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Impact of renewable energy sources technologies on power system stability: a Moroccan case study

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ABSTRACT

Most countries of the world have adopted renewable energy sources (RES) because of consistent policy and industry support. The use of these sources is expanding and will cover a larger part of the generation capacity in the future. Thus, power systems (PS) are experiencing the high scale RES integration. For a power system dominated by RES, the electrical grid characteristics, namely, the inertia constant (H_s) and the rate of change of frequency (ROCOF), should be evaluated. Furthermore, the requirements related to these characteristics should be specified in the grid code (GC) to reflect the actual needs of the transmission system operator (TSO) and to prepare the evolution of the RES penetration level. Due to the delay in specifying or updating these GC requirements, RES that are incorporating unsuitable functionalities for the future perspective, regarding fault-ride-through (FRT) and frequency support requirements, will remain operational by 2030; this will create additional constraints on the PS frequency stability after large-scale RES integration. In this paper, the impact assessment of deployed RES technologies on the Moroccan PS frequency stability is assessed by the year 2030, using MATLAB/Simulink environment. The main reason for focusing on the case study of Morocco is the country's target of installing 52% of the energy supply from RES in the horizon of 2030.

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1. INTRODUCTION

With years of active policy support and the advance of technology, the cost of electricity generated from solar photovoltaics (PV) and wind has noticeably become lower. In fact, nowadays these sources are cheaper than newly installed fossil and nuclear energy generation in many parts of the world. In some places they are even less expensive than operating existing conventional power plants, especially in regions that have suitable resource [1]. Consequently, the use of renewable energy sources (RES) is increasing and will take over a large proportion of total generation capacity in the future. Thus, power systems (PS) over the world are experiencing a large-scale RES penetration. These sources are generally connected to the power grid using power electronics converters, which causes a lack of inertia in the power systems, and will reduce their ability to withstand grid disturbances. In this context, the majority of countries proposed various grid code (GC) to tackle RES integration problems and to ensure the PS stability [2], [3]. All these issues have led to an intensive research activity of PS stability assessment and the design of advanced controllers for RES to tackle the PS stability problems [4]-[8].

Several effects of large-scale penetration of renewable energies have been studied in the literature. The US Western interconnection large-scale stability and frequency response with high wind and solar penetration is studied, and the solutions to mitigate any adverse performance are examined in [9]. In [10], an evaluation model of the PS ability to accept large-scale wind power integration in China is established based on risk theory. Characteristics of net load (conventional load minus the non dispatchable power) in electrical grids, when a large amount of wind and solar power generation is integrated into the grid, is studied in [11], using the data from California's PS. Some recommendations are suggested in [12] on the basis of the existing supportive solar energy policies and proposed policies in Nigeria. Furthermore, different research works have been carried out concerning the evaluation of grid code requirements. An assessment of the Turkish grid code regarding the dynamic operation of wind farms during disturbances by performing simulation using DIgSILENT is elucidated in [13]. Details about the GC requirements of South Africa concerning the integration of RES are given in [14] together with the testing methods that should be carried out to evaluate interconnections. The main requirements of the Kosovo GC concerning the dynamic stability of the PS are evaluated in [15]. The inertial response of United Kingdom PS is investigated in [16] and a comparison of wind turbines technologies regarding the compliance with GC requirements is carried out.

Renewable energies currently represent 33.8% of Morocco's energy mix and the government has also targeted 52% of renewable energies by 2030 [17]. However, for a relatively high level of renewable energy penetration, uncertainty in energy supply is combined with uncertainty in demand, then the electrical grid characteristics can vary in an unpredictable manner. A generation/load imbalance event could disturb the control of the frequency and the electrical grid dynamic stability and represents an additional element to be studied. This paper has the particularity to evaluate the impact of the current RES functionalities on the PS stability during electrical grid disturbances, mainly, those related to the frequency control and the fault-ride-through (FRT) capability. In fact, due to the delay in updating the GC requirements, the PS will be dominated with RES incorporating unsuitable functionalities, which presents additional constraints on the PS stability.

The paper is organized as follows: the second section is devoted to explain the method used for evaluating the impact of RES and their functionalities on the frequency stability of the Moroccan PS, by the year 2030. In section 3, the impact of RES technologies on the Moroccan PS stability is assessed using scenario analysis. The frequency stability reinforcement measures to prepare large-scale RES integration, by 2030, are proposed in the conclusion.

2. RES TECHNOLOGIES IMPACT ON THE FREQUENCY STABILITY OF THE MOROCCAN POWER SYSTEM

The methodological approach used in this paper is based on the following steps:

- Defining the method of PS frequency stability analysis based on the estimation of the electrical grid stability characteristics, namely, the equivalent inertia (H_s) constant and the rate of change of frequency (ROCOF).
- Estimation of the Moroccan production plan and the on-line generating units by the year 2030. In fact, the calculation of the PS frequency stability characteristics (H_s and ROCOF) cannot be carried out without the estimation of the on-line generating units by the year 2030.
- After the estimation of the production plan and using the equations related to the analysis method of the PS stability, the Moroccan PS inherent characteristics will be determined under different scenarios concerning RES penetration levels and for different generation loss percentages.

To carry out the impact assessment of RES and their functionalities (maximum power point tracking (MPPT) controller and FRT capability) on the Moroccan PS stability, two important physical quantities should be analyzed : H_s and ROCOF. These quantities were not taken into consideration when the system was based on conventional sources. In fact, the inertia of these machines counteracts the power imbalance, inherently, in the 2 seconds after the event and then limits the ROCOF.

2.1. Approximation of the equivalent inertia constant (H_s)

A power system consists of N generators. Each generator is characterized by its kinetic energy at synchronous speed E_{kin_i} and its system power rating S_i, where the index i is an integer number. The inertia constant, H_i, is defined as (1).

$$H_i = \frac{E_{kin_i}}{S_i} = \frac{J_i \omega_{sm}^2}{2S_i} \tag{1}$$

Where: H_i: inertia constant of synchronous generator (i) $[MJ/MVA \approx s]$; E_{kin_i}: stored kinetic energy at the generator (i) [MJ]; S_i: rated power of the generator (i) [MVA] ; ω_{sm}: synchronous mechanical speed [rad/s]; J_i: Inertia moment of the synchronous generator rotor (i) [kg.m^2] . A single generator's inertia is characterized by the rotating masses and qualitatively measured by the inertia constant. In the event of a sudden frequency variation, the inertia constant is used to evaluate the PS ability of withstanding this disturbance. When a PS consists mainly of synchronous generators (i), the equivalent inertia constant H_s of the entire system, with a total power rating S_s, is accurately calculated using (2).

$$H_s = \frac{\sum_{i=1}^{N} H_i S_i}{S_s} \tag{2}$$

However, it is a complex task to calculate the inertia constant of a PS, which uses sources decoupled from the electrical grid such as the wind and PV farms, and the accurate identification of the PS equivalent inertia constant has become a challenge [18], [19]. Otherwise, in (2) remains valid to calculate approximately the inertia constant for an electrical grid dominated by RES. Basing on [20], we can identify H_i depending on the machine type and (2) can be written as (3).

$$H_s = \frac{H_{Th}S_{Th} + H_G S_G + H_H S_H + H_W S_W + H_{CSP} S_{CSP} + H_{PV} S_{PV}}{S_s} \tag{3}$$

Where: H_{Th}: thermal power plants equivalent inertia constant; H_G: gas turbine power plants equivalent inertia constant (combined-cycle (CC) power plants are included); H_H: hydraulic generators equivalent inertia constant; H_W: WF equivalent inertia constant; H_{CSP}: concentrated solar power plants (CSP) equivalent inertia constant; H_{PV}: photovoltaic plants equivalent inertia constant; S_{Th}: thermal power plants rated power; S_G: gas turbine power plants rated power (CC power plants are included); S_H: hydraulic generators rated power; S_W: WF rated power; S_{CSP}: CSP plants rated power; S_{PV}: photovoltaic plants rated power. Basing on [20], we assume that: $H_{Th} \simeq H_G \simeq H_{CSP} \simeq 5.5s$ and $H_H \simeq 3s$; $H_W \simeq H_{PV} \simeq 0$ (WF and PV power plants are decoupled from the grid).

2.2. Approximation of the rate of change of frequency (ROCOF)

The ROCOF describes how fast the frequency drops or raises depending on the power imbalance event. It is inversely proportional to the equivalent system inertia. When the system inertia is higher, the frequency deviation (ROCOF) can be easily controlled. This is because the system inertia withstands the change of frequency, as seen in (4) related to each generator in the national grid:

$$\omega_{m_i} \frac{d\omega_{m_i}}{dt} = \frac{P_{mi} - P_{ei}}{J_i} \tag{4}$$

where: P_{mi}: supplied power by the prime mover (W); P_{ei}: electrical power output (W); ω_{m_i}: generator mechanical speed [rad/s]. Using (1) and (4) , the imbalance between generation and load power ΔP_T can be written as:

$$\Delta P_T = P_{mi} - P_{ei} = 2H_i S_i \frac{f_i}{f_s^2} \frac{\partial f_i}{\partial t} \tag{5}$$

where: $f_i = \frac{\omega_{m_i}}{2\pi}$: generator's frequency (i) [Hz]; $f_s = \frac{\omega_{sm}}{2\pi}$: electrical grid frequency [Hz]. In a stability study for a large system with many machines geographically dispersed over a wide area, we should minimize the number of swing equations to be solved. So, for N generators connected to the same grid, (5) on the common system base becomes:

$$\Delta P_T = \frac{2f}{f_s^2} \frac{df}{dt} \sum_{i=1}^{N} H_i S_i \tag{6}$$

where $\Delta P_T = \sum_{i=1}^{N} P_{mi} - \sum_{i=1}^{N} P_{ei}$ and $f_i = f$, because the disturbance on the system affects the machines within their plants and rotors swing together. ΔP_T in per unit becomes :

$$\frac{\Delta P_T}{S_s} = \frac{2f}{f_s^2}\frac{df}{dt}\frac{\sum_{i=1}^{N} H_i S_i}{S_s}(p.u) \tag{7}$$

So, the ROCOF can be written as:

$$\frac{df}{dt} = \frac{\Delta P_T f_s}{2\sqrt{H_s S_s(\Delta P_T\, t + H_s S_s)}} \tag{8}$$

2.3. Estimation of the Moroccan power generation plan by 2030

The Moroccan frequency stability cannot be assessed without defining the estimated power generation plan that will indicate the generating units on-line. The assumptions are the following: the Morocco-Spain interconnection is not available at the imbalance event, the WF load factor is 40% and the electrical energy consumption increases by 6.2% per year [17]. Table 1 shows an estimated power generation plan by 2030.

Table 1. Estimated power generation plan in the horizon of 2030

Power station	Generated power (MW)	Installed power (MW)
Thermal power stations (JLEC, SAFIEC, ...)	3650	
CC power stations (TAHEDDART, ...)	350	10100
Thermo-solar and CC power station plant (Ain Beni Mathar)	300	
CSP plants (NOOR (I, II and III), ...)	1440	4000
PV power stations (NOOR MIDELT, NOOR IV,...)	960	
Wind farms	1600	4000
STEP and hydropower plants	2100	3100
TOTAL	10400	21200

3. RESULTS AND DISCUSSION

In this section, different scenarios are established and analyzed in order to evaluate the frequency stability, of the Moroccan PS by 2030, depending on the current GC requirements and the RES technologies currently connected to the Moroccan electrical grid. The PS has been modeled on MATLAB/Simulink environment and using (3) and (8).

3.1. Impact assessment of RES equipped with power converters on the frequency stability

We assume that the loss of the SAFIEC thermal power generator (650 MW) by the year 2030 is the normative event, which represents 6.3% of the total generated power. Figure 1 represents the Moroccan PS frequency deviation (ROCOF) after a 6.3% loss of generation unit in 2017, 2020 and by the year 2030. From this figure, the increasing use of RES could affect negatively the inertial response by the year 2030 and the frequency attains the lower limit in nearly 6 s (see [21] for more details).

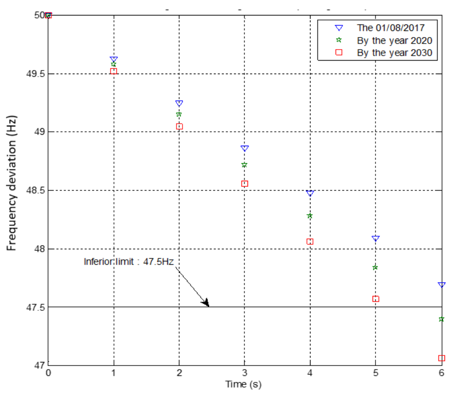

Figure 1. The frequency deviation depending on the RES penetration level (6.3% generation loss)

3.2. Impact assessment of the MPPT controller on the frequency stability

Due to the lack of the frequency support specifications in the current Moroccan GC, RES suppliers choose the MPPT controller in order to get a maximum profit [22], [23]. The experimental setup conditions are imposed by a load loss variation at t=10 s, equivalent to 6.5% of the total generated capacity. The simulations' objective is to evaluate the MPPT controller impact on the frequency stability during an over-frequency event. Figure 2 shows that the frequency curve exceeds the 52 Hz limit, at t=14, in about 4 seconds after the imbalance time. So, the MPPT controller, when used, will aggravate the situation of the Moroccan PS by 2030, during over-frequency events. It should be noted out that the RES penetration level is assumed to be 22%.

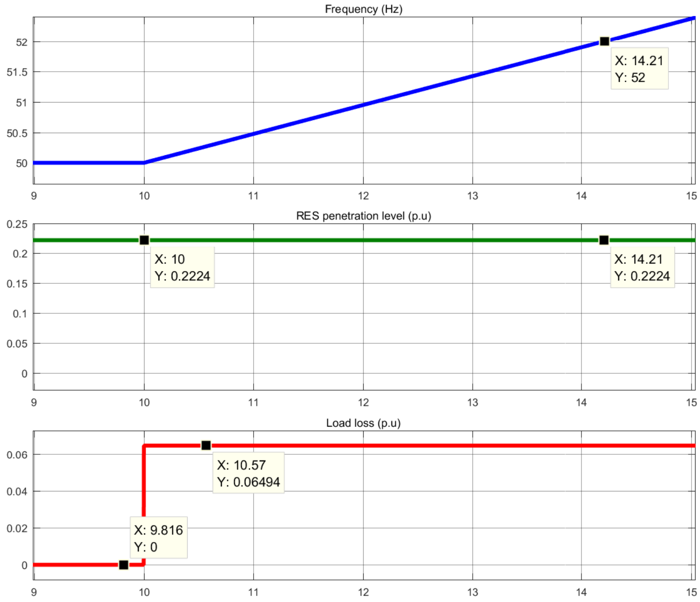

Figure 2. The MPPT controller impact on the frequency stability during 22% RES penetration level

3.3. Impact assessment of the RES FRT capability on the frequency stability

The FRT (or the low-voltage ride through (LVRT)) capability allows RES to maintain its connection and to withstand voltage sags. The LVRT capability specified in the Moroccan GC between 2014 and 2021 is shown in Figure 3. The RES respects the FRT capability shown in Figure 3, if it maintains its connection to the electrical grid in case of voltage sags that exceed the LVRT profile limits (red line). It should be noted out that LVRT requirement is related to voltage dips with short durations (hundreds of milliseconds), which are caused generally by short-circuits events [24].

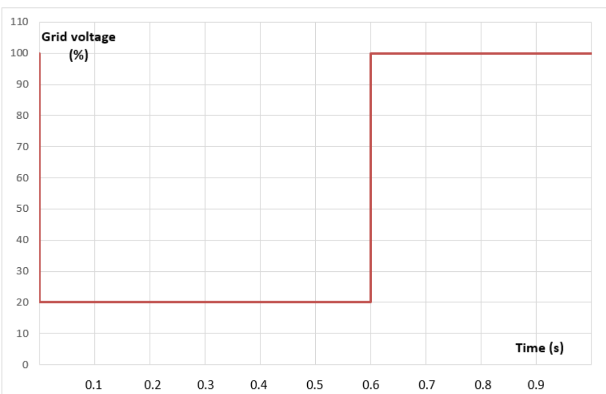

Figure 3. LVRT specification in the Moroccan grid code

To analyze the LVRT requirement, all the possible scenarios causing voltage sags that could exceed the LVRT profile limits have been identified by the calculation of the voltage dips due to the faults in the critical locations. After the calculation the voltage sag characteristics in all the possible scenarios, the following limits of the existing LVRT profile have been identified as follows (see [25] for more details) :

– The magnitude of the voltage sag caused by three-phase fault, which is located in the RES stations common point of coupling (PCC) exceeds 80% Un.
– The voltage sag duration for the grid faults positioned in the 22 kV level exceeds 0.6 s. In fact, the feeders relays configuration parameters doesn't take into account the existing RES stations connected to the 60 kV electrical grid.
– The post-fault depends on the characteristics of the national grid and has a certain response time that it is not taken in consideration in the LVRT profile.

Figure 4 shows that the frequency curve drops below 47.5 Hz, at t=11.54, in about 1.54 s after the RES stations disconnection. Thus, the LVRT profile respected by the deployed RES stations will aggravate the situation of the Moroccan PS by 2030 during transient faults. So, this requirement should be updated to maintain the PS stability. In Figure 5, a LVRT profile is proposed basing on the analysis of the existing requirement. It takes in consideration the limits of the LVRT profile indicated in Moroccan grid code. In order to generalize the LVRT capability mentioned in Figure 5 for all the WF respecting the LVRT requirement indicated in Figure 3, the incorporation of a protection circuit called "active crowbar" remains an adequate solution [26].

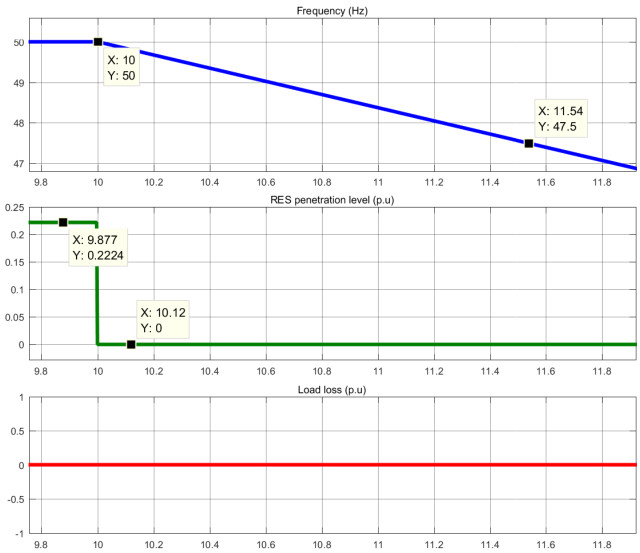

Figure 4. The LVRT impact on the frequency stability during 22% RES penetration level

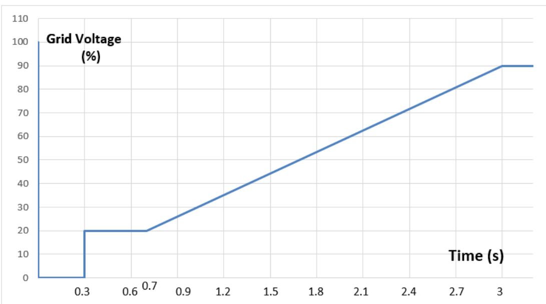

Figure 5. Proposed LVRT profile for the connection of RES in the Moroccan grid

4. CONCLUSION

The main conclusions of the RES impact assessment on the frequency stability of the Moroccan power system are the following: i) due to the delay in specifying or updating these GC requirements, RES are currently incorporating unsuitable functionalities in the future perspective, regarding FRT and frequency support requirements; this will create additional constraints on the PS frequency stability after large-scale RES integration by 2030; ii) the requirements related to the frequency support and the ROCOF should be specified in the Moroccan GC. In fact, the ROCOF could exceed the limit of 0.5 Hz/s following the lack of inertia constant estimated by the year 2030; and iii) the LVRT profile should be updated, as proposed in Figure 5, to take in consideration the limits of the existing LVRT profile. It should be noted out that most RES manufacturers can be aligned with more restrictive LVRT profiles and can even follow the zero-voltage-ride-through profiles, the Moroccan GC has to be more demanding regarding the LVRT requirement.

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