0-1 knapsack problem for intentional controlled islanding under severe operational conditions

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Abstract – Nowadays, due to the increasing share of renewable energy sources (RES), system inertia is decreasing and as a result, we can expect much more significant frequency fluctuations than usual. One way to adapt to the new conditions and keep an electric power system (EPS) dynamic stability at a high level is the adaptation and further development of existing system splitting and controlled islanding procedures. A basic assumption is that a need for the islanding arises from serious operational troubles in the entire interconnection, heading towards a widespread blackout. A network used for a case study includes a small part of an ENTSO-E interconnection, supplying a capital city of one of the European countries. An unreliable power supply of this area would undoubtedly have a significantly negative socio-economic impact and this is why it is necessary to avoid it. In this paper, we apply an integer linear programming approach for assuring stable transition of a selected part of the network into the islanding operation. We proved the viability of the presented approach in terms of root mean square (RMS) off-line dynamic simulations. The network also includes a battery energy-storage system (BESS) and this is why we provide the results of an investigation how beneficial the role of BESS in the controlled islanding process is. The main idea of controlled islanding is to keep the power supply uninterrupted in a selected portion of the network, which is additionally helpful in the upcoming overall EPS restoration process as well. This is why in this paper we tackle a further expansion of the initially stabile island as well.

Keywords: power system stability, power-system frequency, controlled islanding, linear optimization, under-frequency load shedding.

1 INTRODUCTION

There is a tendency to interconnect individual electric power systems (EPSs) with a purpose of increasing their resilience to different events. A typical example of such an interconnection is the one in the continental Europe operated by individual transmission system operators (TSOs) joined into an ENTSO-E organization (European Network Transmission System Operators for Electricity). However, even though interconnecting EPSs does increase the stability it does not make it fully bulletproof against every possible contingency. Even though N-1 criteria is respected at each point in time, there is always a possibility of a domino effect appearing that might begin either with a simple equipment malfunctioning, human error, inadequate vegetation management or a natural disaster. The most recent event taking place in ENTSO-E on 8th January is a perfect example [1]. An unexpected trip of a 400 kV busbar coupler led to a cascading event that ended in the ENTSO-E split within 30 seconds. The two formed islands had a surplus/deficit of an active power around 6.3 GW. Apart from that, the frequency was fluctuating significantly in one of the islands due to a small quantity of available generation. Two years earlier (2019), a lighting strike in the United Kingdom caused multiple generation units tripping (both conventional as well as renewable). This ended up with a frequency dropping down to 48.8 Hz, which was successfully handled by under frequency load shedding (UFLS) protection temporary curtailing a power supply for approximately 900 MW of consumers [2]. In comparison, reports [3] and [4] indicate that avoiding blackout is not always successful. In order to reduce the negative socio-economic effect of a blackout, its duration has to be minimized. In this respect, EPS restoration process is crucial. For instance, Italian TSO required approximately 18 hours to restore the power supply to all costumers after an Italy blackout in 2003 [5].

We should dedicate a special attention to a power supply of capital cities. System integrity protection schemes (SIPS) [4] have been researched and developed to avoid partial or total blackouts by taking corrective actions during emergency situations. Most typical representative of SIPS are under-frequency/under-voltage load shedding (UFLS and UVLS, respectively) and intentional controlled islanding (ICI) schemes. In the existing literature, ICI philosophy and algorithms were mostly constructed based on faults (e.g. three phase to ground short-circuit fault in [6] and [7]) and inter-area oscillations ([8]). Only a few researchers have considered other causes that might require ICI activation. To authors' best knowledge only few research papers analyze how ICI is impacted or should be coordinated with UFLS after major power-imbalance event ([9], [10]). In 2019, researchers in [11] came to the conclusion that "*the coordination of UFLS plan and the controlled islanding plan during UFLS design is an open question for further researches*".

A huge increase in the number and capacity of battery energy storage systems (BESSs) in the last couple of years suggests a careful study of their potential to participate in voltage, reactive power and frequency control (mostly primary and secondary). BESS's fast response times could widen its usage in other fields as well, such as ICI. This was recognized by the authors in [12] (2019), which wrote "*no ICI approach exists that considers the changes in structure and operation that modern power systems are experiencing due to the increasing integration of grid-scale BESSs*" .

It is therefore safe to conclude that the subject of this paper is timely. Authors intend to further develop and significantly extend the study [13], in which authors considered splitting EPS in two islands. Only the second island was assumed unstable in certain cases, yet the optimization approach was implemented in the first one. Apart from that, multiple scenarios were considered for the integration of BESS.

This paper is structured as follows. Chapter 2 describes the simulated network. Chapter 3 presents the optimization approach, whereas in Chapter 4 we present the simulation results. With chapter 5 we conclude the paper and present our plans for the future work.

2 POWER SYSTEM MODELLING

We constructed the use case model from publicly available data. The topology including busbars, lines, transformers and generators was taken from [14] and [15]. For reader's convenience, a single-line diagram of the network is depicted in Figure 1. For determination of line lengths, approximate estimations from [16] was used. A sole power plant includes three synchronous generators of the following rated powers: 49.4 MVA (G1), 49.4 MVA (G2) and 63 MVA (G3) [14]. Corresponding dynamic data of machines was selected among typical data for fossil steam generator units in [17] (Appendix D). As for controllers, IEEEG1 [18] was chosen for turbine governors and URST5T [19] for automatic voltage regulators. The transformers' data was taken from [20].

The remaining interconnection was modeled in a simplified manner with two equivalent synchronous machines, the first one representing a thermal (TPP_{eq}) and the second one a hydro generating unit (HPP_{eq}). Since most of the dynamic simulations in [21] considers HYGOV turbine governor in hydro-power plants (almost 65 % in North America), we adopted the same approach. In fact, a selection of TPP_{eq} and HPP_{eq} parameters does not play any significant role in our test case since we decided to model the remaining interconnection with two equivalent sources with a single reason, i.e. to impose a significant frequency drop to the observed network after sudden tripping of TPP_{eq}.

An important key segment considered during the modelling is the behavior of the loads. After power-imbalance events (either generator or load tripping) both frequency and voltage are a subject to changes. Therefore, it is important to include the frequency and voltage dependency of the loads in the model to approach real-life conditions. For this purpose, a typical set of parameters was used for the loads, e.g. such as the one in [22]. Factors describing the frequency/voltage load dependency differs depending on the load type, season within a year, period within a day, etc. A capital city we had in mind mostly consists of resident population, whereas factories are either located outside the main city or are present in negligible percentage.

In ENTSO-E, most of the countries are using conventional UFLS settings. This is why UFLS scheme was modelled according to a selected national legislation [23], which complies with ENTSO-E legislation in [24] and [25]. Therefore, modelled UFLS consists of six stages in total, first five stages curtails 10 % of the loading each, whereas a sixth stage a bit less (5 %).

We added BESS into the model to be able to show its impact to system restoration procedure. For this purpose we selected the model already integrated in PowerFactory DIgSILENT software (one can find parameters and functionalities in [26]). From all possible BESS functionalities, we activated frequency control solely, which means that its reactive power injection into the network was set to zero for the entire period of observation and working only into generation mode is considered.

3 OPTIMIZATION

After imposing a significant frequency decline in the use case model, UFLS is activated at 49.0 Hz with the aim of halting the frequency decline. However, the amount of power imbalance was intentionally set such that UFLS alone does not suffice for the active-power stabilization. This is why after frequency passes the last UFLS stage at 48.0 Hz, the island is formed. The goal of the optimization, presented in this paper, is to obtain most suitable island topology for each operating condition in which the amount of available power corresponds to the island loading. Therefore, in the first step, we had to determine which substations are going to remain connected.

3.1. A mechanism behind EPS frequency

In each EPS, active-power generation and consumption are constantly being balanced in order to keep the electrical frequency at (as much as possible) constant value, either 50 Hz or 60 Hz, depending on the system. In such stabile conditions, the mechanical torque T_m supplied to synchronous generators by corresponding turbines equals the electrical torque T_e, imposed to the machine by the consumed electrical power. The increased/decreased rotating velocity of the machine (reflected in electrical frequency changes) is therefore a consequence of a torque mismatch on the synchronous machines' shafts. Mathematically, we can describe this in terms of a swing equation:

$$2H\frac{d\omega}{dt} + D\omega = T_\mathrm{m} - T_\mathrm{e} \tag{3.1}$$

where, T_m and T_e are in p.u., H is the machine's inertia constant in seconds, D is the damping factor and ω is rotor's mechanical speed in radians per second. From (3.1) one is able to derive an expression for a so-called rate of change of frequency (ROCOF), that aggravates the machine when subjected to a specific torque imbalance.

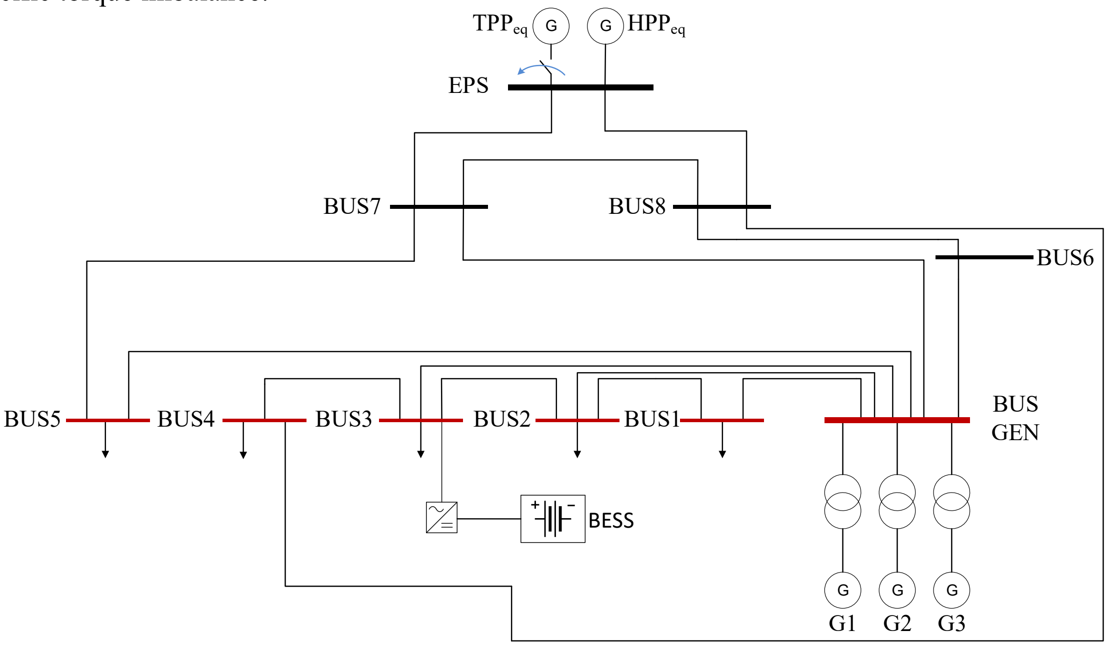

Figure 1: Single line diagram of the test system, based on [27, p. 93]

3.2. Integer (0-1) linear programming

Linear programming is one of the most basic known optimization approaches. Nevertheless, it suffices when the nature of our optimization problem is linear. Apart from that, it is extremely fast. In our specific case we used its variation, i.e. an integer linear programming (ILP), also known as a knapsack problem. Its naming arises from a mathematical problem of finding the number of items that can be put in a knapsack having a known capacity. The problem analyzed in this paper, is to find out which substations with a known loading at each point in time fits best to the available generation provided by G1, G2 and G3. With other words, we are trying to find the most appropriate combination of loads that matches best to the generation. Mathematically, this can be represented by the following expressions:

$$\begin{gathered}\mathrm{argmax}_{x_i}\left(\sum_{i=1}^{n} x_i P_{\mathrm{d},i}\right)\\ x_\mathrm{i} \in \{0,1\}\\ \sum_{i=1}^{n} x_i P_{\mathrm{d},i} \le P_\mathrm{g}\end{gathered} \tag{3.2}$$

where, x_i is a boolean variable for bus i, $P_{\mathrm{d},i}$ load demand at bus i in MW, P_g the available generation in MW and n the overall number of buses in the network. Parameter n corresponds to the number of red colored busbars in Figure 1 (i.e. $n = 5$).

In the optimization process, the network constraints (line power flows) are neglected. This does not represent a drawback, since our analysis indicated that overloading is not a concern in this network for any potential configuration.

4 RESULTS

As mentioned in chapter 2, tripping TPP_{eq} imposes a fast frequency decay that results in all six UFLS stages being exhausted before the island is formed. PowerFactory DIgSILENT 2021 SP1 was used for the RMS dynamic simulations. All simulations were performed on a PC with IntelCore-i7 1.8 GHz and 16 GB RAM.

Several scenarios were conducted to cover the most likely operating points, which include daily and seasonal fluctuations in generation and consumption. Two of them are presented in this paper. In the former one, a total consumption of 1200 MW was simulated, representing the low demand, while in the latter one a total consumption of 2000 MW was simulated. In addition, generation (TPP_{eq}) operates with approximately 900 MW when the consumption is low and with 1200 MW when the consumption is high. The rest of the generation is provided by HPP_{eq}. In the first scenario, only G1 is operating, while in the second scenario all three generators are operating (which is the authors' assumption). For more information on the generation and consumption data used for the simulations, see [28]. In each scenario 5 cases, where *w* in the legend means with and *w/o* means without, while the initial state means no BESS and no ICI is activated. The ICI implementation was performed using Python 3.9, library PuLP, with an average optimization time of 2 ms.

As can be seen from Figure 2 and Figure 3, the impact of this particular BESS model during UFLS is negligible. The contribution of BESS to the system frequency response is negligible in both of the cases when it operates from the beginning of the contingency or is included right after the activation of the last UFLS stage (purple and red curve overlap). On the other hand, there is a beneficial contribution from BESS usage in islanding operation when one generator (G1) is operating. In the second scenario, the influence of BESS is diminished due to the higher inertia in the system. Nevertheless, in both scenarios, the use of ICI ensures a stable operation of part of the EPS. Without ICI, in the first scenario, the power plant will be tripped due to the under-frequency protection, which is mostly at 47.5 Hz for steam turbines (see the red horizontal line), while in the second scenario, oscillations occur, which are poorly damped and further measures are required.

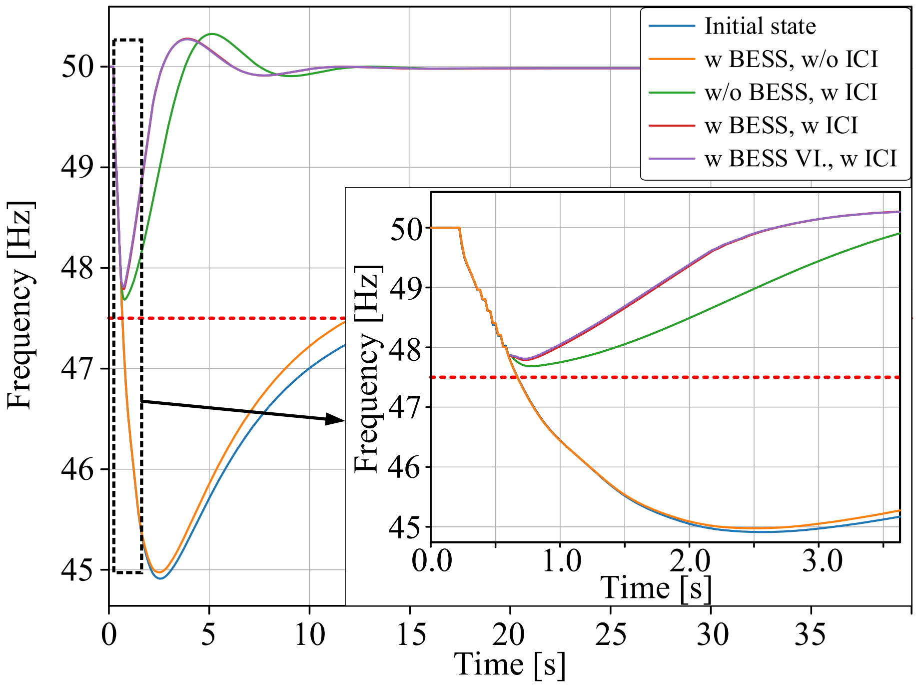

Figure 2: Electrical-frequency at bus 3 for scenario 1.

Also in the first scenario, there is a small difference between the mechanical and electrical power and the frequency is nearly 50 Hz (see green, red and purple line in Figure 2). In contrast, in the second scenario, the generation (mechanical power) is larger compared to the consumption of the island and consequently the frequency is higher (see green, red and purple line in Figure 3).

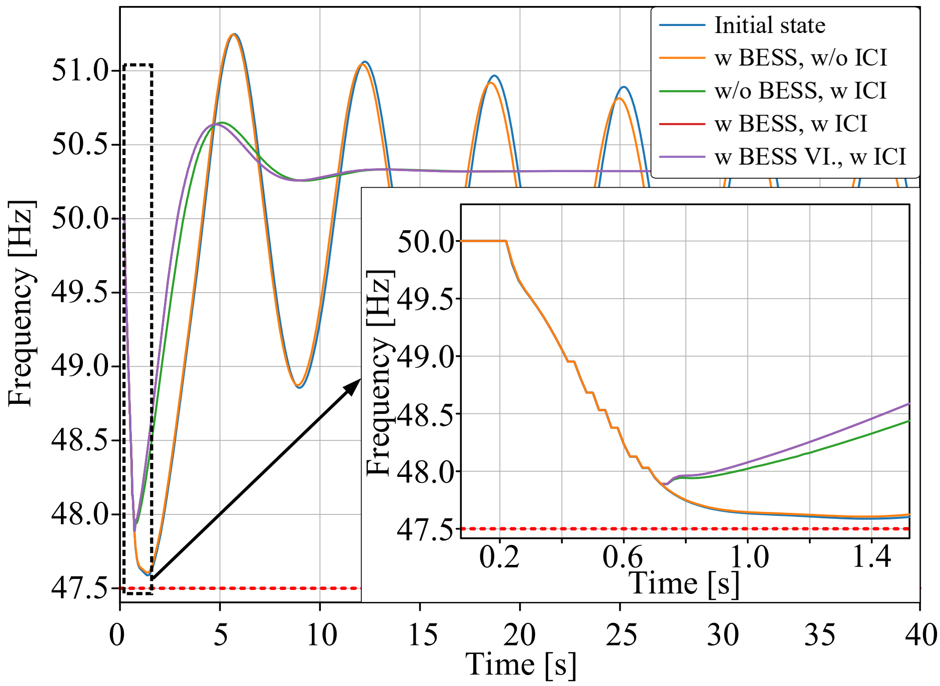

Figure 3: Electrical-voltage frequency at bus 3 for scenario 2.

5 CONCLUSIONS

In the future, more and more power-converter elements will be included in EPSs at the cost of reducing the amount of conventional generation. More extreme frequency excursions are expected due to the decrease of inertia and the number of SIPS activations is expected to increase. ICI is one of the mechanisms, which could be considered to solve these concerns. One of ICI examples is provided in this paper. Consideration of generation data before the event and current states of the loads and UFLS scheme provided for improvement of the approach. Further research would include real-time digital simulator (RTDS) hardware-in-the-loop (HIL) testing, which would prove the approach is appropriate for real life applications.

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