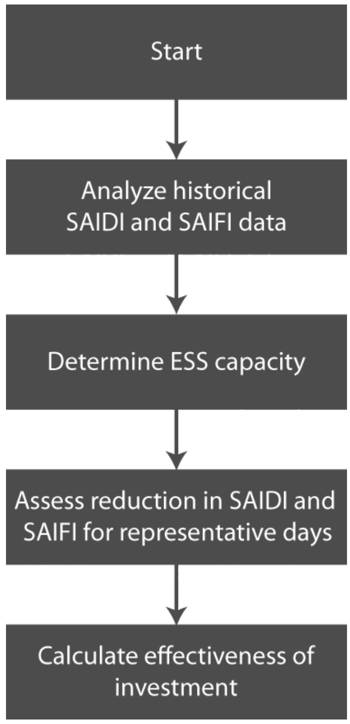

Fig. 2. Method diagram

Integration of renewable generation in Croatian power system is examined in [10], where the authors analyze optimal capacity of wind power plants and how they affect the existing transmission power grid. The investments in renewable generation are highly dependent on the current incentive tariffs and quotas [11].

Impact of ESS to the transmission expansion planning results is presented in [12]. The authors conclude that presence of ESS significantly reduces the redundant and rarely fully utilized transmission capacity investments. Transmission expansion planning considering deployment of ESS is considered in [13]. Integration of ESS in transmission expansion planning is proven to reduce expansion costs, although majority of investments is still directed towards transmission lines.

II. Methodology

Methodology of our approach is presented in Fig. 2. First, historical data on SAIDI and SAIFI indices needs to be gathered and analyzed. Based on these, ESS capacity is decided. This capacity is then simulated for representative days to assess the reduction in SAIDI and SAIFI indices. Generally, we consider three represents states to analyze the consequences of an outage of the radial transmission lines:
1) during maximum consumption in summer (or winter),
2) during minimum consumption in spring (or fall), and
3) during average consumption represented as a common day in spring or fall.

III. Case study

A. Description

The proposed method is applied to a specific part of the Croatian power system, whose overall demand in 2014 was 16,196 GWh [14]. According to [14], this demand is expected to grow in the next decade. On the other hand, as in many power systems worldwide, transmission infrastructure is increasingly old. This particularly refers to the submarine cables, which are used to connect the mainland and islands, as well as to make connections between islands. None of the submarine cables in this part of the country is less than 10 years old, and the majority is older than 40 years.

Our aim is to investigate how integration of an ESS can improve power system security at a Croatian island. Geographical and electrical representation of the simulated part of the Croatian transmission system is shown in Fig. 3. There are many specifics that affect the operation of the electric power system on these islands:

- frequent thunderstorms,
- severe storm wind (wind speed over 237 km/h),
- wind coats salt on insulation of transmission lines, substations and power transformers, which leads to leakage currents and system failures (often blackouts),
- high variations in voltages levels (much higher than the rated $\pm 10\%$ due to the impact of cable capacitance, different loads and network topology).

The observed island connection consists of the following islands: Krk (substations Omišalj, Krk and Dunat), Lošinj (substation Lošinj), Rab (substation Rab), and Pag (substations Novalja snd Pag). These islands are interconnected using the submarine cables, while the connections toward the mainland are Omišalj–Melina, Krk–Crikvenica, Novalja–Karlobag and Pag–Nin.

Although there are many locations where an ESS could provide its services and increase reliability of supply, here we focus on island Lošinj, whose consumers are supplied from a substation of the same name. This substation is radially supplied from substation Krk using a five-segment line (see Fig. 3): 1) overhead line Krk–M.Bok; 2) submarine cable M.Bok–Merag; 3) overhead line Merag–Osor1; 4) submarine cable Osor1–Osor2; 5) overhead line Osor2–Lošinj. The overall number of end users on island Lošinj is 14,500. In this case study, we consider construction of an ESS on this island in order to reduce unserved electricity, i.e. the values of SAIDI and SAIFI. The proposed batteries are NaS type. These batteries guarantee up to 6 hours of discharging and are often referred to as energy–intensive batteries. The rated output of one battery block is 1,200 kW and 8,640 kWh [15]. We consider two cases:

- Mini ESS – single ESS block (1.2 MW and 8.6 MWh capacity) that can protect against short interruptions/outages of 110 kW line Krk–Lošinj during low demand.
- Maxi ESS – seven ESS blocks (8.4 MW and 60 MWh capacity) that contains sufficient capacity for longer transmission line down time and can provide energy for higher load levels.

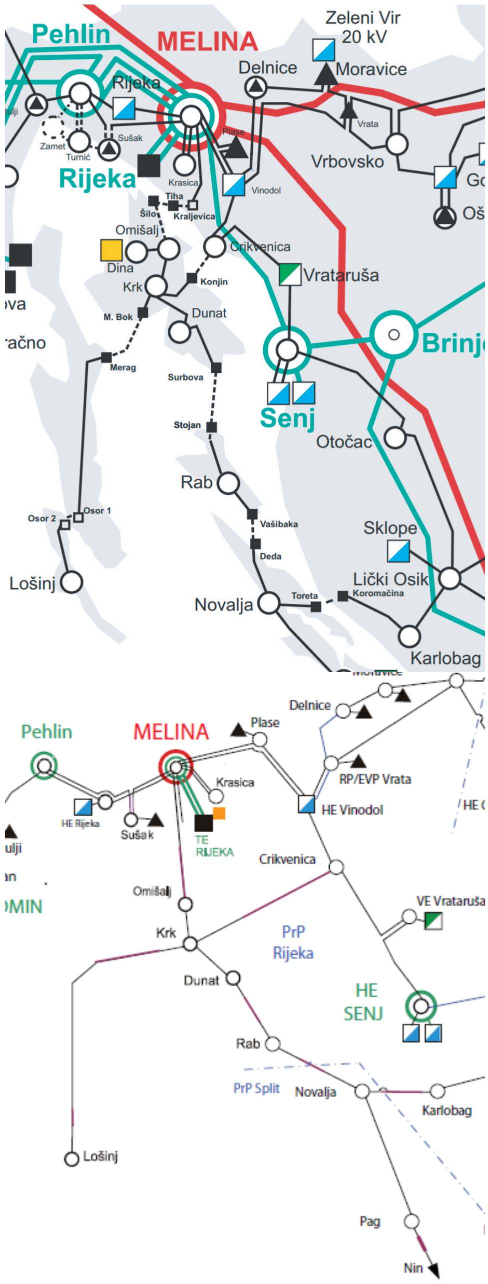

Fig. 3. Geographical and electrical representation of the simulated area

The total consumption of island Lošinj during three representative days in a year, as well as the capacity of a submarine distribution line that can be used to supply a part of the load (8 MVA) at island Lošinj are shown in Fig. 4. Three representative days show data collected in April (minimum consumption), July (maximum consumption) and November (average day).

Mini ESS installation would cover the interruptions on an average day (yellow line in Fig. 4), while the maxi ESS

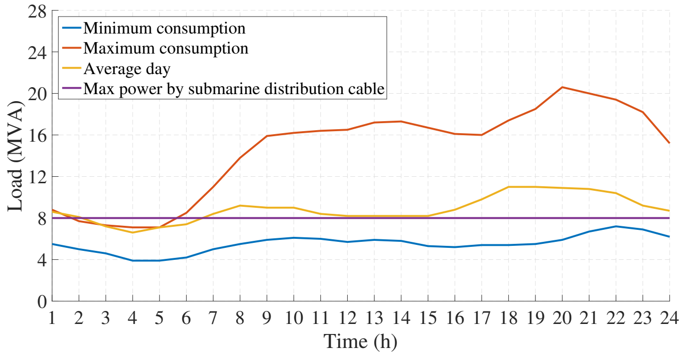

Fig. 4. Load curves for representative days

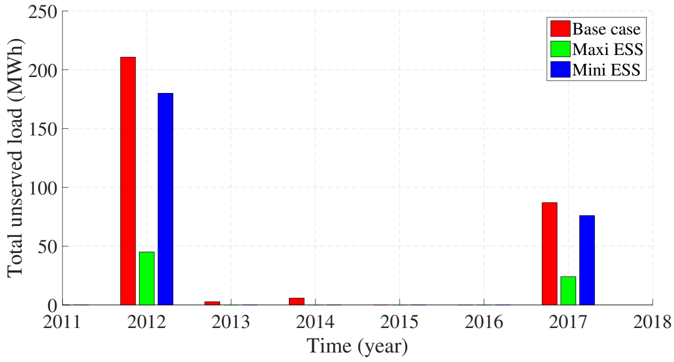

Fig. 6. Total unserved load in time period 2011–2017

installation is intended to cover the load during the maximum consumption representative day (red line in Fig. 4).

In general, Fig. 5 shows peak and off-peak demand, at hours 20 and 3, respectively, on third Wednesday of each month. The highest load levels occur during the summer season, from June to September, which means this period is prone to unserved load in case of interruptions.

B. Results

Fig. 6 shows total unserved load between 2011 and 2017 for three cases: i) base case without ESS, ii) maxi ESS and iii) mini ESS. The highest number and duration of outages in the base occurred during 2012 with overall unserved load reaching 210 MWh, followed by 87 MWh in 2017. After introducing the mini and maxi ESS, these amounts are decreased with respect to the capacity of installed NaS battery blocks. Installation of maxi ESS is able to supply energy during almost all interruptions, besides the two longest ones, resulting in 45 MWh unserved load in 2012 and 24 MWh of unserved load in 2017. When mini ESS is connected, short interruption are entirely avoided (years 2011 and 2013-2016), but unserved energy during long-lasting interruptions in 2012 and 2017 is only slightly reduced to 180 MWh and 86 MWh, respectively.

For further analysis, we calculate SAIDI and SAIFI values in maxi ESS and mini ESS cases and compare them to the base case. Tables I and II contain values of SAIDI and SAIFI indices for all three cases. After introducing battery ESS, duration of the outages as well as their number, are significantly reduced. Mini ESS is sufficient to completely eliminate interruptions of supply in 2011 and 2013-2016. In 2012, it reduces the number of interruptions from 10 in the base case to only 3. However, these three interruption are long and thus SAIDI is reduced only by 4%, from 1,209 to 1,159 min. Similarly, in 2017 the number of interruptions is reduced from 3 to 1, but the remaining interruption is still responsible for 190 min of interruption duration. ESS capacity in maxi ESS case is sufficient to cover the long interruption in 2017, but its capacity can only reduce the duration of the long interruption in 2012 to 537 min.

C. Economic Assessment

In order to analyze the economic implications of interruptions and ESS investment, we assume value of lost load to be 10,000 €/MWh. In the base case, this results in unserved load cost during the period 2011–2017 of 3.1 M€, where year 2012 is the most critical one with 2,107,000 € of unserved load cost. After introducing the maxi ESS, the overall savings are 2.37 M€ throughout the entire period and 1,657,000 € in 2012 (Table III). Savings in the mini ESS case are much lower, reaching only 510,000 € in the entire period and 307,000 € in 2012. A similar reduction as in 2012 appears in 2017. Cost of unserved load is 870,000 € in the base case, which is reduced

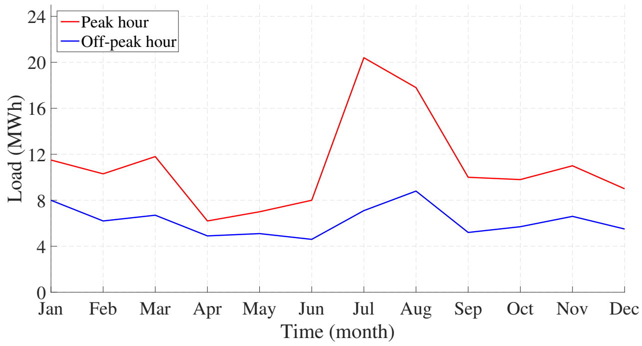

Fig. 5. Load at peak and off-peak hours in 2016

TABLE I
SAIDI INDICES

	SAIDI (min)		
Year	Base case	Maxi ESS	Mini ESS
2011	3	0	0
2012	1,209	537	1,159
2013	7	0	0
2014	115	0	0
2015	0	0	0
2016	0	0	0
2017	215	0	190
Overall	1,434	537	1,349

TABLE II
SAIFI INDICES

	SAIFI (-)		
Year	Base case	Maxi ESS	Mini ESS
2011	1	0	0
2012	10	1	3
2013	1	0	0
2014	3	0	0
2015	0	0	0
2016	0	0	0
2017	3	0	1
Overall	18	1	4

to 240,000 € in the maxi ESS case, and 760,000 € in the mini ESS case.

Investment cost of 1 kWh of NaS battery is around 450 € [16], which brings the maxi ESS investment cost to 27.21 M€ and mini ESS investment cost to 3.88 M€. On the other hand, investment in a parallel transmission line, which would entirely void unserved load, is estimated at 17.77 M€. Considering the results in Table III, as well as the estimated lifetime of the transmission line of 40 years as compared to 15 years for ESS, the investment in transmission line is more economically sound option than ESS.

Since there is a strong obligation for the TSO to ensure the N-1 criterion, investment into the transmission lines is economically still much more attractive than investment in ESS. Large ESS that could provide zero unserved load is much more expensive than constructing a transmission lines, despite the length and terrain difficulties related to installation of the submarine cable. Although s small ESS could provide large reduction in SAIFI, long-lasting outages of radial transmission line that supplies island Lošinj that occur every five years in average make the ESS case infeasible.

An analysis of SAIDI and SAIFI per months is available in Figs. 7 and 8, where one can notice that most interruptions occur during winter months (January and February), July and November, while in the remaining months there are no outages.

TABLE III
OVERALL INVESTMENT COSTS, SAIDI AND SAIFI INDICES, AND SAVINGS IN PERIOD 2011–2017

	Maxi ESS	Mini ESS	Lines
Investment cost (M€)	27.21	3.88	17.77
SAIDI (min)	537	1,349	0
SAIFI (-)	1	4	0
Savings (M€,%)	2.37	0.51	3.1
	76%	16%	100%

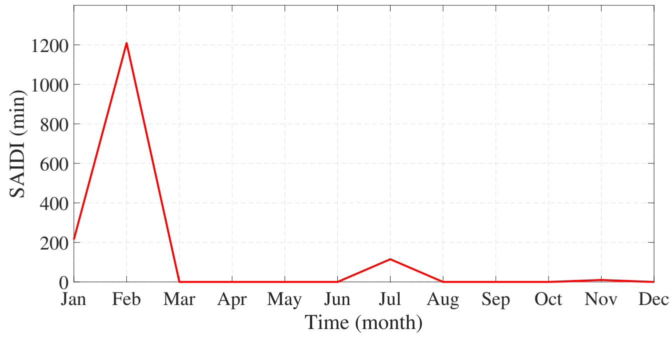

Fig. 7. SAIDI represented by occurance in Base case

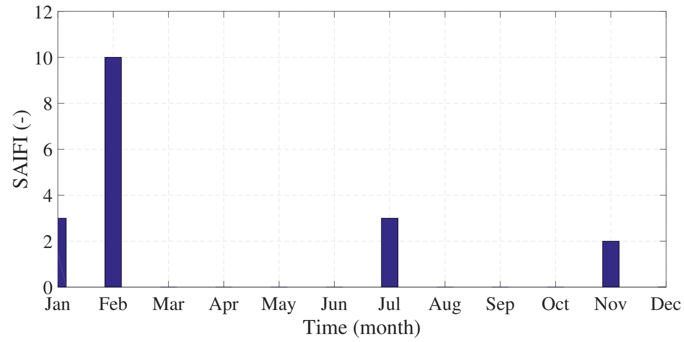

Fig. 8. SAIFI represented by occurance in Base case

IV. CONCLUSION

This paper investigates an assessment of N-1 criterion provided by an ESS as opposed to the transmission line. In general, battery ESS could help in providing the energy during a short outage of the 110 kV submarine cable, but not in the worst cases with extremely high amounts of unserved energy. The role of ESS would be to discharge up to 6 hours and supply the local load along with 20 kV distribution submarine cable, used as an auxiliary supply route.

From economical point of view, investment into mini ESS could be a good solution in ensuring the N-1 criterion during the average daily load. However, to ensure the high security level, TSO should invest into the new transmission lines.

However, there are still some research directions that should be investigated in order to improve the case for ESS. Namely, battery ESS could be used for other transmission services such as the voltage regulation. This stream of value is not considered in this paper and will be investigated in the future.

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