Non-synchronous Generation Impact on Frequency Response – A case from Albania

Ersi Ago, *Student Member, IEEE,* Harold R. Chamorro, *Senior Member, IEEE,* Erick F. Alves, *Member, IEEE,*
Francisco Gonzalez-Longatt, *Senior Member, IEEE,* Wilfredo C. Flores, *Senior Member, IEEE,*
Vijay K. Sood, *Fellow, IEEE,* and Wilmar Martinez, *Member, IEEE*

***Abstract*—Albanian electric power generation has been almost totally dependent on hydropower since its system inception. Within the past decade, although modest, there has been some share of power produced from Renewable Energy Sources (RES), mostly from Solar Power Plants. Going forward, the Albanian government has promoted renewable energy as an important part of its energy mix and is planning to increase the share of injected RES composed of hydro, Photovoltaic (PV) and Wind. Among these, wind energy is one of the most promising sources. This paper gives an overview of the studies performed regarding System Frequency Response (SFR) by replacing hydro inertia with non-synchronous generation. A study of frequency behavior under several penetration levels of non-synchronous generation is presented with cases which show how system frequency is affected when replacing hydro-power inertia with wind turbine converter inertia**

***Index Terms*—Non-synchronous Generation, Converter-based Generation, Renewable Energy Sources, Frequency Response.**

I. INTRODUCTION

THe power sector is a key weapon to lower global CO2 emissions. It can do this by changing the way electricity is produced and meets consumer needs. Since the global power demand is expected to increase, renewable energy (RE) technologies are the key to have emissions-free renewable electricity for industrialized and developing nations alike. RE have smaller power plants, which can start generating power as soon as the first turbines are connected to the grid [1].

Sweden possesses all types of the RE sources and can generate power from water, wind, sun or any other source that generates through a natural process. The share of RE used in Sweden is growing day by day. The government's target of 50% was reached in 2012 [2]. By the year 2040, the target for the power sector is achieving 100% RE production. In recent years, wind power has been the fastest growing source of RE around the world. Sweden has increased its total production from 0.5 TWh in 2000 to 16.6 TWh in 2018. Today, there are about $3,600$ wind turbines in Sweden

In 2019, Germany had the largest reduction in the amount of gas emissions. In this year, it emitted about 805 million tons of greenhouse gases, which was approximately 6.3% less than in 2018. Also, last year Germany's greenhouse gas emissions continued to decline. Except for the global economic crisis in 2009, Germany's emissions reduction in 2019 was its largest annual decline since 1990. Since then, Germany has already reduced its emissions by 35.7% [2]. The German government has set a target of emissions reduction of at least 55% by 2030 and intends to realize this with wind power.

In 2018, energy consumption accounted for 59% of Ireland's greenhouse gas (GHG) emissions. Industry, transport and households were deemed to be the major contributors. After energy results in 2020, reducing GHG emissions was set as a main target and was followed by numerous actions to be done. By tackling the climate crisis across all sectors of the economy, the reduction of GHG emissions should reach 36%. In this Climate Plan, homeowners were allowed to generate their own electricity and sell it back to the grid under a micro-generation scheme from 2021 [3].

Canada has also increased its renewable electricity generation by up to 18% between 2010 and 2017, showing the largest growth primarily with solar and wind. Almost 82% of electricity in Canada came from non-CO2 GHG emitting sources in 2017. Hydro made up 60%, nuclear 15%, and other renewable the remaining 7%. RESs make up 70% of Canada's electricity mix production. The Government of Canada has also targeted to reduce methane emissions from the oil and gas sector by 40% - 45% from 2012 levels by 2025 [4].]. Also, it set the targets of reducing GHG emissions 17% by 2020 from 2005 levels, and by 30% by 2030.

Based on the actual conditions of Albania, it is foreseen that 4% of the total amount of electric energy produced in country (around 400 GWh/year) until 2025 is to be produced from wind [5]. It is assumed that a priority will be given to the buildings of 20 Wind Electro-Central (WEC) near 20 pumping stations located along the Adriatic Sea. A considerable number of areas with high wind energy potentials have been identified along the coastline, with a potential production of 30 GWh/year or 0.7% of the actual national electric energy production [5]. Figure 1 presents an overall geographic view of the principal generation power sources in Albania. The circles in red and green indicate the zones with a high density of sun

Ersi Ago is with INNOGRID ENGINEERING Renewable Energy Solution Studies, Polytechnic University of Tirana - Faculty of Electrical Engineering , Power Systems Department. (ersi.ago@ige-al.com).

Harold R. Chamorro is with KU Leuven, Katholieke Universiteit Leuven, Leuven, Belgium. e-mail: hr.chamo@ieee.org.

Erick F. Alves is with NTNU, Norwegian University of Science and Technology, Trondheim, Norway. e-mail: erick.f.alves@ntnu.no.

Francisco Gonzalez-Longatt is with University of South-Eastern Norway, Porsgrunn, Norway. (f.gonzalez-longatt@usn.no).

Wilfredo C. Flores is with Universidad Tecnologica Centroamericana, Tegucigalpa, Honduras. (wilfredo.flores@unitec.edu.hn).

Vijay K. Sood, is with the Department of Electrical and Computer Engineering of the University of Ontario, Institute of Technology,Ontario, Canada, e-mail: vijay.sood@uoit.ca

Wilmar Martinez is with the Department of Electrical Engineering (ESAT) at KU Leuven, Diepenbeek, Belgium, (email: wilmar.martinez@kuleuven.be)

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and wind respectively. Here, both types of RE generations are planned to be installed in the future. The blue circles indicate the main hydro-based generation sources.

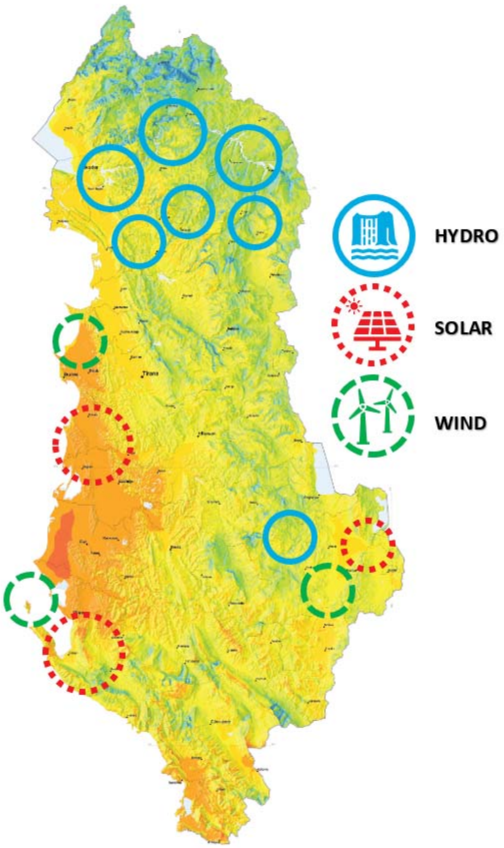

Fig. 1. Albania Overall Renewable Energy Resource geographic map

The average annual wind speed in these areas is $4-6$ m/s (height 10 m), and the annual energy density is $100-250$ W/m2. This potential is considered as low, but it can be improved, by using the height of 50 m, where the speed is $6-8$ m/s, and energy density is $250-600$ W/m2 [6].

Although Albania has high-voltage interconnection lines with neighboring countries like Kosovo, Montenegro and Greece, maintaining synchronism with them is one of the important issues when installing renewable energy. In an electric system, the energy contained in rotating machines at power stations and industrial facilities provides inertia as they rotate at the same frequency (50 Hz) as the electricity grid.

Figure 2 shows a representative view of main lines and generations in Albania. Included are the main generation units and bus voltage levels. As described above, these interconnections are an important part of the Albanian transmission system with up to three main interconnections at 400 kV.

The rotating masses are missing when considering connection of wind and solar energy [7]. Although a wind turbine contains a rotor, it does not behave in the same way as a mass that rotates at synchronous frequency with the grid as traditional power plants [8], [9]. This is due to the frequency converter between the wind turbine and the electricity grid. In situations where the frequency changes, the kinetic energy rotating of the mass is not automatically transmitted to the electricity grid through the converter. The combined inertial response of a wind power plant will depend on the electrical characteristics of the technology of each wind turbine. Wind turbines with a constant-speed have a different inertial response than synchronous generators. However, they do not essentially decrease the power system inertia because of their electromechanical characteristics. This study is focused on replacing the hydro-inertia of rotating masses with the converter-based inertia of wind turbines and observing the impact on the frequency response.

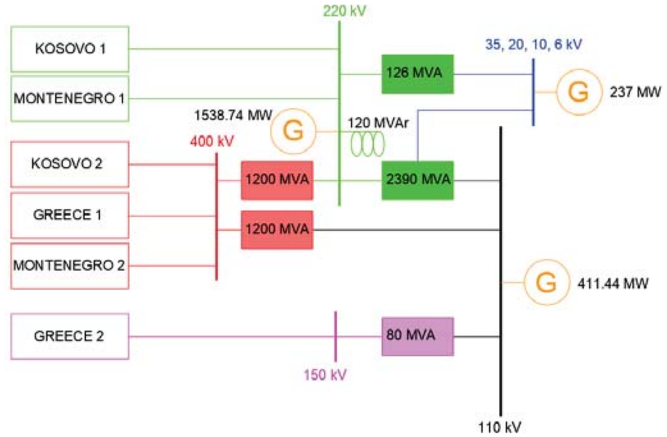

Fig. 2. Representative Scheme of main lines and generations in Albania

The remaining paper is organized as follows: Section II describes the theoretical framework of the frequency response, complete methodology and models used. Section III explains the study cases performed. The simulation results and discussions are presented in Section IV. Finally, the conclusion are given in Section in V.

II. PRELIMINARIES

A. Frequency Control Preliminaries

Upon losing a generation unit in a synchronous system, the frequency drops because of the imbalance between generation and load and this is instantaneously reflected in the power system [10]. During the first period, the inertia of the spinning machines in the entire system react by either releasing or storing kinetic energy tending to reduce the frequency deviation. System inertia is defined as the total amount of kinetic energy stored in all the rotating masses. Fixed-speed wind turbines have the identical inertial response behavior similar to synchronous generators. In case of a frequency reduction, the ratio of machine deceleration is determined by the generator's inertia mass which includes the shaft, gearbox and blades. Figure 3 represents the frequency control process, which is characterized by four different stages and multiple time frames; Inertial Response (<10 s), Governor Response ($10-30$s), Automatic Generation Control ($10-30$ minutes) and Reserve Deployment (¿30 minutes). Out of these Inertial Response and Frequency Containment Reserve (FCR) are considered as primary control, and Frequency Restoration Reserves (FRR) is considered as secondary control [11], [12].

The rotating masses of synchronously connected machines respond to maintain frequency after a fault or after disconnecting a generation plant [13].

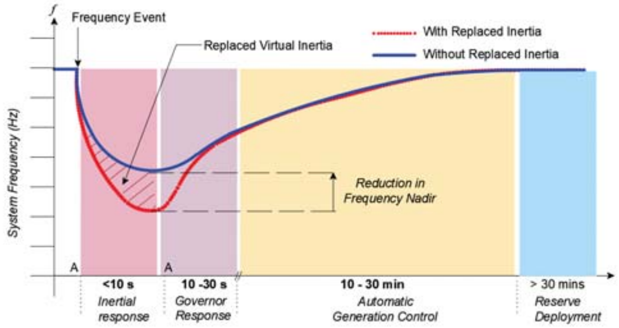

Fig. 3. Multiple time-frame frequency response in a power system following a frequency event

The sudden disconnection of one of the generators in an interconnected system will initially produce rotor swings between remaining generating units within the same power plant and generators at other locations in the system [14], [15]. This inertia response starts by consuming the kinetic energy stored on the turbine rotor, because the release of this energy is faster than the time response of controllers [16], [11]. Area-based inertia constants H, of different types of power plants, are calculated as the ratio of the weighted sum of individual generator inertia constants and the maximum capacity of generating units of the same type currently available in the scheme model as individual areas:

$$H_{area} = \frac{\sum_{i=1}^{n} S_i H_i}{\sum_{i=1}^{n} S_i} \tag{1}$$

where S_i is the capacity of i_{th} considered plant (MVA), H_i is inertia constant of i_{th} plant and n is the total number of plants in the area. The numerator presents total rotational kinetic energy (RKE) of synchronously connected power plants in the area.

Replacing the hydro-plant mass inertia with the converter-based inertia of wind turbines has its own impact but at a slight affection value [17].

Figure 4 explains this type of methodology where a hydro-based inertia mass is replaced by the non-synchronous generation-based inertia where IR - Inertia Response, GR - Governor Response, AGC -Automatic Generation Control and RD - Response Deployment. One of the main hydro generators (called Vau Deja = 50 MW) is replaced with an equivalent power of a wind farm composed of 10 turbines having 5 MW power each. The rotational block, indicated in blue, shows the nadir response of a rotating mass. The green block indicates the frequency response of the wind farm; but in this case, there is no more a concentrated central mass. Ten converters, responsible for frequency stabilization, are integrated together. The type of wind turbine used is a modern type with a fully rated back-to-back converter. However, a power converter isolates the rotational speed from the system frequency so a WTG with a fully rated converter does not offer a natural response to system frequency [18]. They are represented connected to each other but without a central mass in it. The third block, which consists of both mass inertia and converter-based inertia, shows that in the Albanian system a harmonious co-operation between hydro-inertia and wind-inertia may only be possible if some hydro generating units, at certain locations, are replaced but without touching the main high-scale hydro power plants.

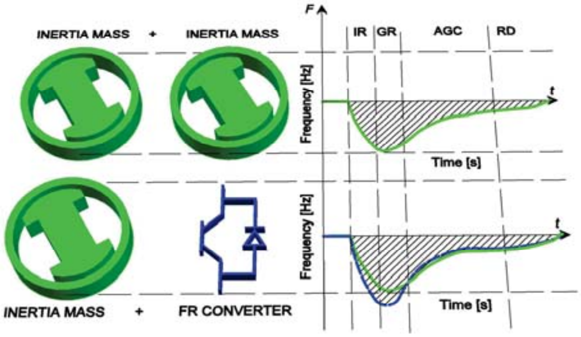

Fig. 4. Replacing Hydro Inertia with Converter based Inertia, IR

Since Albanian electrical system has almost its entire power generation based on hydro-power plants (with large rotating masses), and its 400 kV interconnection lines with Greece, Montenegro and Kosovo, it can be considered a strong system against system frequency disturbances.

B. Hydro Plants Models

In the Albania system, all the hydro power plants are modeled as Salient Pole Generator Models [19] while hydro turbine is IEEEG3 model [19].

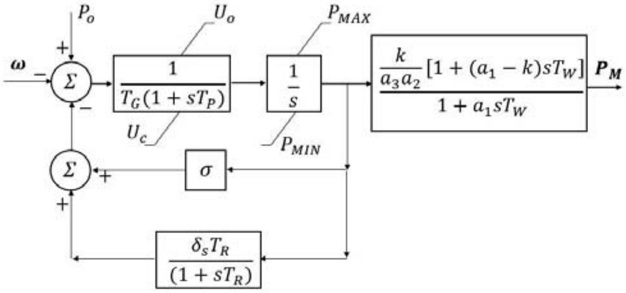

Fig. 5. IEEEG3 model

where T_G is the gate servomotor time constant, T_P is the pilot value time constant, U_o is the opening gate rate limit, U_c is the closing gate rate limit, P_{MAC} is the maximum gate position, P_{MIN} is the minimum gate position, σ is the permanent speed droop coefficient, ρ is the transient speed droop coefficient, T_W is the water starting time, and a_1, a_2, a_3, T_R are turbine coefficients, k - simplified constant of $a_{13}a21/a_{23}$

The dynamic model used for dynamic simulations in PSS/E is also composed of the Exciter and Turbine-Governor part. For the large hydro generator up to 150 MW, the "EXPIC1" and the ”ESST2A” model types are used. For the small hydro power plants, the ”EXST1” and ”ESDC1A” models are used.

C. Wind Turbine Models

The wind turbine model for the study is required to change its operation mode between ’limited frequency sensitivity mode’ and ’frequency regulation capability mode’ [20]. First, in the limited frequency sensitivity mode, the wind turbine model is required to reduce its power output at a pre-defined rate of the generator’s instantaneous available capacity per Hertz when the system frequency rises above a pre-defined frequency (e.g. 50.5 Hz in the Albanian system). In our study, Modern Wind Turbine Generation (Type 4 - or converter-based wind turbine generator) are used. Figure 6 shows a Type 4 Wind Turbine as a variable-speed wind turbine with synchronous or asynchronous generator connected to the grid via a full-scale power converter [21].

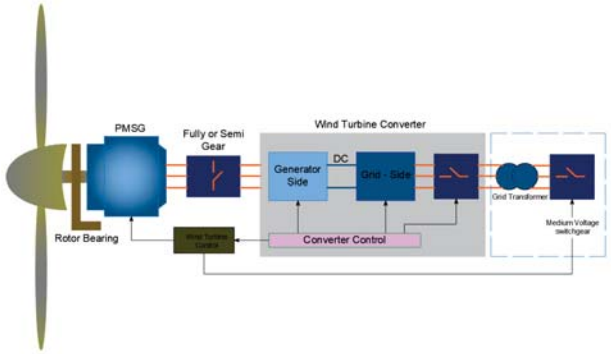

Fig. 6. Wind Turbine Type 4 (IEEE aproved model)

In the PSS/E simulation program, those models can be found in the Generic Renewable Electrical Control Models section. The Wind Turbine model is composed of the generator and electrical parts. The most suitable models that comprise the Wind Turbine Type 4 in PSS/E program are the “WT4G1” and “WT4E1” for the generator and electrical parts respectively. The model calculates the current injection to the grid based on filtered active and reactive power commands from the electrical control module. Both components of the injected current are processed under the high/low voltage conditions by means of a special logic. The model (WT4E) is an equivalent of the controller for the power converter [22].

III. STUDY CASES

Figure 7 shows the simplified single line Diagram of the Albanian Power System. [23] This Transmission System has 120 km of 400 kV lines, 1100 km of 220 kV and 1210 km of 110 kV lines . The 220 kV network is completely meshed and connects the main plants in the North of Albania with load centres in areas of Tirana, Elbasan and Fieri.

The 110 kV network is used for the supply of the Distribution System; this network is partly meshed and partly radial. The 12 substations in the 220 kV and 400 kV are being upgraded and are generally constructed with double busbar. The 110 kV side in these Substations generally have a single busbar.

The cases used for simulation on this paper consist on observing Rate of Change of Frequency (RoCoF) during disconnection of a particular generation plant without the presence of wind power and the presence of wind power by replacing hydro power with wind power. The generation plant that is disconnected, is a small scale considerable hydro plant with a power approximately of 25 MW. The disconnection occurs at time 0.5 seconds and the simulation is intended to last for 30 seconds. Table I shows the simulated cases in form of percentage of replaced and disconnected power where RP stands for Replaced Power.

TABLE I
CASES REPRESENTATION TABLE

Case	Replaced Gen	RP [%]	Disconn.Unit [%]
1	No Gen	0	1.85
2	Vau Deja 1	3.7	1.85
3	Vau Deja 1,2	7.4	1.85
4	Vau Deja 1,2,3	11.1	1.85
5	Vau Deja 1,2,3,4	14.8	1.85
6	Vau Deja 1,2,3,4,5	18.5	1.85
7	Fierza 1 + Vau Deja	27.7	1.85

IV. SIMULATION RESULTS

From the below Table II, the lowest values of nadir occur when we replace high amount of hydro power with wind energy (Case No.7) - (RP stands for Replaced Power). Figure 8 represents the Case No. 1 when no generating unit is replaced with wind generation; this is the base case. The ROCOF indicators for the nadir are shown. The approximate time of stabilization of this case is beyond 23 seconds. The nadir for Case No.1 is 49.99621 Hz. Figure 9 shows a comparison between the Case No. 1 (no wind replacement) and Case No. 7 (where 375 MW are replaced). The approximate time of stabilization of each case is beyond 23 seconds. The nadir for Case No. 7 is 49.99544. An improvement of frequency nadir is observed between Case No. 5 to Case No. 6. This is due to the fact that the removed generator is the last one left from five generators of ”Vau Deja” zone and so on, other hydro generators have responded more forcefully to the inertial response. Figure 10 shows a comparison between all the seven cases as indicated in Table II. One noteworthy point is that none of the cases breach the value of nadir frequency margin (50 Hz +/- 0.5 Hz) set by the Albanian TSO and Regulation Entity. This is due to the fact that Albania is totally dependent on hydro generation.

On examining the frequency response and nadir curves, we see that replacing hydro inertia with converter-based inertia from Wind Turbines, the nadir goes on more lower values. The core of cases is observing the ROCOF and nadir of Albania Electrical System when disconnecting a generating unit. In every case, the disconnected generating unit has a (considerable) power of approximately 25 MW. The nadir value when no power is replaced by wind is 49.99621 Hz. This value is due to the high inertia of hydro governors (generating units up to 150 MW) and the allocation of those hydro

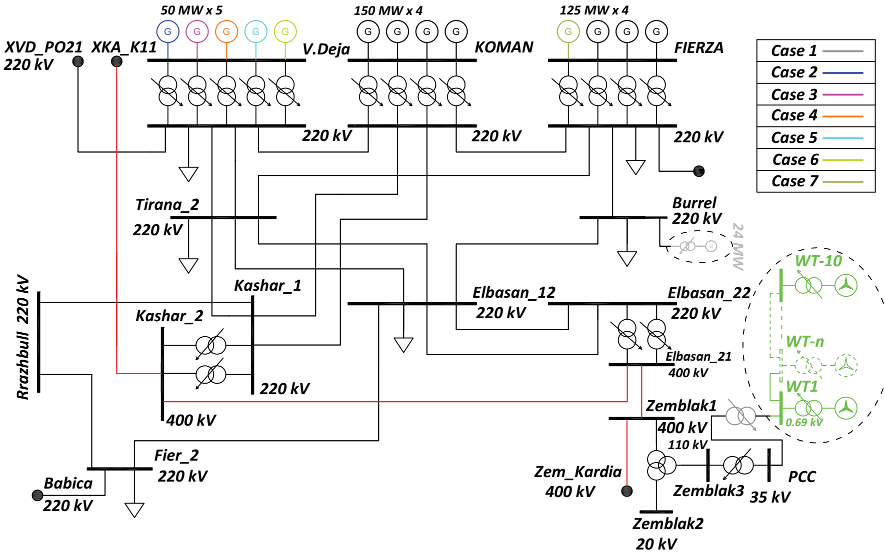

Fig. 7. Simplified SLD of Albanian Transmission System

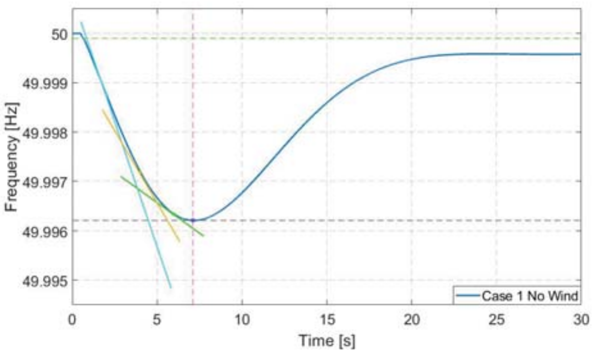

Fig. 8. Frequency Nadir [Hz] Main Case - Case 1

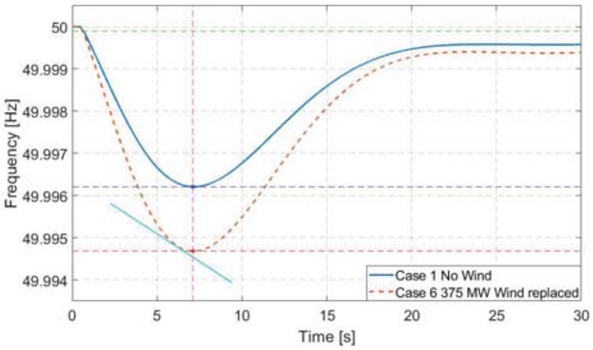

Fig. 9. Frequency Nadir [Hz] Case 1 - Case 7

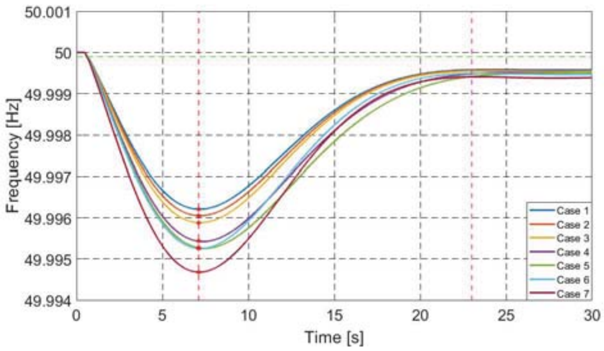

Fig. 10. Frequency Nadir [Hz] All Cases representation

TABLE II
FREQUENCY NADIR FOR EACH SIMULATED CASE (RP - REPLACED POWER)

Case	Generator	Bus	RP [%]	Freq Nadir [HZ]	ROCOF
1	G_{p}	KO	0	49.99621	0.278
2	G_{VD1}	VD1	3.7	49.99605	0.291
3	G_{VD2}	VD2	7.4	49.99587	0.300
4	G_{VD3}	VD3	11.1	49.99544	0.311
5	G_{VD4}	VD4	14.8	49.99527	0.314
6	G_{VD5}	VD5	18.5	49.99526	0.317
7	G_{F1}	F1	27.7	49.99468	0.319

generators. Almost 1350 MW of generation are allocated in the north of Albania and this fact coincides with a high inertia concentrated on a specific area.

As explained in the methodology section, the effect of nadir falling was more obvious when replacing very high hydro power with wind farms. There are also other factors indicating the nadir response after shedding of generation units. Some of those factor include the type of Wind Turbine used, the type of configuration of installation of those wind turbines, place of location etc. The Wind Turbine model used is the type 4 model which offers full management of power through fully rated converters. Figure 10 presents all cases. If we compare the case when a high amount of hydro power (375 MW) is replaced, the nadir drop value and the ROCOF are higher. This is an expected result but the difference between main case (when we have completely hydro inertia) and the case when we have the most replaced inertia is very low. Furthermore, as we observed the results during generation unit shedding while replacing with the wind energy inertia, the frequency deviation and the nadir response time were within the margins of frequency defined by the Regulation Entity of Electrical Energy and the Transmission System Operator in Albania [24].

V. CONCLUSIONS AND FUTURE WORK

Using renewable energy (from solar or wind energy plants) to reduce CO_2 emissions is not without its challenges since maintaining frequency deviations within the margins defined by regulatory bodies and TSOs is concern.

In this paper, the impact of converter-interfaced generation on the frequency response in the Albanian grid was analyzed. The Albania grid is totally dependent on hydro generating plants, and is classified as a strong high-inertia grid that is able to support a high penetration of renewable energy without affecting power quality parameters. Wind Energy in Albania is a potential opportunity for power production. Therefore, the objective of this study was to see the impact of the Albanian grid of penetration of wind-based renewable energy on the power quality.

The Albanian grid was modeled in detail using the PSS/E environment with respective models for hydro and wind.

Seven different cases were simulated in order to observe the impact of replacing hydro-power by wind turbines. The first case considered the frequency deviations when a large generating unit without penetrating wind energy was disconnected. Then, by observing ROCOF and nadir value, it was concluded that the system frequency was within the defined frequency margins specified by the TSO. The other 6 cases consisted of replacing strategically placed main hydro generators with wind generators without changing the total production capacity. The nadir values of respective cases indicated slightly increased falling values, but stayed within the frequency margins.

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