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Impact of renewable energy resources on frequency of a power system based on mathematical approach

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Abstract— Renewable Energy Sources (RES) are the energy sources of the future. However, RES have negative impacts on system's frequency stability because of their intermittency and low inertia characteristics. While intermittency property results in power balance in the system, which is reason for frequency variation, low inertia characteristic influences frequency change such as Rate of Change of Frequency, the minimum and maximum values of the frequency. This paper focuses on these influences of RES on frequency variation when a power imbalance occurs in the system according to mathematical theory. The results obtained show similarities with studies using simulation tools or events occurring in operational practice.

Keywords— renewable energy, frequency stability, inertia of renewable energy, impacts of renewable energy.

I. INTRODUCTION

The energy that we use today is mainly fossil energy. However, the use of this energy sources is facing two major challenges: exhaustion and environmental pollution, renewable energy sources (RES) are, therefore, inevitable alternative to traditional energy sources. RES's annual installed capacity is increasing year by year, especially wind and solar power (as shown in Fig. 1). International Energy Agency has published the world's first comprehensive roadmap to net-zero emissions by 2050 [1], which confirms continuous RES increasing trend.

However, RES have some features such as intermittency, low inertia, etc. adversely affects frequency stability of a power system. Research on this effect are mostly performed on a specific grid by simulation tools or analysis of event in practice. The goal of this article will analyze the impact of RES on the frequency variation of the power system in general in terms of mathematical analysis by establishing and solving differential equations, thereby provide a comprehensive look on this influence.

The paper is organized as follows: Section II discusses about the inertia of some types of power plants and the impact of RES on the system's inertia. The influence of RES on system frequency is demonstrated in section III by using the swing equation and load model. Finally, section IV summarizes the conclusions drawn from the study.

II. POWER SYSTEM'S INERTIA WITH PARTICIPATION OF RENEWABLE ENERGY SOURCES

2.1. Inertia of conventional, wind and solar power units

In general, the inertia H [s] is expressed in its elementary

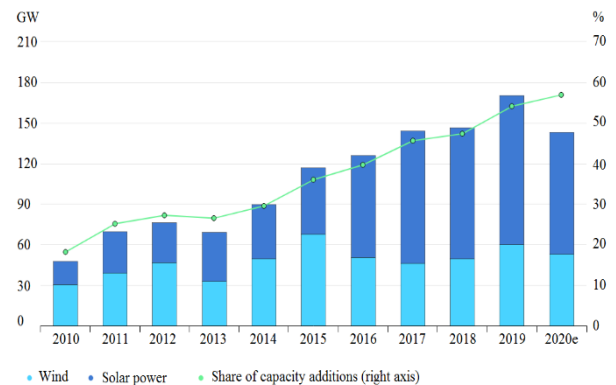


Fig. 1. Global solar PV and wind power capacity additions, 2010-2020e [2]

form as the resistance of any physical object to a change in its state of motion, including changes in (rotational) speed and direction [3]. It also can be defined as the ratio of the kinetic energy of rotating masses of the system and the rated power S [MVA] of synchronously rotating machines [4] as shown in (1):

$$H = \frac{J \cdot \Omega_r^2}{2 \cdot S} \quad (1)$$

Where: J is the total moment of inertia of the system [kg.m²], Ω_r is the angular speed of rotor [rad/s].

The inertia constant can be expressed in seconds as it indicates the time in seconds a generator can provide its rated power solely using the kinetic energy stored in the rotating mass of its drive train [3].

a) Conventional plants

The inertia of conventional units like e.g. coal fired, gas, oil, nuclear and hydropower plants using synchronous generators to convert mechanical energy into electricity is typically in the range of 2-9s [5, 6]. Fig. 2 shows the inertia constant of several steam and hydro generators with different power ratings. It can be clearly seen that there is no apparent consistency in the inertia constant for a particular type of technology or size, which means that the generator's inertia constant depends strongly on the design of both generator and turbine.

b) Wind power units

Currently, there are 4 wind generator configurations in use [3] as depicted in Fig. 3.

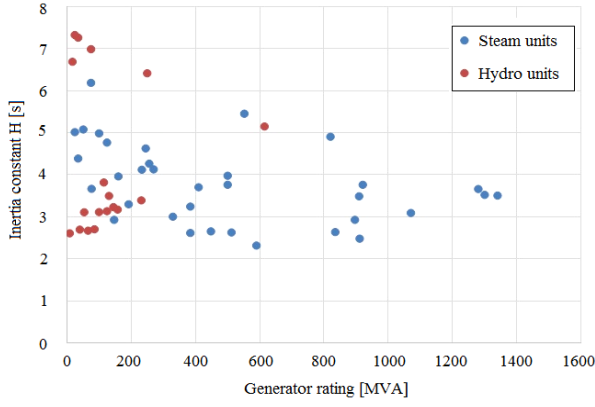


Fig. 2: Typical inertia constants for conventional units [3]

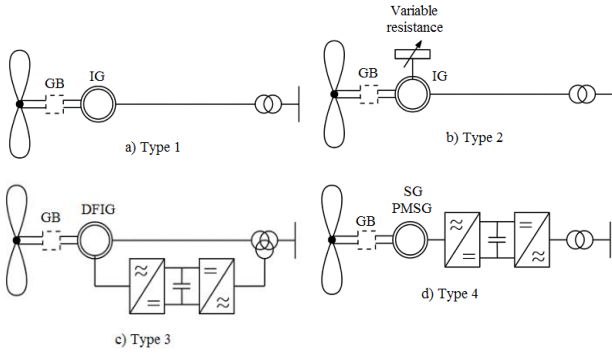


Fig. 3: Common wind turbine topologies (GB: gearbox, IG: induction generator, SG: synchronous generator, DFIG: doubly fed induction generator, PMSG: permanent magnet synchronous generator) [3]

The most basic (and oldest) wind turbine topology applied is type 1 and type 2. They offer a simple and robust power conversion, but they have also many disadvantages, such as the need for reactive power compensation and the limited ability of varying its rotational speed with the windspeed resulting in a low efficiency over the whole wind speed range, so they are gradually squeezed out of the market as new installations or the repowering of old turbines consist predominantly of variable speed wind turbines equipped with a DFIG (type 3) or full-scale converter interface (type 4). According to some calculations, the inertia of generators of the two topologies 1 and 2 can be approximately 5 seconds [3]. However, these generators are inductor generators so the way this inertia is delivered slightly differs from a synchronous machine. Due to the slip of the inductor machine, the inertial response from these generators is slightly slower and lower [7, 8].

Type 3 - wind generator connects to the system through 2 branches: line 1 connects directly to the grid and the other line is connected to the power system through converters. Regarding the amount of power transferred through converters, there is absolutely no response when the system frequency is changed because these converters take samples of previous cycles to convert DC power (after AC/DC converter) to AC power (after DC/AC converter) synchronizing with the system. This means that the wind generator's inertia cannot be transmitted through the converter, or inertia in this direction has a value of 0s. In the other direction, generator provides a partial direct grid coupling via the stator windings of the DFIG, but the inertial response from these units seems to be almost negligible, mainly due to the fast-acting converter controller which is usually designed to regulate the electrical torque [3].

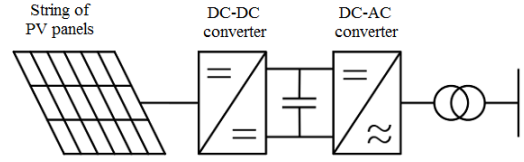


Fig. 4: Typical solar (PV) topology

Finally, type 4, which is a back-to-back configuration consisting of an alternating current/direct current (AC/DC) and DC/AC converter, allows an extended variable speed operation in order to obtain maximum efficiency. Typically, synchronous generators and permanent magnets or electrical excitation are used in this configuration [9]. In case a direct driven multipole generator with a large diameter is applied, the generator and the blades can operate at the same speed so that the gearbox can be omitted. Obviously, in this type, between the generator and the grid are completely decoupled by the power electronic interface (AC/DC and DC/AC). It is for this reason that there is no inertia provided to the system when using this topology.

c) Photovoltaic (PV) units

In a PV system (see Fig. 4), similar to type 4 of the wind power system, there is no inertia provided to the system in this case because between the PV system and the power system is connected via converters DC/DC and DC/AC.

2.2. Power system's inertia with participation of renewable energy sources

The inertia of the system is calculated by using (2):

$$H_{\text{sys}} = H_{\text{gen}} + H_{\text{load}} \quad (2)$$

With: H_{sys} – the total inertia of the system; H_{gen} , H_{load} – The total inertia of the generators (rotating) and of the loads in the system, respectively.

In which, the total inertia of the (rotating) generators in the system is calculated according to (3) below:

$$H_{\text{gen}} = \frac{\sum_i^N H_i \cdot S_{G,i}}{S_{\text{sys}}} \quad (3)$$

Where:

$S_{G,i}$, H_i – the power and the inertia of the i^{th} generator in the system, respectively;

$S_{\text{sys}} = \sum_i^N S_{G,i}$ – the total power production (the total power consumption) of the system.

When there is participation of RES in the system, in order to maintain the balance between the generation power and power consumption, there is only the number of M ($M < N$) rotating generators operating in the system at this time. The total power of the amount of the synchronous generators not participating in the system ($N - M$) is equal to the total power of the RES injecting the system.

Since the inertia of RES is 0s as mentioned above, then the system's inertia will now be determined as (4) below:

$$H_{\text{sys_RES}} = H_{\text{gen_RES}} + H_{\text{load}} = \frac{\sum_i^M H_i \cdot S_{G,i}}{S_{\text{sys}}} + H_{\text{load}} \quad (4)$$

From (2), (3) and (4) it can be easily seen that the inertia of the system is smaller with the participation of RES ($H_{\text{sys_RES}} < H_{\text{sys}}$).

III. IMPACT OF RENEWABLE ENERGY RESOURCES ON FREQUENCY OF A POWER SYSTEM

3.1. Load model

In general, the load power can be considered consisting of the following components:

- Independent power component, regardless of voltage and frequency fluctuations of the power system;
- The frequency dependency of load characteristic;
- The voltage dependency of load characteristic.

Equations (5) and (6) below describe the power of the load according to the above contents [10]:

$$P = P_0[P_{ZIP} + P_{EX1} + P_{EX2}] \quad (5)$$

$$P_{ZIP} = p_1 \cdot \bar{V}^2 + p_2 \cdot \bar{V} + p_3$$

$$P_{EX1} = p_4 \cdot \bar{V}^{a1} \cdot (1 + K_{pf1} \cdot \Delta f)$$

$$P_{EX2} = p_5 \cdot \bar{V}^{a2} \cdot (1 + K_{pf2} \cdot \Delta f) \quad (6)$$

$$\bar{V} = \frac{V}{V_0}$$

$$\Delta f = f - f_0$$

Where:

P_0 – Rated power of load at reference voltage V_0 and frequency f_0 ;

P – actual power of load at real voltage V and frequency f ;

K_{pf1} , K_{pf2} – the dependent coefficients of the load power on frequency;

p_1 , p_2 , p_3 , p_4 , p_5 – the dependent coefficients of the load power on frequency.

Substitute (6) into (5) and rearrange, get (7):

$$P = k_{f1} \cdot f + k_{f2} \quad (7)$$

Where:

$$k_{f1} = P_0 \cdot (p_4 \cdot \bar{V}^{a1} \cdot K_{pf1} + p_5 \cdot \bar{V}^{a2} \cdot K_{pf2})$$

$$k_{f2} = P_0 \cdot [P_{ZIP} + p_4 \cdot \bar{V}^{a1} \cdot (1 - K_{pf1} \cdot f_0) + p_5 \cdot \bar{V}^{a2} \cdot (1 - K_{pf2} \cdot f_0)]$$

The coefficient k_{f1} in (7) reflects the self-regulation of load characteristic, which is typically assumed within the range of 1% - 2% [11,12].

3.2. Impact of renewable energy resources on frequency of a power system

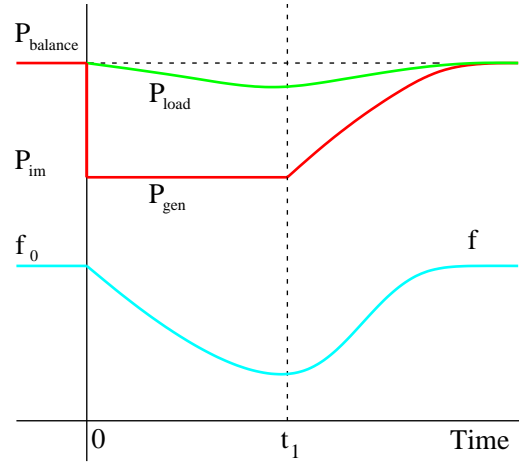


Fig. 5: Power imbalance

Assume that, before $t_0 = 0$, the system is in power equilibrium state, meaning P_{gen} (the total power production) equal to P_{load} (the total power consumption) equal to P_{balance} as illustrated in Fig. 5, with nominal voltage and frequency V_0 , f_0 , respectively.

At t_0 , a power imbalance occurs in the system due to a sudden drop in the output power of the RES because of weather conditions (the intermittency characteristic of RES). The total power production of the system is now at P_{im} (P_{im} less than P_{balance}) and maintained until t_1 , before the primary control is activated and takes effect.

Frequency change of the system in time period $[0; t_1]$ is described in the swing equation below [3, 4,14]:

$$2H \frac{df}{dt} = f_0 (p_{\text{gen}} - p_{\text{load}}) \quad (8)$$

During the observation period $[0; t_1]$, the system voltage is assumed to be always maintained at the rated voltage V_0 . This assumption makes the calculations much simpler, thus, attention can be focused on the main problem of determining stability. That means $p_{\text{gen}} = \frac{P_{\text{im}}}{S_{\text{sys}}}$ and $p_{\text{load}} = \frac{k_{f1} \cdot f}{S_{\text{sys}}} + \frac{k_{f2}}{S_{\text{sys}}}$, substitute these formulas into (8) and rearrange, we have:

$$\frac{df}{dt} + \frac{k_1 \cdot f}{H} = \frac{k_2}{H} \quad (9)$$

With $k_1 = \frac{f_0 \cdot k_{f1}}{2S}$; $k_2 = \frac{f_0 \cdot (P_{\text{im}} - k_{f2})}{2S}$, the root of (9) is:

$$f = \frac{k_2}{k_1} + \left(f_0 - \frac{k_2}{k_1} \right) e^{-\frac{k_1}{H} t} \quad (10)$$

And Rate of Change of Frequency (RoCoF) is:

$$\text{RoCoF} = \frac{df}{dt} = -\frac{k_1}{H} \left(f_0 - \frac{k_2}{k_1} \right) e^{-\frac{k_1}{H} t} \quad (11)$$

In the operational practice of the power system, we often care about the magnitude of the RoCoF:

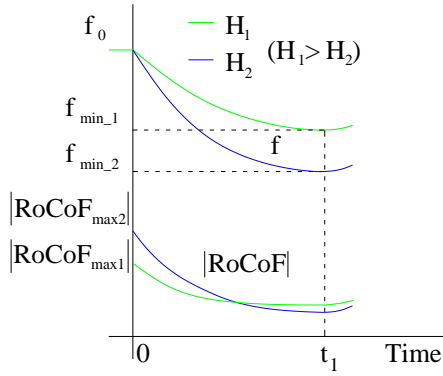


Fig. 6: Change in frequency and RoCoF

$$|\text{RoCoF}| = \left| -\frac{k_1}{H} \left(f_0 - \frac{k_2}{k_1} \right) \right| e^{-\frac{k_1}{H}t} \quad (12)$$

It is easy to recognize that $k_1 > 0$ while the value of k_2 depends on the value of P_{im} and k_{f2} . In case of $k_2 < 0$, let:

$$|\text{RoCoF}| = \frac{k_1}{H} \left(f_0 - \frac{k_2}{k_1} \right) e^{-\frac{k_1}{H}t} \quad (13)$$

From (10) and (12), there are some comments (as indicated in Fig. 6):

- The results are similar to those published by other authors analyzing actual events or using simulation tools;
- The frequency in the system decreases exponentially with minimum frequency achieved at t_1 .

$$f_{\text{min}} = \frac{k_2}{k_1} + \left(f_0 - \frac{k_2}{k_1} \right) e^{-\frac{k_1}{H}t_1} \quad (14)$$

- The magnitude of the RoCoF also changes exponentially with the maximum magnitude in the interval $[t_0, t_1]$ achieved at t_0 :

$$|\text{RoCoF}_{\text{max}}| = \frac{|k_2 - k_1 \cdot f_0|}{H} \quad (15)$$

- The smaller the inertia is, the smaller (greater) the minimum frequency f_{min} (the maximum frequency f_{max}) and the greater the $|\text{RoCoF}|$ are.

In the operational practice, there are a number of requirements in the operation of the power system:

- The frequency of the system must always be in the range $[f_{\text{min}_s}; f_{\text{max}_s}]$, if the frequency is out of this range, the outage will occur. From (14), we will find the required inertia of the system (with a given power imbalance) so that the frequency of the system is always greater than f_{min_s} and less than f_{max_s} :

$$H_1 \geq \frac{1}{k_1 \cdot t_1} \cdot \ln \frac{k_1 \cdot f_0 - k_2}{f_{\text{min}_s} \cdot k_1 - k_2} \quad (16)$$

- The RoCoF of a power system needs to always be less than a threshold of $\text{RoCoF}_{\text{max}_s}$, because if RoCoF exceeds

this value there will be a loss of synchronism in the system [15]. Based on (15), the required inertia of the system is also found:

$$H_2 = \frac{|k_2 - k_1 \cdot f_0|}{\text{RoCoF}_{\text{max}_s}} \quad (17)$$

The inertia required of the system satisfies the two above criteria: $H = \max\{H_1; H_2\}$

IV. CONCLUSIONS

The intermittency of output power of RES is one of the causes of power imbalance incident in the system. This power imbalance in turn is reason for the system's frequency change. In addition, The inertia of RES is very low inertia, they, therefore, reduce the inertia of the power system when connected to the system. This results in the frequency variation of the system to be faster when a power imbalance occurs in the system. If there are no solutions when the value of the frequency or the RoCoF exceeds a particular threshold there will be serious consequences such as outage, loss of synchronism. The mathematical model in this article has provided a comprehensive analysis on this issue. The model can even analyze the effectiveness of the control measures to counteract this change if the control function is put into the model.

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