Stability Effects After Massive Integration of Renewable Energy Sources on Extra-Large Power Systems

Christoph Rüeger, Jean Dobrowolski, Petr Korba, Felix Rafael Segundo Sevilla
Zurich University of Applied Sciences
ZHAW - IEFE
Winterthur, Switzerland
Email: rueo@zhaw.ch, xdow@zhaw.ch, korb@zhaw.ch, segu@zhaw.ch

***Abstract*—In this work, a security metric to quantify the stability effects after integration of different levels of renewable energy sources (RES) in extra-large power systems is presented. The comparison is carried out through extensive number of Root Mean Square (RMS) simulations, using as a test system the initial dynamic model of continental Europe under different scenarios representing the implementation of combined energy strategies across Europe. The RMS simulations were performed using the commercial power system software DIgSILENT PowerFactory. The stability effects in the entire system are analysed, as result of massive integration of RES in 13 of the most significant countries e.g. those who have been modelled in more detail. The result of three study cases are presented, corresponding to the increase of different levels of renewable penetration: 10%, 20% and 30%, respectively. The results are compared in terms of the frequency response but also on the evolution of the proposed stability metric. The results suggest that countries located in the Eastern part of Europe are more sensitive to massive integration of RES than the rest of the network, from a global stability perspective.**

***Index Terms*—power system dynamics, stability, performance, control, wide-area monitoring**

I. Introduction

With the general trend of significant integration of renewable energy sources (RES) in power systems and the political appeal for decommissioning nuclear based energy, like is the case in Switzerland [1], the general landscape of the European grid is drastically moving for a more sustainable electric grid. The implicit topology changes derived from the lack of conventional generation, have awaken the research interest of the power system community worldwide, particularly at transmission [2], [3] and distribution levels [4] were most of the related challenges will have a direct impact. Moreover, in the particular case of extra large power grids, like is the case in the European system, these problems become even more challenging due to the fact that it is not possible to have real case implementations or testing directly with utilities. Additionally, there is an evident lack of extra large bench mark models in the literature for simulation and validation of algorithms in such systems. Extension of existing power grids via electrical interconnections are the most suitable solution to fulfill the increasing demand of electricity over the next years. Cross border exchange (interconnections) among power systems make possible to trade electricity and incorporate flexibility in the operation [5]. However, extending the grid represents driving more generators running synchronously and in the face of contingencies in the system, groups of generator can react adversely, causing inter-area oscillations [6], [7]. These low frequency fluctuations of (0.1 - 1 Hz) are one of the main challenges when dealing with extra large power grids. Additionally, inter-area oscillations can create cascading events that could lead to system collapse (blackouts) [8], [9]. Developing effective measures to handle these problems is not new and many papers have been proposed, which consider different control loop solutions [10], [11]. In this work, we show how the gradual increase of RES has a negative effect on the stability of transmission systems using the extra large power system referred as the initial dynamic model of continental Europe, which was developed by the European Network of Transmission Systems Operators (ENTSO-E) and who made it available for research purposes [12]. This model is the most comprehensive representation of the European network, comprising more than 30'000 assets such as generators, loads and lines and mimics in a realistic way the dynamic behaviour of this large area. The model has been extensively tested [13] to investigate its robustness and appropriateness for stability analysis. Furthermore, in [14] a methodology to assess the severity of events using frequency measurements was proposed and poses the base of this work. The ranking and index developed in [14] are used as a basis of the proposed research on this document. The integration of RES as progressive substitute of rotating masses is causing a natural reduction of the system inertia, as it can be observed in the change of physics in the swing equation [15]. Lack of inertia has a direct impact in the transient response in most of the system's variables, particularly in the frequency, e.g. lower drop values at shorter periods of time. The novelty of this work resides on contributing with 3 different variants of the ENTSO-E model, where potential future scenarios with 10%, 20% and 30% of more renewable penetration are considered. For modelling renewable generation on each future scenario, the corresponding amount of conventional generation was replaced by distributed static generation at each country in the model.

TABLE I
TOTAL OF EVENTS PER CRITERIA

Element	Number of events	Criterions	
Lines	54	Longest	Most loaded
Loads	24	Largest	
Static Gen	60	Largest	Most loaded
Synchronous Gen	46	Largest	Most loaded
Total	184		

Then, several simulation for different faults in the system were performed for each model variation and the results are analysed with the help of the index proposed in [14] with the final objective of identifying sensitivity in terms of stability, of the EU countries to different levels of RES penetration. The paper is organized as follows: Section II presents an overview of [14] and the severity index that is the base for the results presented on this paper. Then, the procedure to implement different levels of RES in the model is introduced on Section III. Section IV discusses the simulation results and the ranking of the most affected countries, in term of stability, following the gradual increase of RES penetration. Finally, conclusions and discussion are presented.

II. BACKGROUND

On a previous work [14], a new stability evaluation based on three criteria for frequency measurements was presented and is the basis of analysis of this document. These criteria used for classification are:

1) The damping of the oscillation, with the aid of the Lyapunov Exponent (LE) methodology.
2) The second criteria is the amplitude of the oscillation with respect to grid codes, in order to avoid cascade events.
3) The third criteria is the speed variation of frequency, which is measured based on the so called Rate of Change of Frequency (RoCoF).

These criteria combined together constitute the stability index described in equation (1):

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

where α_{le}, α_{am} and α_{de} represent the performance evaluation of the damping, the amplitude of the oscillation and the frequency speed variation, respectively. ω_{le} , ω_{am} and ω_{de} are weighting factors chosen to give the same importance to all the mentioned criteria. Since the initial dynamic model of Continental Europe contains tens of thousand of elements, performing simulations for each element is unrealistic. Hence, it was decided to focus on three types of elements: lines, loads and generators. Considering that transformers between different voltage levels are not accurately represented in the studied model, the proposed analysis focuses on frequency stability following only disconnection of elements in the grid. The selection of lines, loads and generators was performed through the criteria for each country depicted on Table I.

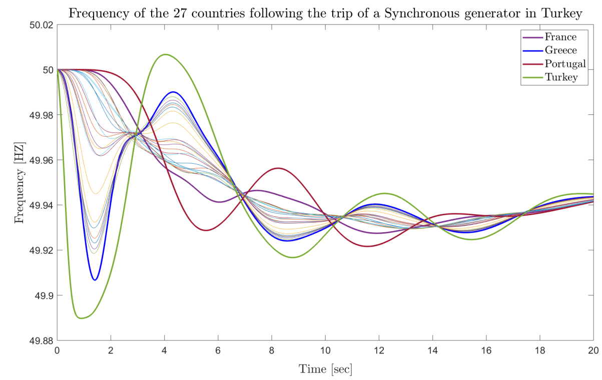

Fig. 1. Frequency of 27 countries following the trip of a synchronous generator in Turkey (selected countries displayed in legend). An inter-area oscillation of 0.125 Hz can be identified.

In total, 184 simulations were considered for the analysis, tracing the frequency on one random busbar per country only (27 frequencies). For the analysis the stability index depicted on equation (1) were calculated for each simulation performed and a ranking was created, showing a tripped synchronous machine in Turkey to be the most critical event in the system [14]. Fig. 1 displays 27 frequencies traces, following this most severe event and demonstrate the existence of inter-area oscillations caused by groups of generators between the East and West part of the system swinging against each other. To extend the results presented in [14], the dynamic model was modified and three new variations are presented in this document. Each variation represents a future scenario of the European system with different level of RES integration in the most significant countries of the model.

III. VARIATION OF THE ORIGINAL MODEL

A. Modelling and integration of RES in the dynamic model

Integration of RES in dynamic models is not straightforward, moreover it has been proven [17] that substituting a synchronous generator by a renewable unit such as wind or photovoltaic (PV) of the same size, is irrational in terms of grid stability analysis. For this reason, in this work the integration of RES has been performed implementing distributed RES to replace synchronous machines as in [17]. Since the objective of this work is to focus on transmission phenomena, the particular source of RES is not relevant for this study, the only requirement is that the model of generation does not include any rotating masses and thus inertia. Based on these assumptions, the static generator model available on DIgSILENT PowerFactory fulfills all requirements and it represents a generator connected to the main grid through a static converter. The static generator from DIgSILENT PowerFactory is typically used to represent PV sources, fuel cells or storage devices just to mention some, more details can be found in [18].

In order to integrate massive amounts of RES on selected countries as close to reality as possible, the voltage level of the busbars where the static generators are connected plays

TABLE II
PERMUTATIONS IN THE 13 COUNTRIES

Country	***RES***	***Scenario 1 10%***		***Scenario 2 20%***		***Scenario 3 30%***	
	N_i	N_k	*MW*	N_k	*MW*	N_k	*MW*
Austria (AT)	40	4	409	4	1092	4	1640
Switz. (CH)	80	4	712	4	1458	4	2186
C. Rep. (CZ)	76	4	653	4	1304	4	1955
Germany (DE)	111	6	5301	13	8012	21	14046
Spain (ES)	646	4	2620	6	5241	9	7861
France (FR)	956	4	6600	11	13185	16	19784
Greece (GR)	363	4	726	4	1069	6	1604
Italy (IT)	319	4	2025	9	3211	16	4030
Nether. (NL)	166	4	1538	4	3076	5	4630
Poland (PL)	185	4	1125	4	2252	5	3376
Belgium (BE)	36	4	981	4	1959	4	2940
Slovenia (SI)	59	4	155	4	517	4	613
Turkey (TR)	316	5	3641	14	7278	23	10918

N_i = number of static generators, N_k = number of synchronous generators.

an important role. Following recommendations from [17], all static generators that are used to replace synchronous generation have to be connected to busbars where there is load connected. In the model under investigation with more than 23'000 buses and 7'000 loads, two levels of high voltage busbars per selected country were selected and all static generators operate with a voltage of 15kV.

B. Implementing different levels of RES penetration

Since in the original dynamic model some countries are represented by a small number of synchronous machines (less than 20), these countries were not affected when developing model variations. Only countries with more than 20 synchronous generators were changed. These 13 countries out of 27 are listed in Table II. A maximum penetration of 30% was considered based on the assumption that a higher levels of RES would not be feasible to implement. Three scenarios were investigated, representing 10%, 20% and 30% of RES penetration, respectively. For each country listed on Table II, one model variation was developed for each scenario, thus 39 models were derived (13 countries times 3 variations). In Table II, the number of static generators (N_i) per country used to substitute synchronous machines (N_k) is displayed in the second column (*RES*), the number of synchronous machines removed (N_k) is given in the third, fifth and seventh columns respectively, and the total amount of active power representing the different levels of RES integration is given in MW. In order to be in phase with most of the European energy policies, where nuclear and fossil power plants will be substituted by distributed generation, an optimization procedure was performed in order to remove the minimum number of synchronous machines per country for the desired amount of active power. Then, the corresponding active power for each model variation, was randomly reallocated in the new static generators. For each model derived (39 combinations), 184 events were simulated, resulting in more than 7'000 simulations which are analysed and compared in the subsequent Section.

IV. SIMULATION RESULTS AND COMPARISON

In this section, the simulations resulting after applying 184 events (one at the time) to the 39 model variations described in the previous section, are compared against the results of applying the same set of events to the original model [14]. Since the same events are applied to the model variations for different RES penetration levels and to the original model, the results are presented in three parts as follow:

i. *Scenario 1 (S1) vs Base case (B)*. The 13 variations implementing 10% of RES in different countries are compared against the original model.
ii. *Scenario 3 (S3) vs Base case (B)*. The 13 variations implementing 30% of RES in different countries are compared against the original model.
iii. *Discussion of Results*. Provides a summary and conclusion of the comparison between subsections A to C.

The comparisons described before are performed using the same procedure, which is described in the following points:

a) The measure used to compare scenarios is the absolute value of the difference between the frequencies of each variation and the frequencies of the original model, more details are provided next.
b) The main results are presented in the form of 3D-plots where:
   - The $x-$ axis represents the country where the RES were implemented. For simplification, only the country codes are displayed and the country names are listed in Table II.
   - The $y-$ axis indicates the simulation number from 1 to 184, which is related to different types of events (discussed in Section II) and is summarized below:
     * 1-27 severe synchronous machine events
     * 28-57 most loaded synchronous generators
     * 58-84 most loaded lines
     * 85-111 events related to loads
     * 112-138 longest lines
     * 139-161 largest static generators
     * 162-184 most loaded static generators events
   - the z axis corresponds to the sum of the frequency differences, which are given by:

$$\begin{pmatrix} \sum_{i=1}^{N_G} \left|f_{B_1}^i - f_{AT_1}^i\right| & \dots & \sum_{i=1}^{N_G} \left|f_{B_{N_E}}^i - f_{AT_{N_E}}^i\right| \\ \vdots & \ddots & \vdots \\ \sum_{i=1}^{N_G} \left|f_{B_1}^i - f_{TR_1}^i\right| & \dots & \sum_{i=1}^{N_G} \left|f_{B_{N_E}}^i - f_{TR_{N_E}}^i\right| \end{pmatrix} \tag{2}$$

where N_G is the number of measurements per simulation (27), N_E is the number of events (184), $f_{B_j}^i$ represents the frequency measured in the i-th country after the j-th event for the base case model [14] and $f_{AT_j}^i$ is the frequency measured in the i-th country (Austria in this case) after the j-th event for the n-th scenario (S_n) of renewable penetration.

c) After the frequency differences have been estimated, the stability indexes introduced on equation (1) are calculated for every model variation and then compared against the base case [14] using a heat map. In these graphical representation, the $y-$ axis represents the country where the RES were implemented and the $x-$ axis provides the simulation number related to the type of event as in the 3D plot. The colors of the heat map represent the relation among stability indexes, which are given as:

$$\begin{pmatrix} \alpha_{AT_1} - \alpha_{B_1} & \dots & \alpha_{AT_{N_E}} - \alpha_{B_{N_E}} \\ \vdots & \ddots & \vdots \\ \alpha_{TR_1} - \alpha_{B_1} & \dots & \alpha_{TR_{N_E}} - \alpha_{B_{N_E}} \end{pmatrix} \quad (3)$$

where α_{B_i} is the stability index of the base case for the i-th event and α_{AT_i} is the stability index in the j-th country (Austria in this case) after the i-th event for the n-th scenario (S_n) of renewable penetration. It is important to note that:

- Negative values in matrix (3) represent stability improvement as result of the RES penetration.
- Positive values depict a larger variation with respect to the base case, which result in a negative effect in terms of stability as result of the RES implementation.

A. Scenario 1 (10%) vs Base Case

Fig. 2 shows the absolute difference of frequencies between the base case system and 10% increase of RES. To create these model variations, 4 to 6 synchronous generators were removed in some countries to compensate up to 6.6 GW of active power and 163 Mvar of reactive power (see Table II). By observing only the absolute value of the metric proposed on equation (2) and depicted on the z-axis of Fig. 2, it can be noticed that despite the evident small peaks and outliers, the response of the system variations are approximately the same to the base case for all the different events. Fig. 3 supports this observation since major changes in the stability index rarely happen. In this figure, dark blue colouration represent events with negative value indicating an improvement on the stability of the system. The positive effect of an increment of 10% of RES in some countries, particularly in Greece (GR), is explained by the stability index on equation (1). As predicted on [19], reducing inertia produces an improvement of the rate of change of frequency (RoCoF) and at the same time produces an increase of the damping and the natural frequency. For most of the studied events in Greece, the increase on the RoCoF is lower than the increase on the damping, leading to a smaller value of α.

It is worth noticing that one event in Switzerland triggers the largest peak on Fig. 2 and 3, respectively. This event is related to the trip of a synchronous generator connected directly to a line between Switzerland and Italy. In the ENTSO-E model, this element is subject to market restrictions, so the active power flowing through this line must remain constant. Additionally, one synchronous generator decommissioned in Switzerland was geographically close to this line. As result, the reallocation of the power was changed causing a large variation in the frequency.

B. Scenario 2 (20%) vs Base Case

The analysis of the comparison between the 20% of RES integration and the base case are omitted here due to page limit restrictions. However, the overall impact of 20% RES integration is marginal compared with the previous case with a small increase on the negative effect in countries such as Germany, Spain, France and Turkey.

C. Scenario 3 (30%) vs Base Case

The last scenario is the most aggressive RES implementation, which produce the largest impact on the models. Fig. 4 depicts the absolute difference between frequency measurements and a significant increase in the volume of variations on the most critical countries such as Germany, Spain, France, Italy and Turkey. It is important to note that, as a difference to the previous case studies, most of the displayed countries are actually affected as result of the 30% increase of the renewable sources. Fig. 5 displays the heat map corresponding to this case. Turkey is, as in the previous cases, the most sensible country to renewable penetration. However, Germany and France are also severely affected in this case. The problems in Turkey can be explained by the results depicted on Fig. 6, where 27 measurements resulting after a severe event in one of the most loaded static generator in Turkey, are displayed (in blue) and the results are compared against the base case (in red). From these results, it can be seen that even if the damping of the oscillations is improved for the 30% RES implementation (displayed in red), there is a clear degradation in the amplitude and RoCoF in comparison with the base case (in blue). As result, there are electromechanical oscillations caused by groups of generators oscillating against each other (east against west), which were already identified using the stability index developed in (1).

D. Discussion of Results

It can be determined that the stability index presented on equation (1) provides an indicator to quantify the deterioration on transmission systems, in terms of stability. This is supported by the results presented on Fig. 7, where the sum of the differences are given by α: $\sum_{j=1}^{13}(\alpha_{MOD_j} - \alpha_{B_j})$ where j is the index of the event and MOD is the country where the variation was applied. In Fig. 7, it is interesting to observe the consistency on the results. The 30% variation case caused the largest amount of stability issues in the system in comparison with the 10% variation case. Turkey is the most sensitive country to variations, where 10% of RES penetration already show a negative impact, even larger than in some other countries for the 30% variation. Despite the negative effects in Turkey, Fig. 7 also illustrates the improvement of stability in some countries such as Greece, where the increment of RES integration has a positive impact on this country. In all the case studies, about two to three recurring outliers were found where

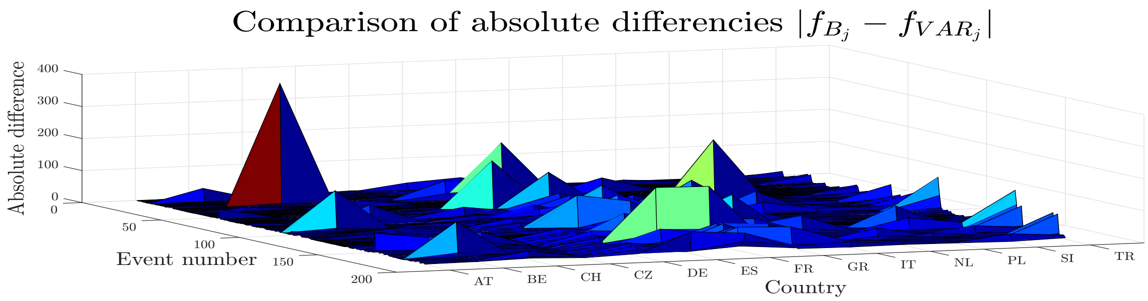

Fig. 2. Absolute differences between the frequency behaviour in the original model and following 10% of renewable implementation.

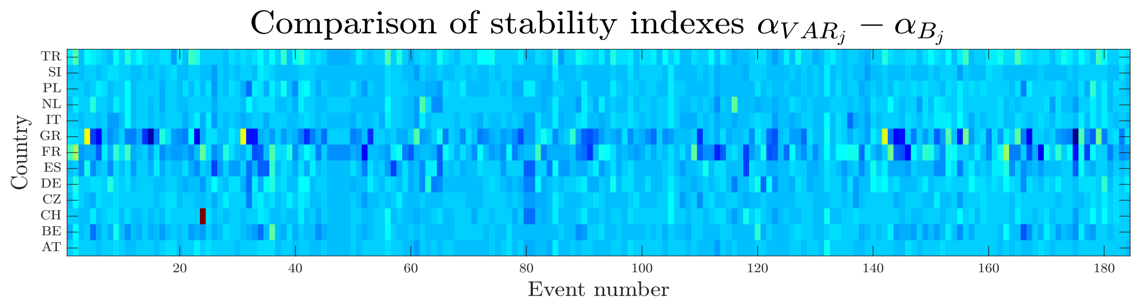

Fig. 3. Comparison of the stability index in the original model and following 10% of renewable implementation.

α rose the value of 10 or even 20 in few cases. These isolated events arise from the fact that faulty assets were geographically close to international borders and thus had a major influence on cross border exchange. Finally, Fig. 6 shows that inter-area oscillations, which were already identified in [14], are the most critical events according to (1), and the problem is accentuated by the massive RES implementation in Turkey.

V. Conclusion

In this paper, the dynamic behaviour of the European grid following massive implementation of renewable sources was investigated. To identify potential issues, the green energy sources were represented as distributed static generators in different countries to replace the traditional synchronous generators. Thirteen of the most relevant countries were selected in terms of detailed modelling of these countries. Three levels of RES penetration were investigated; 10%, 20% and 30%, respectively, deriving on a total of 39 model variations. A stability assessment was performed through the index described on equation (1). It was observed that 10% of renewable penetration does not have a significant effect on the stability in most of the system. However, for this level of penetration, Turkey already experienced stability issues, accentuating the inter-area oscillation effects, particularly by events located within Turkey. The 20% scenario does not show a significant difference in comparison with the 10% case. However, it was demonstrated that 30% renewable penetration produces a significant deterioration on the stability in most of the system, particularly in Turkey were the frequency response is considerable degenerated in terms of amplitude of the oscillations and the RoCoF. Future research directions include to investigate renewable integration in different countries at the same time.

Acknowledgment

The authors acknowledge the Swiss National Science Foundation (SNSF) under the project number PZENP2_173628 of the program Ambizione Energy Grant. This research is also part of the activities of the digitalisation as well as the Swiss Centre for Competence in Energy Research on the Future Swiss Electrical Infrastructure (SCCER-FURIES), which is financially supported by the Swiss Innovation Agency (Innosuisse – SCCER program).

References

[1] EU Commission, *Strategic Energy Technology (SET) Plan- Towards an Integrated Roadmap: Research&Innovation Challenges and Needs of the EU energy system*, 2014. [online]. Available : https://setis.ec.europa.eu/

[2] N. IqtiyaniIlham, M. Hasanuzzaman, M. Hosenuzzaman, *European smart grid prospects, policies, and challenges*, Renewable and Sustainable Energy Reviews, Volume 67, 2017.

[3] M.D.A. Rounsevell, F. Ewert, I. Reginster, R. Leemans, T.R. Carter, *Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland*, Agriculture, Ecosystems & Environment, Volume 107, Issues 2-3, 2005.

[4] F. Steinke, P. Wolfrum, C. Hoffmann, *Grid vs. storage in a 100% renewable Europe*, Renewable Energy, 2013.

[5] F. Zhu, H.-G. Zhao, Z.-H. Liu, and H.-Z. Kou, *The influence of large power grid interconnected on power system dynamic stability*, Proceedings of the CSEE, vol. 1, pp. 1–7, 2007.

[6] P. Kundur, *Investigation of low frequency inter-area oscillation problems in large interconnected power systems*, Canadian Electrical Association, 1993.

[7] V. Vittal, N. Bhatia, and A. A. Fouad, *Analysis of the inter-area mode phenomenon in power systems following large disturbances*, IEEE Transactions on Power Systems, vol. 6, no. 4, pp. 1515–1521, Nov 1991.

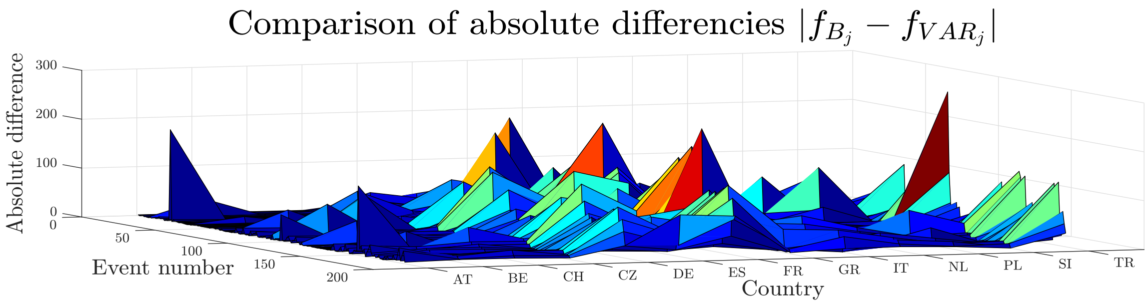

Fig. 4. Absolute differences between the frequency behaviour in the original model and following 30% of renewable implementation.

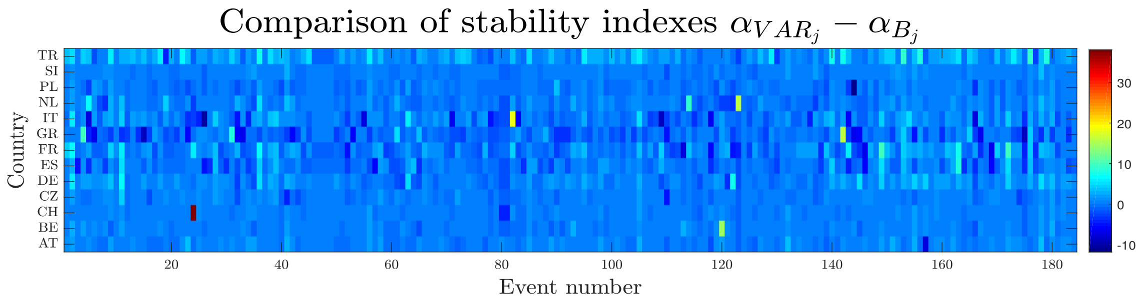

Fig. 5. Comparison of the stability index in the original model and following 30% of renewable implementation.

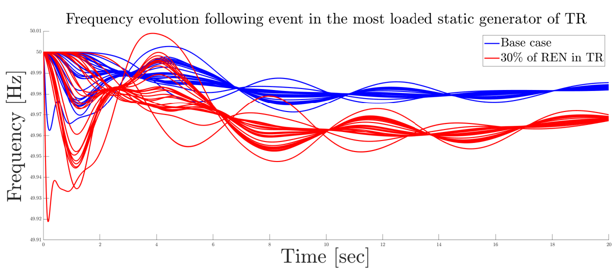

Fig. 6. Comparison of frequency behaviour following the trip of static generator in Turkey with the original and the 30% variation models.

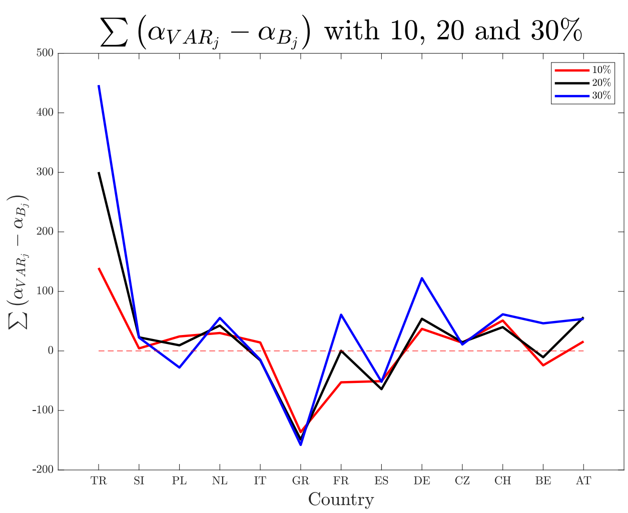

Fig. 7. Comparison of the sum of differences in the stability index for all the variations.

[8] Z. Tashman, H. Khalilinia, and V. Venkatasubramanian, *Multi-dimensional fourier ringdown analysis for power systems using synchrophasors*, IEEE Transactions on Power Systems, vol. 29, no. 2, pp. 731–741, March 2014.

[9] V. Venkatasubramanian and Y. Li, *Analysis of 1996 western american electric blackouts*, Bulk Power System Dynamics and Control-VI, Cortina d'Ampezzo, Italy, pp. 22–27, 2004.

[10] J. Dobrowolski, F. R. Segundo, F. A. Zelaya A and M. R. A. Paternina, *Inter-area Oscillation Control Based on Eigensystem Realization Approach*, 2018 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), Ixtapa, Mexico, 2018, pp. 1-6.

[11] J. Dobrowolski, P. Korba, W. Sattinger and F. R. Segundo, *Centralized Wide Area Damping Controller for Power System Oscillation Problems*, IEEE PES PowerTech, MIlano, Italy, 2019.

[12] European Network of Transmission System Operator for Electricity (entso-e). [online]. Available: https://www.entsoe.eu/publications/system-operations-reports/

[13] F. R. Segundo, P. Korba, K. Uhlen, E. Hillberg, G. Lingahl and W. Sattinger, *Evaluation of the ENTSO-E initial dynamic model of continental Europe subject to parameter variations*, Romania,2017.

[14] C. Rüeger, J. Dobrowolski, P. Korba and F. R. Segundo, *Lyapunov Exponent for Evaluation and Ranking of the Severity of Grid Events on Extra-Large Power Systems*, IEEE PES ISGT-Europe, Bucharest, Rumania,2019.

[15] H.J. Nardelli, Pedro, N. Rubido, C. Wang, S. Baptista Murilo, C. Pomalaza-Raez, P. Cardieri, M. Latva-aho ,*Models for the modern power grid*, The European Physical Journal Special Topics, 2014.

[16] F. Li et al., *Smart Transmission Grid: Vision and Framework*, IEEE Transactions on Smart Grid, vol. 1, no. 2, pp. 168-177, Sept. 2010.

[17] M. Reza. *Stability analysis of transmission system with high penetration of distributed generation.*, 2006.

[18] DIgSILENT. *DIgSILENT PowerFactory 2018 User Manual.*, 2018.

[19] P. Kundur, J.B. Neal and G.L. Mark. *Power system stability and control.* Vol. 7. New York: McGraw-hill, 1994.