Lyapunov Exponent for Evaluation and Ranking of the Severity of Grid Events on Extra-Large Power Systems

1st Christoph Rüeger
ZHAW - IEFE
Winterthur, Switzerland
rueo@zhaw.ch

2nd Jean Dobrowolski
ZHAW - IEFE
Winterthur, Switzerland
dobr@zhaw.ch

3rd Petr Korba
ZHAW - IEFE
Winterthur, Switzerland
korb@zhaw.ch

4th Felix Rafael Segundo Sevilla
ZHAW - IEFE
Winterthur, Switzerland
segu@zhaw.ch

Abstract—**In this paper, a method to evaluate and rank the severity of events in extra-large power systems is proposed. The methodology is based on the analysis of the transient behavior of electrical frequency following severe disturbances on the system. Three different evaluation criteria such as damping of oscillation, speed variation and amplitude of the oscillation were implemented among other things in the sophisticated Lyapunov Exponent approach to assess the severity of a system event. To demonstrate the effectiveness of the proposed approach, simulations results on the initial dynamic model of Continental Europe from ENTSO-E using the commercial power system software DigSilent PowerFactory were performed to represent on a realistic form the transient behavior of the system. The study cases shown here, were carefully selected among more than 30 000 possible event combinations. The proposed algorithm can be used to analyze and compare the impact of topology changes in the future power grid e.g. massive introduction of renewable energy sources (RES) as prognosticated by several European energy policies.**

Index Terms—**European Grid, Lyapunov Exponent, Ranking, Events, Stability, Frequency.**

I. INTRODUCTION

With the general trend of massive penetration of renewable sources in power systems and the expected decommissioning of nuclear based energy in Switzerland [1], the general landscape of the European grid is about to drastically move to a more sustainable and green system.

These topology changes in the European power system are currently a topic of interest worldwide, especially at transmission [2], [3], and distribution levels [4] were most of challenges are expected to come. Most of the proposed solutions agree on having massive integration of renewable energies including large areas of photovoltaic panels (PV) or offshore wind connected through High Voltage Direct Current (HVDC) and as consequence significant integration of power electronics devices in an already complex electric network [5]. Since power grids are natural oscillatory systems that require continuous control and adjustments, the above mentioned changes represents a significant challenge to keep the stability of the system. Additionally, the reduction of rotating machines, which contribute with the system inertia, will considerably affect the transient behavior of the frequency as predicted on the well-known swing equation [6]. As result, new tools to assess the stability of the future power system are required.

For this reason, in this work is presented and algorithm to rank the severity of selected grid events based on the transient frequency behavior. The results are a preliminary work, which focus on highlighting the problems faced on the European grid today. The aim is to compare the results presented here on a subsequent study, with the analysis of events in the dynamic model after including topology changes, as prognosticated in most of the European energy transitions.

The European Network of Transmission Systems Operators (ENTSO-E) has recently made available for research purposes the initial dynamic model of Continental Europe [7]. This model, which mimic dynamic behavior of the interconnected network in Europe, has been tested in [8] to investigate its robustness. In this document, a total of 184 events were selected among more than 30 000 possibilities. The criteria to select these events is also presented.

Assessing severity of an event is not straightforward since many criteria can be take into account. Modal analysis is a current solution for offline analysis since it offers an overview of the system?s stability [9], [10]. Other recent research propose indexes to assess the severity of an event from a voltage perspective, based on its geographical localization [11]. Among the existing solutions, three criteria were selected for frequency stability: 1) damping of the oscillation, which represents the capability of the system to restore, 2) variation speed, since fast transients are detrimental to global stability and synchronism [12], and 3) amplitude of the oscillation, to ensure respecting of the grid codes. From these criteria, a global stability indicator, which is referred as the ”performance indicator? is proposed. The index is based on the Lyapunov Exponent (LE) calculation [13], the maximum of the derivative calculation, and the maximum of the amplitude calculation.

This paper is organized as follows: Section II presents a brief description of the model under investigation. Then the procedure to select events is depicted in section III. Section IV gives technical details on the way to calculate online or offline the stability indices. Finally, section V presents simulation results in the European system, and the ranking of the worst events in term of stability.

II. MODEL UNDER INVESTIGATION

The initial dynamic model of ENTSO-E is the most comprehensive representation of the interconnected Continental European power system. Table I shows information about the number of elements in each country represented in the ENTSO-E model, more details about the model can be found in [8].

TABLE I
NUMBER OF ELEMENTS IN THE DYNAMIC MODEL

Code	Country	Lines	Buses	Loads	Generators
AL	Albania	193	339	110	77
AT	Austria	123	104	40	31
BA	Bosnia & Herz.	312	294	164	37
BE	Belgium	178	140	36	52
BG	Bulgaria	787	798	419	77
CH	Switzerland	244	193	82	88
CZ	Check Rep.	106	288	76	113
DE	Germany	3378	3939	859	898
DK	Denmark	250	397	66	71
ES	Spain	1338	1385	646	496
FR	France	2599	2665	991	1564
GR	Greece	1133	1312	367	128
HR	Croatia	334	329	171	73
HU	Hungary	94	120	37	28
IT	Italy	817	1264	341	458
LU	Luxembourg	41	38	11	12
ME	Montenegro	80	94	35	18
MK	Macedonia	146	163	85	25
NL	Netherlands	905	1031	244	178
PL	Poland	988	648	199	140
PT	Portugal	365	506	87	158
RO	Romania	1194	1171	654	185
RS	Serbia	619	553	303	62
SI	Slovenia	111	230	65	73
SK	Slovakia	52	48	18	82
TR	Turkey	1943	4888	1245	1022
EU*	Europe	9	316	26	1
	Total	18339	23253	7377	6147

*Elements not labeled for a specific country

The model is available in the commercial power system software DigSilent Power Factory. For simplification purposes, e.g. storing excessive volume of data, only one bus per country was chosen to monitor the electrical frequency. The selected buses were randomly selected among the eight voltage levels available in the model [7]. Since transformers between different voltage levels are not accurately represented on the studied model, the proposed analysi focuses on frequency stability following only disconnection of elements in the grid.

III. METHODOLOGY FOR EVENT SELECTION

Since the dynamic model contains tens of thousands of elements (see table I), performing simulations for each element is unrealistic. Hence, it was decided to focus on three types of elements: lines, loads and generators. The general idea was to apply different disturbances to multiple components, one at the time and compare its severity with the proposed index, which is presented on Section IV. The selection of lines, generators and loads was done through several criteria, which are explained in the following subsections.

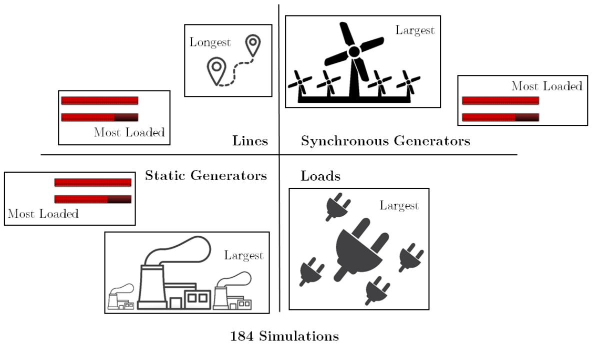

Fig. 1. Selection of the events of interest following seven criteria.

A. Line Selection

Two different criteria for line selection were used: the most loaded line on each country and the longest line one each country, respectively. These two criteria narrowed down the possibility to a manageable number of 54 lines in the model. Since the model was not built to handle 3-phase short circuits as described before, only line outages were considered as disturbances for these type of elements on the system.

B. Generator Selection

In the software where the model is available (DigSilent PowerFactory) it is possible to distinguish between static generators and synchronous machines. Similarly to the procedure for line selection, the most relevant static generators and synchronous machines on each country were found. To achieve this goal, first the largest machines and generators based of their actual dispatch of apparent power were selected. However, this quantity only gives the maximum possible apparent power and not how much is actually provided on a given simulation. For this reason, this criteria was complemented comparing these ratios and only those with the highest ratios were shortlisted reducing the list of elements to 46 synchronous machines and 60 static generators.

C. Load Selection

The selection of the most relevant loads was simpler as compared to the selection of transmission lines and generators. The model under investigation has been modeled using only one type of load. Thus, after comparing their apparent power, the largest load on each country was selected and as result, 24 loads were selected. Fig. 1 summarize the selection of the 184 events of interest following seven categories.

IV. STABILITY EVALUATION

To assess the severity of an event, a performance parameter α must be calculated. Especially when 184 simulations are performed, an automatic calculation of this parameter is necessary. In power systems, the quality of the frequency can be evaluated through three different criteria during a given disturbance. First, the damping of the oscillation reflects the capacity of the system to restore following an event [13]. Secondly, the amplitude of the oscillation is another important variable to respect grid codes in order to avoid cascade events related to sudden loss of renewable generation that might create frequency fluctuations [14]. Finally, the last criteria concerns the speed of variation of frequency, which is known as the Rate of Change of Frequency (RoCoF). Fast frequency variations are detrimental to load behavior [15] and connected wind farms are tripped following RoCoF values [16]. Thus, in the following part, α is defined by:

$$\alpha = \alpha_{le}.\omega_{le} + \alpha_{am}.\omega_{am} + \alpha_{de}.\omega_{de} \tag{1}$$

Where α_{le}, α_{am} and α_{de} represent the performance evaluation of the damping, the amplitude of the oscillation and the speed of variation of frequency, respectively and ω_{le} , ω_{am} and ω_{de} are weight parameters.

Since every event result in 27 frequencies (one per country), α_{le}, α_{am} and α_{de} are average values of all countries.

A. Damping evaluation

Damping evaluation following an event is not a new topic. Modal analysis is the most accurate way to measure damping and provide modal information. To deal with potential online evaluation of severity and with the presented objective to measure one average value per country, the so-called Lyapunov Exponent calculation was performed [13]. This methodology is based on three main steps:

- First step is the fault detection. In this work, we defined d as the instant where frequency is out of a predefined range [δ_{min},δ_{max}]
- Second step is to measure the size of the first oscillation N. To do so, the sense of the first oscillation is calculated from the point d and N is the index when frequency sense has change two times.
- The third step is to compare the first oscillation to the rest of the signal through a sliding window methodology. For every index $k > N + d$, the LE value is:

$$\lambda_k^i = \frac{1}{N\Delta t} \times \sum_{m=1}^{N} \log\left(\frac{\left|f^i_{(k+m)\Delta t} - f^i_{(k+m-1)\Delta t}\right|}{\left|f^i_{(m)\Delta t} - f^i_{(m-1)\Delta t}\right|}\right) \tag{2}$$

Where f_j^i is the frequency in country number i at time j. With the proprieties of the log function, λ_k^i will be negative if the damping is negative and positive otherwise. In this work, the LE is calculated offline from $k = N+d$ to $k = M-N-d$, with M the number of samples of frequency. (2) is adapted from [13] to give the same weight to every index. Fig. 2 resumes the calculation of the LE with the three steps defined before. Thus, for every country, an average LE can be calculated:

$$\alpha_{le}^i = \frac{\sum\limits_{m=N+d}^{M-N-d} \lambda_m^i}{M-2N-2d} \tag{3}$$

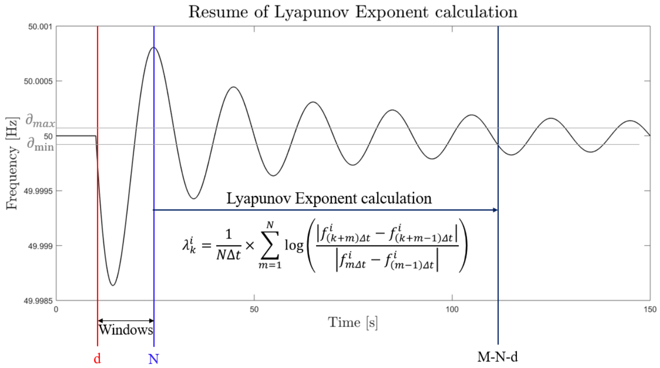

Fig. 2. Resume of LE calculation.

Then, the average LE for the performance calculation can be define as:

$$\alpha_{le} = \frac{\sum\limits_{i=1}^{27} \alpha_{le}^i}{27} \tag{4}$$

B. Amplitude of frequency evaluation

The amplitude of frequency, ?am corresponds to the average value of the maximum of amplitude in every country:

$$\alpha_{am} = \frac{\sum\limits_{i=1}^{27} \max\left(\left|f_0 - \min(f_i)\right|, \left|f_0 - \max(f_i)\right|\right)}{27} \tag{5}$$

Where f_0 is the nominal frequency before the event and f_i is the frequency in i -th country.

C. Speed variation evaluation

For speed variation, the recommendation of [16] to calculate the RoCoF was used as follows:

$$RoCof = \frac{\partial f(t)}{\partial t} = \frac{f_m - f_{m-1}}{\Delta t} \tag{6}$$

Where f_m is the frequency at time t. Then, α_{de} can be written:

$$\alpha_{de} = \frac{\sum\limits_{i=1}^{27} \max RoCof_i}{27} \tag{7}$$

V. SIMULATION RESULTS

To achieve the main goal, a combination of different software were used. DigSilent PowerFactory allows outside control. Taking advantage of this feature, it is possible to start scripts within the program and to come up with a certain automatic processes and calculations. However, the visual interface of PowerFactory is computationally expensive, which slows down certain operations. With over 180 simulations, having a fast performance is crucial. To achieve a better and faster performance, the graphic interface of PowerFactory was completely omitted by accessing it through Python. With Python it was possible to select the desired elements, define the different events and select the appropriate bus bars and their parameters to monitor the system faster. The calculations

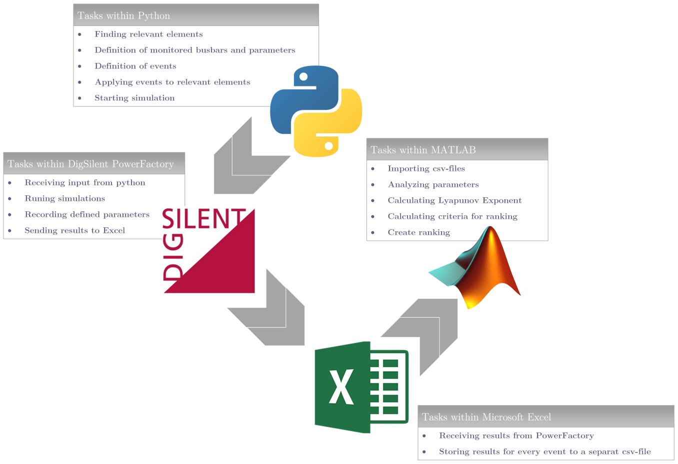

Fig. 3. Exchanges between software to obtain ranking.

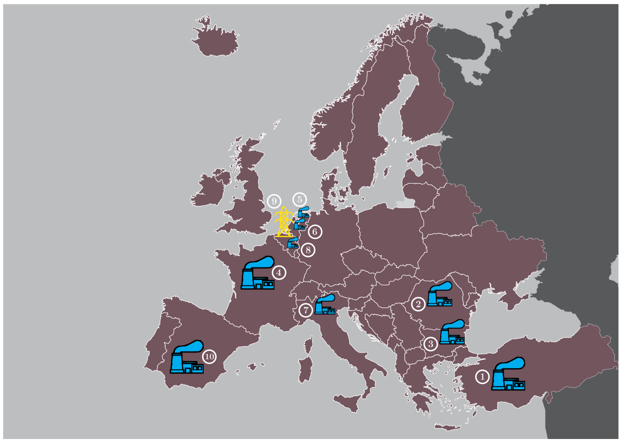

Fig. 4. Geographical representation of the ten worst events following the three selected criteria.

TABLE II
10 WORST EVENT ACCORDING TO PERFORMANCE INDEXL

Ranking	Country	Type	Performance Value
184	TR	Sync. Machine	1
183	RO	Sync. Machine	0.903
182	BG	Sync. Machine	0.886
181	FR	Sync. Machine	0.699
180	NL	Sync. Machine	0.571
179	NL	Sync. Machine	0.569
178	IT	Sync. Machine	0.559
177	BE	Sync. Machine	0.518
176	BE	Line	0.517
175	ES	Sync. Machine	0.512

and power system analysis were performed on PowerFactory controlled via Python. The results were then exported and stored into 184 individual comma separate values files (csv-files), one for each simulation.

In MATLAB the results were analyzed and the meaning performance index was calculated for each event. From this calculation, the global ranking is then performed. Fig. 3 resumes the exchanges between several software to obtain the final ranking.

A. Main results: Ranking table

As presented in Section III, three parameters were considered for the severity evaluation: The Lyapunov Exponent, the derivative of the frequency and the maximum amplitude of the frequency. These three indicators were weighted equally in this study case with the three parameters of Section III. After ? has been calculated, the performance parameters is obtained as the summation of the three indexes. Fig. 5 shows the main result of this paper since it presents the ranking of the 184 events according to the defined performance parameter. On this Figure the first element (left) represents the less relevant event and the last element (right) represents the most critical. The span of the Performance Value has been standardized and +1 represents the most severe event and -0.65 the less critical event.

To illustrate the results, Fig. 4 provides a graphical representation of the worst 10 events and Table II depicts the list of elements including performance value and location.

Note that nine of the top ten elements correspond to events related to synchronous machines and only one is related to line-outages.

B. Discussion of two randomly selected events

To understand in more detail the proposed approach, Fig. 6 depicts the frequency and Lyapunov Exponent of two randomly selected events. Fig. 6-(a) present the results after disconnecting the largest generator in Turkey. The event was ranked in the middle (position 111). Fig. 6 -(a) shows a small frequency drop of 0.6 mHz following the disturbance on the system and a mild oscillation. The second event is related to the disconnection of a synchronous machine in Hungary and was sorted in the 20th place (rank 165 in figure 5). After the detection of a fault, displayed by "d", the window of the first oscillation was defined which is essential for the calculation of the Lyapunov Exponent. Within this window the methodology of the LE explained in Section III.A is applied. LE on Fig. 6 -(b) shows that just after the end of the window (displayed by "N") the first LE calculation is done. Since the second oscillation is smaller, the LE is negative. On this example, a perfect oscillation is shown in the frequency trace, which helps to show and explain the special case. In some occasion (as example (b)) small oscillations have been distorted the calculation leading to a wrong size of the window and so to an incorrect and incoherent LE. By identifying and understanding this problem, the results were improved as shown in the example (b) of figure 6 . With an oscillating frequency, the calculated LE is varying between positive and negative back and forth, indicating a rather unstable scenario. This result is normal since the first oscillation amplitude is almost the same as the others.

The frequency in both examples represent a monitored 220kV bus bar in Switzerland.

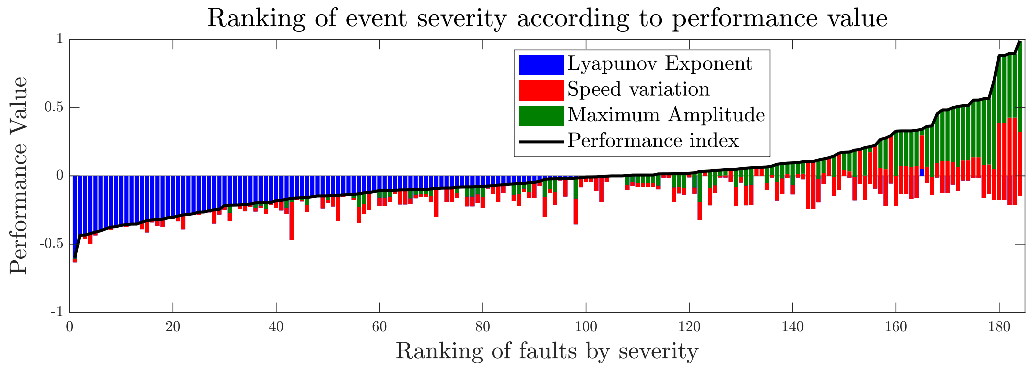

Fig. 5. Ranking of fault by severity following the three chosen criteria.

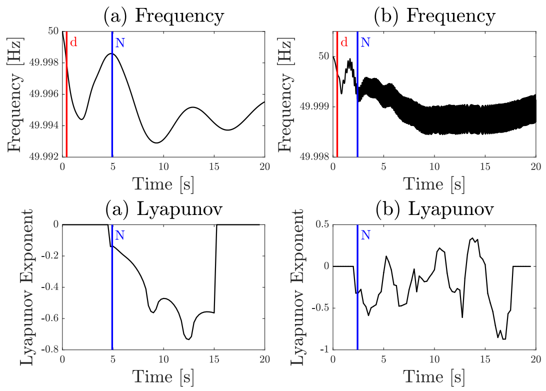

Fig. 6. Example of Lyapunov exponent analysis based on frequency measurement.

VI. Conclusion

In this paper, a ranking of the worst events for 180 simulations was presented. The simulations were performed on the initial dynamic model of ENTSO-E and a performance index was defined based on three stability criteria. Thus, the ranking presented in Section V classifies the selected events based on the damping, the speed of variation and the amplitude of the frequency signal.

The main result shows that events related to synchronous generator are the most detrimental to frequency stability. Since frequency is linked to active power, the results confirm this statement. Future work include integration of renewable sources in the model according to recent international decisions and to analyze the impact of these changes using the same performance index presented here.

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