

# Grid Inertia and Frequency Control in Power Systems with High Penetration of Renewables

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**Abstract**—With increasing power generation out of renewable energy sources, there is a rising interest to investigate their impact on the power system and its control. In this paper, both the impact on frequency control and the capability to deliver frequency support by renewables is presented. A test grid is used to also investigate the variation of system inertia as a function of time. It is shown that by integrating renewables in the generation mix, the frequency support deteriorates, but through additional control, the frequency support can be improved. Finally the control of an inertialess grid is shortly described and some recommendations for future research are given.

**Index Terms**—power-frequency control, renewable energy integration, grid inertia

## I. INTRODUCTION

AT the start of 2011, after a decade of significant growth, the installed wind and solar power in the EU-27 countries reached a capacity of respectively 86 GW [1] and 29 GW [2]. To meet the 2020 targets of the European Union, the installed capacity of renewable energy sources (RES) is expected to increase even further.

While already dealing with aging infrastructure and an ever increasing demand for electric power, this projected increase of electric power coming from renewable energy sources will put an even higher stress to the already highly loaded power system.

From a power system perspective, this dispersed renewable electricity generation behaves quite different from traditional, centralized generation facilities. Apart from their intermittent nature, most of these sources do not contribute to system reserves and to the total system inertia. This system inertia is often considered as one of the vital system parameters upon which the synchronized operation of current day power systems is based: the inertia in the rotating masses of synchronous generators and turbines determines the immediate frequency response with respect to inequalities in the overall power balance. When a frequency event occurs, the synchronous machines will inject or absorb kinetic energy into or from the grid to counteract the frequency deviation. The lower this system inertia, the more nervous the grid frequency reacts on abrupt changes in generation and load patterns.

Wind turbines are generally equipped with back-to-back converters, in the form of doubly fed induction generators (DFIG) or full converter synchronous generators (FCSG), which electrically decouple the generator from the grid. Therefore no inertial response is delivered during a frequency event,

although a lot of kinetic energy is stored into the blades and the generator. Unlike wind turbines where there is actually some kinetic energy available (although rarely used), solar panels are virtually inertialess.

The paper is organized as follows. Section II elaborates the impact of replacing conventional power plants with renewable energy sources on frequency control. Next, in section III, a small power system is used as a test case to investigate both the variation of system inertia during the day as well as the influence of integrating renewables on the system inertia. Section V deals with inertialess grids. Finally, section VI gives some recommendations for future research and section VII resumes the main conclusions.

## II. IMPACT OF RENEWABLE ENERGY SOURCES ON FREQUENCY CONTROL

The frequency control in a power system can be roughly split up into two phases. In a first phase, the frequency controllers of the power plants have not yet been activated. The generators will absorb or release their kinetic energy to arrest the change in frequency. This phase is called inertial response, because the inertia dampens the frequency changes. In a second phase, the frequency is first stabilized and then restored to the nominal frequency by respectively the primary control (governor action) and secondary control [3], [4]. Additional measures, like automatic load shedding, can be taken in case of severe frequency deviations. In the following sections, the impact of integrating renewables on both phases is described.

### A. Inertial response

Focussing on the inertial response, the frequency variation, directly after a significant generation-load imbalance is determined by the equation:

$$P_g - P_l = \frac{d\left(\frac{1}{2}J_{system} \cdot \omega_{el}^2\right)}{dt} \quad (1)$$

with  $P_g$  the generated power,  $P_l$  the power demand,  $\omega_{el}$  the electrical angular frequency and  $J_{system}$  the inertia of the system. The right-hand side of equation (1) is the derivative of the kinetic energy stored in all the generators of the power system. The kinetic energy stored in a single generator shaft is often expressed proportional to its power rating and is called the inertia constant  $H_{gen}$ :

$$H_{gen} = \frac{J_{gen} \cdot \omega_{el,0}^2}{2 \cdot S_{gen}} \quad (2)$$

With  $S_{gen}$  the nominal apparent power of the generator,  $\omega_{el,0}$  the nominal system frequency and  $p$  the number of pole

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pairs. The inertia constant is measured in seconds and it falls typically in the range of 2-9 s for large power plants [5]. In general, for power plants with the same technology, the inertia constant is inversely proportional to the rating, see also Figure 1 [6]. Writing equation (1) in per unit, together with (2) results in:

$$\bar{P}_g - \bar{P}_l = 2 \cdot \sum_i \frac{H_{gen} S_{gen}}{S_{base}} \cdot \bar{\omega}_{el} \cdot \frac{d\bar{\omega}_{el}}{dt} \quad (3)$$

$$= 2 \cdot H_{system} \cdot \bar{\omega}_{el} \cdot \frac{d\bar{\omega}_{el}}{dt} \quad (4)$$

With  $H_{sys}$ , the inertia constant of the whole power system. Assuming  $\bar{\omega}_{el} \approx 1$ , the initial rate of change of frequency (ROCOF) can be expressed as:

$$\frac{d\bar{\omega}_{el}}{dt} = \frac{\bar{P}_g - \bar{P}_l}{2 \cdot H_{system}} \quad (5)$$

The ROCOF is thus mainly determined by the magnitude of the power imbalance and the system inertia. This system inertia depends mainly on two factors: the number of operating generators and the inertia of each of these generators. Synchronous generators in classical power plants can contribute to this inertia, because of the strong coupling between their rotational speed and electrical frequency. Wind turbines and photovoltaic (PV) units on the other hand, equipped with converters which decouples electrically the motion of generator from the grid frequency, typically deliver no inertial response. Replacing conventional generation by wind and solar power will thus result in a lower system inertia, which in case of a frequency event can lead to a high ROCOF.

This increase in ROCOF can lead to a cascade effect of disconnecting distributed generation (like solar and smaller wind farms) if they are protected against islanding by ROCOF relays. Islanding occurs when a part of the power system becomes electrically isolated from the rest of the power system, yet continues to be energized by generators connected to the isolated subsystem. This islanding can be detected by ROCOF or vector shift relays. ROCOF relays rely on the fact that, when islanding occurs, the local generation will not exactly balance the remaining load. Consequently, the frequency will change rapidly, depending on the power imbalance and the inertia of the islanded network, and the islanded grid will be disconnected.

If the protection of a power system is equipped with many ROCOF relays and this system has a low inertia, the relays can also have an impact on the frequency control. In case of a major load-generation imbalance (high ROCOF), the relays will disconnect much of the installed distributed generation. Due to these disconnections, the produced power will even further decrease and aggravate the original frequency event [7].

Typical ROCOF relays, installed in a 50 Hz system are set between 0.1 and 1 Hz/s, depending on the inertia of the grid [8]. Studies for the island grid of Ireland show already that the thresholds of current ROCOF relays should be increased to accommodate the anticipated wind power up to 2025 [9].

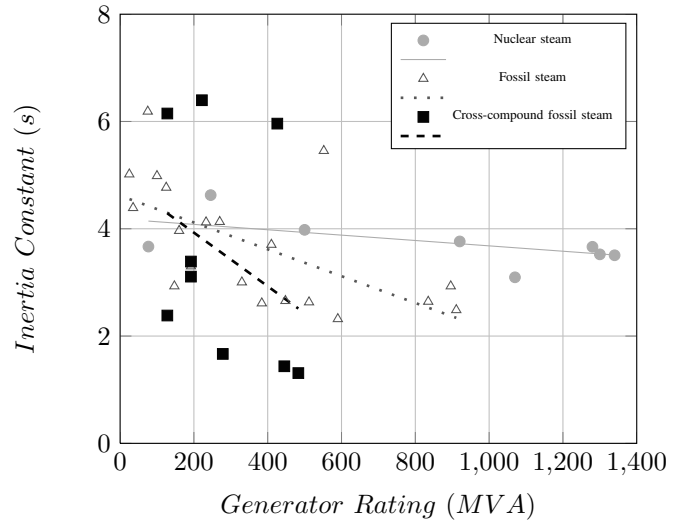


Fig. 1. Inertia constants for conventional units (derived from data in [6])

### B. Primary and secondary control

Wind turbines and other forms of renewable energy sources are generally exempt from delivering primary or secondary control [10]. Together with their lack of inertia, replacing conventional generation with renewables will highly influence the frequency response. Not only the ROCOF is increased as explained in the previous section, also the minimum/maximum frequency is changed. Due to the lower system inertia, the remaining synchronous generators have now less time to react. Together with a smaller amount of generators delivering primary control, this will result in a lower minimum or higher maximum frequency when a comparable grid event occurs.

With a higher penetration, further decrease in minimum frequency can lead to load shedding or may even cause a black-out. Especially in island grids which already have a lower inertia than large interconnected systems, the frequency response will be highly deteriorated when conventional generation is replaced by solar or wind power.

In some countries however (with existing or planned high wind penetration), TSOs require wind power plants already to behave as close as possible to conventional power plants. For instance, the TSO of Ireland requires wind turbines to deload at nominal frequency and request a frequency response as described in Figure 2. As the frequency falls below point B, the frequency response system integrated in the turbine shall act to ramp up the wind turbine active power output, in accordance with the droop characteristic defined by line B-A [7].

## III. INERTIA IN POWER SYSTEMS WITH HIGH PENETRATION OF WIND AND SOLAR

In order to further examine the variations of the system inertia during a day, a small island power system is used as a test grid. Different cases with high and low demand are considered.

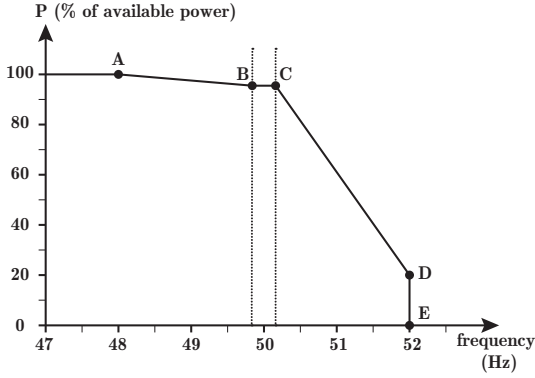


Fig. 2. Power-frequency capability chart of wind turbines in Ireland [7]

### A. Power system model

The power system used in the simulations consists of eleven conventional power plants with a total capacity of 762 MW together with a wind farm of 100 MW and a solar PV plant of 30 MW. For more details of each generator, see Table I in the appendix. Two different 24 hour cases are considered. A high demand case with a peak demand of 645 MW and a low demand case with a peak demand of 430 MW. To solve the unit commitment model, mixed integer programming is used [11], [12]. The objective function that needs to be minimized, together with the constraints is:

$$\min_i \quad cost = \sum_i c_i \cdot P_i \quad (6)$$

$$\begin{cases} \sum_i P_i = P_{load} \\ P_i \leq z_i \cdot P_{i,MAX} \\ P_i \geq z_i \cdot P_{i,MIN} \\ \sum_i (z_i \cdot P_{MAX} - P_i) \geq P_{UPWARD} \\ \sum_i (P_i - z_i \cdot P_{MIN}) \geq P_{DOWNWARD} \end{cases}$$

With  $c_i$  the marginal cost (fuel cost and CO<sub>2</sub> cost) and  $P_i$  the power output of each power plant.  $z_i$  is 1 if the power plant is operating and 0 when it is shut down. The constraints that are implemented are the minimal and maximum power production of each plant, an available upward reserve of 60 MW and a downward reserve of 30 MW. Wind and solar are considered as ‘negative demand’. Ramp rates and start-up costs are not taken into account. Line limits and grid losses are also not considered.

### B. Results and discussion

The results are displayed in Figure 3 and Figure 4. Looking at the two cases, it is clear that there are large variations in system inertia during a day. During the night, when the demand is low, few power plants are operating and the inertia is low. During high demand, the opposite is true. Comparing the cases with and without renewables, the inertia drops significantly when integrating renewables into the generation mix, due to smaller amount of operating generators. Especially during the night, the integration of renewables can lead to a very low inertia. When a sudden power imbalance occurs

during this period, the frequency variations will be very large. Because solar power coincides with periods of high demand (high inertia), the effect of solar power on system inertia will be smaller than that of wind, which will occur both during periods of high and low demand.

## IV. FREQUENCY SUPPORT BY RENEWABLES

Although renewable energy sources without special controls do not contribute to the system inertia, the stored kinetic energy in wind turbines can be used to support the frequency. Solar panels on the other hand store no kinetic energy but only a limited amount of energy in the DC capacitor, but they also can be controlled, in combination with a battery unit to support the frequency control.

Both wind farms and solar PV plants can also potentially contribute to frequency support in case they are curtailed. In the following section, the inertia of wind turbines is compared with that of conventional power plants. Next, the different control methods that can be used to support the frequency control by renewables are further elaborated.

### A. Inertia of renewable energy sources

In a wind turbine, the gearbox and the blades contribute to the stored energy. Although the speed of the generator is 80-100 times higher than the blades if a gearbox is present, most of the kinetic energy is coming from the blades due to their high inertia. Expressed as an inertia constant,  $H$  varies from 2-5 s [13], [14]. This is comparable with the inertial constants of conventional power plants. However when comparing the kinetic energy and their use in frequency control to conventional power plants, several differences should be mentioned:

- The kinetic energy stored in a wind turbine varies with time. When for instance the wind speed increases, the rotor speed will also increase to operate at maximum efficiency. A higher rotor speed results in an increase in stored kinetic energy. In a conventional power plant, the stored kinetic energy is virtually constant, since the generator speed is coupled with the system frequency.
- The strong coupling between the rotor speed and the frequency has an other consequence. When the frequency for instance drops, the kinetic energy release will be proportional with the ROCOF. The release of energy from a wind turbine (or PV unit), can be controlled independently from the ROCOF. In theory it can thus even deliver a larger inertial response than a classical power plant. Therefore, we also can not simply add the inertia constant of a conventional power plant with that of a renewable, since the latter has a controlled release of kinetic energy.

### B. Frequency support methods

To improve the frequency control in a grid with high penetration of renewables, four main control methods can be found in literature:

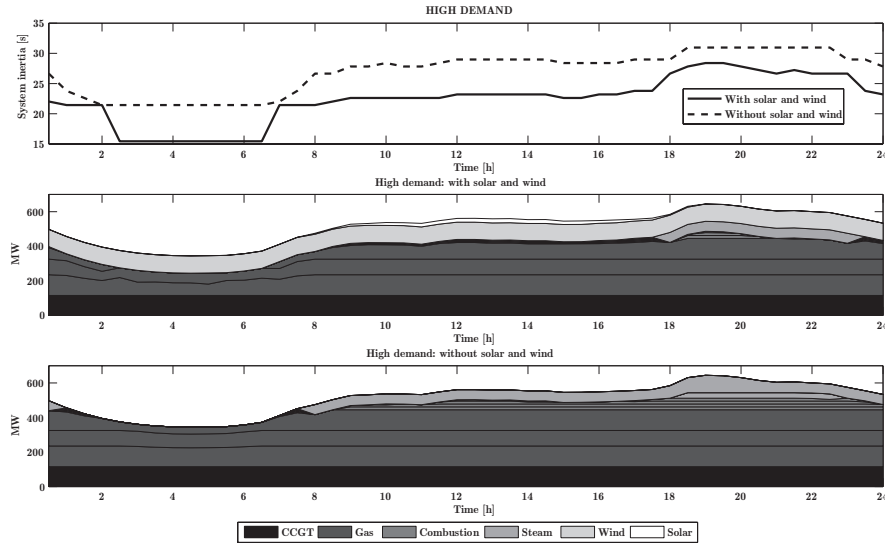


Fig. 3. Inertia and power generation for the high demand case: with and without solar and wind ( $S_{system} = 100MVA$ )

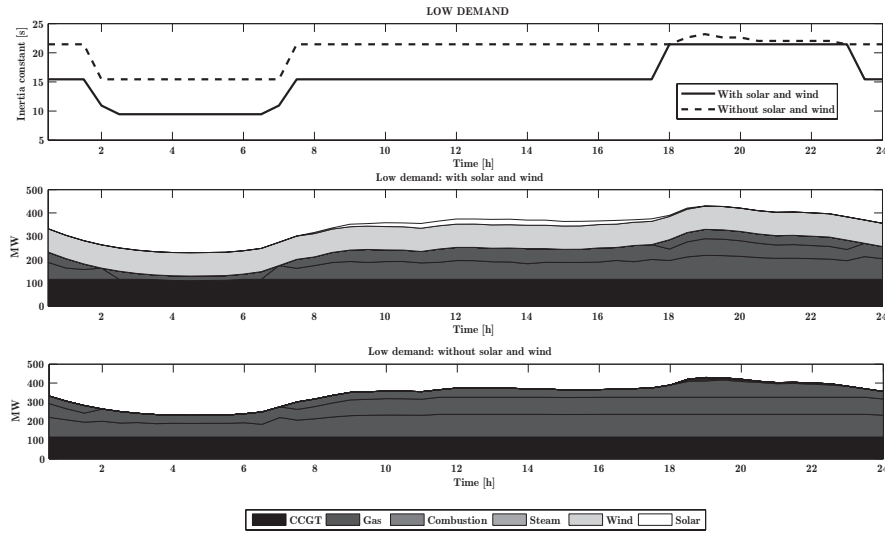


Fig. 4. Inertia and power generation for the low demand case: with and without solar and wind ( $S_{system} = 100MVA$ )

- In a first method, an energy storage system (ESS) like batteries or capacitors is added together with a PV unit or wind farm [15], [16]. A coordinated control is necessary between the ESS and the wind farm/PV unit, to optimize the power output by the renewables and the frequency support.
- Another possibility is deloading or curtailing the wind turbine or PV unit. By deloading, the units operate at a sub-optimal operating point and a power reserve is created which can be used for frequency control [17]. The main advantage of this option is that frequency control can be delivered for a longer period of time and thus participate in primary and secondary control like conventional power plants do. However, keeping reserves by renewables is relatively expensive due to the production support mechanisms and the negligible marginal costs [18].
- A third option (only applicable to wind turbines) uses the kinetic energy to support the frequency by interchanging this energy with the grid (Figure 5). For instance, during a frequency dip, the wind turbine will raise its power output during  $t_{dec}$  to deliver frequency support. As a consequence, the rotor speed will drop. To bring it back to the optimal rotor speed, the power output decreases [19], [20]. In this case, no power is spilled during normal operation. On the other hand, frequency control can only be delivered for a short time and a second frequency dip can occur because of the decrease in power output during  $t_{acc}$ .
- Finally, we can also intervene at the load side through demand side management (DSM). In [21] for instance, a control method is proposed to control a voltage-independent load to support the frequency.

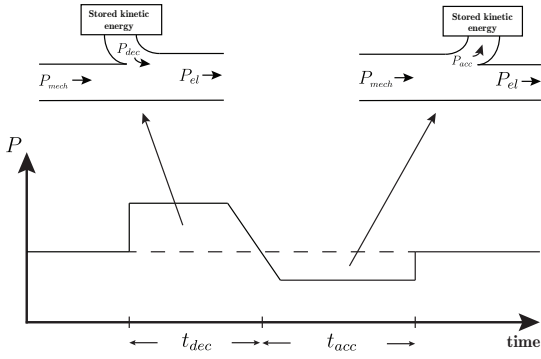


Fig. 5. Frequency control by interchanging kinetic energy

## V. INERTIALESS GRIDS

By integrating more and more renewables in the generation mix, the inertia drops, and the power system can even become completely inertialess. One of the important tasks in current day research is to provide new control strategies for such inertialess systems as a whole, as well as to include so-called ‘virtual inertia’ in the control of inverter-fed renewable energy sources connected to the power system. Advanced control strategies can make these inverter-fed renewable energy systems to behave in a way similar to synchronous generators [22]. Using the system frequency as one of the controlled variables and inputs to the controller, it becomes possible to mimic a power response similar to that of classic synchronous generators. This is shown in Figure 6. An extra control signal is sent to the inverter to deliver frequency support. The control emulates both the inertial response (virtual inertia) as the primary (droop) control of a synchronous generator. The power reserve for the frequency control is created by adding an energy storage or by deloading the wind turbine/PV unit. A coordinate control is necessary between the inverter, the energy storage and the deloading of the unit [23], [24].

In the liberalized context it is important to recognize that the operation of the grid will be fundamentally different, yet the system operator is limited in its operations. Adequate grid codes are needed so that the independent generators do not disturb the power system in a detrimental way. This includes a careful study of the available ancillary services that can be made available from the PV units and wind turbines.

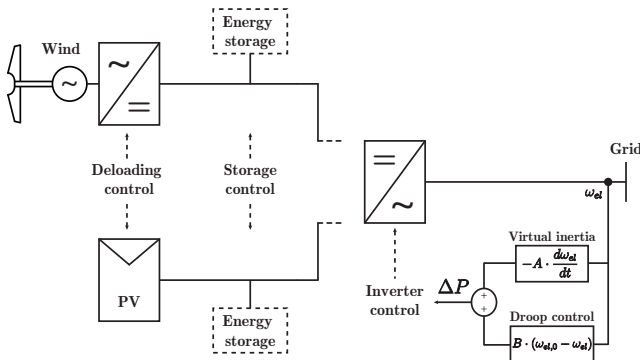


Fig. 6. Frequency support by renewables: control diagram

## VI. FUTURE RESEARCH

Future research is needed on systems with low inertia and the impact of high penetration of PV and wind. The main research questions are:

- What are the limits of the electrical power system with increasing participation of inertialess generation when maintaining current operation principles? What are the drivers to implement additional control features in converter connected devices and generators?
- What is the role of the system operator, and how can he deal with a high concentration of large-scale PV?
- How should virtual inertia respond to grid faults?
- Is there a difference in frequency response by distributing this virtual inertia amongst all the power plants or concentrate it?

## VII. CONCLUSION

It is obvious that the increase of renewable energy sources results in an urgent need for the assessment of their impact on grid stability. Both the inertial response as the primary and secondary control are highly influenced by integrating renewables. Some control methods were presented in this paper to mitigate this impact of integrating renewable energy sources on frequency support. Also the variations in system inertia were further investigated.

The effect of the penetration of renewables is most noticeable during low load situations as the use of renewables will cause the deactivation of traditional power plants and consequently lower the overall grid inertia. Wind power is in this respect worse than solar power, as solar power only reduces the grid response during moments of high load (higher initial inertia). On the other hand, wind turbines store a significant amount of kinetic energy, while solar units are completely inertialess.

It is clear that when the power system has a very small inertia or even becomes inertialess, the whole frequency control methodology needs to be redefined and new methods need to be developed to maintain the frequency.

## APPENDIX

TABLE I  
PARAMETERS FOR EACH CONVENTIONAL GENERATION UNIT

Type	Fuel	Minimum power [MW]	Maximum power [MW]	Cost [€/MWh]	Inertia constant [s]	
ST1	Steam	oil	58	130	112.2	4
ST2	Steam	oil	32	60	144.9	3.3
ST3	Steam	oil	32	60	144.9	3.3
CCGT1	CCGT	gas	45	115	56.8	4.3
C1	Combustion	oil	6	16.7	107	3.5
C2	Combustion	oil	6	16.7	107	3.5
C3	Combustion	oil	6	16.7	107	3.5
C4	Combustion	oil	6	16.7	104	3.5
G1	Gas	gas	40	120	98	5
G2	Gas	gas	40	120	98	5
G3	Gas	gas	20	90	98	5

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