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Contribution of Power Converters in Frequency Stability of Low-inertia Power Systems

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ABSTRACT - Integration of low carbon electricity generation technologies such as Renewable Energy Sources (RES) has been increasingly considered as a potential way to decrease Green House Gases (GHG) emissions from conventional fossil fuel power plants. With such increased penetration of such RES specially those interfaced with the network through power electronic converters (RES-CI), new challenges emerge in the way the resulting future power systems are conceived and operated. In this manuscript, we discuss the challenge of low-inertia prevailing in such systems, we touch down upon the roots of the problem, and assess a potential solution by considering the possibility of converters contributing to the grid's operation, stability and robustness. A small signal dynamic model of a converter outer control emulating inertial response is utilized to prove the concept. Results show decreased ROCOF and increased nadir values. Additional conclusions related to tuning, control and stability analysis were also drawn from the results. Finally some future research directions to proceed in this domain are proposed.

Keywords - Low-Inertia Systems, Inertia emulation, Frequency Stability, Frequency Regulation, Inverter-based Resources (IBR), Converter-interfaced Generation (CIG), Microgrids.

1. Introduction

Climate change was identified by the United Nations and other environmental organization as the most critical threat humans might face in the twenty-first century [1]. The UN Sustainable Development Goals (UN-SDG) concerned this threat with two of its seventeen goals [2], [3]: UN-SDG7 - Affordable and Clean Energy and UN-SDG13 - Climate Action, setting serious goals for international community to act on [4]. The increase of the RES share is at the heart of the measures taken to decrease the GHG emissions and help mitigate the effects of Global Warming. Other measures include also employing low carbon emissions power sources and the respective shift from fossil-based power plants. Many of the low or 100% carbon free technologies deployed are interfaced to the network through a power electronic converter. Nevertheless, other portion of these low carbon emissions technologies can also rely on the conventional synchronous generators to produce electricity and thus are directly connected to the power system. Fig. 1 shows that many of the technologies that provide 100% Carbon-free emissions are synchronous based while as many are interfaced using power electronic converters [5]. At the present, power systems mostly utilize power generation units from the right portion of Fig. 1. These units are mostly of very large capacity and usually centralized. Large centralized facilities are mostly economic due to their large scale, but they usually have to transmit power to consumers far away, hence may affect the environment negatively [6].

At a certain instant in the future, the weight of the power-electronic-based and converter-based generation technologies will exceed that of the more conventional, synchronous generator-based production units. With that new challenges emerge, such as; the small inertia related to these converter-based units, their intermittency and stability related issues [6]–[9]. The majority of these CIGs are wind and PV units. The volatility and uncertainty of the primary energy resources harnessed by these units can be of significant problem to the operation of the power system. Large-scale penetration of such CIG units into the conventional Synchronous Generator (SG) based power system leads to frequency stability issues. This is due to the fact that the power electronic converter interfacing such units and the grid prevents them from having an inertial response to any eventual unbalance. Conventional power plants such as those generation units at the right-hand-side of Fig. 1 utilize synchronous generators to produce electrical power. These synchronous generators are directly connected to the grid without any power electronic interface and thus exhibit the natural inertial response to any eventual unbalance in the network.

CIG units on the other hand does not inherit such natural response. For instance, PV arrays require power electronic dc–ac inverters to integrate with the grid and do not offer an inertial response, and certain types of wind turbines utilizes variable frequency ac – dc – ac converters, which decouple the wind turbine inertia from the grid. Consequently, the inertia of the power system decreases as the penetration of RES-CI/CIG increases. The reduced inertia in the power system leads to an increase in the rate of change of frequency (ROCOF) and frequency deviations in a very short time, under power imbalances that substantially affect the frequency stability of the system [7], [10]. Studies such as that performed on the Eastern US Interconnection system shows that the system's frequency response will decrease dramatically when the renewable penetration reaches 60 to 80% [11].

This article examines the challenge of decreasing network's synchronous inertia, its root causes, and investigates a proposed solution through the contribution of power converters to the network stability and robustness through emulating

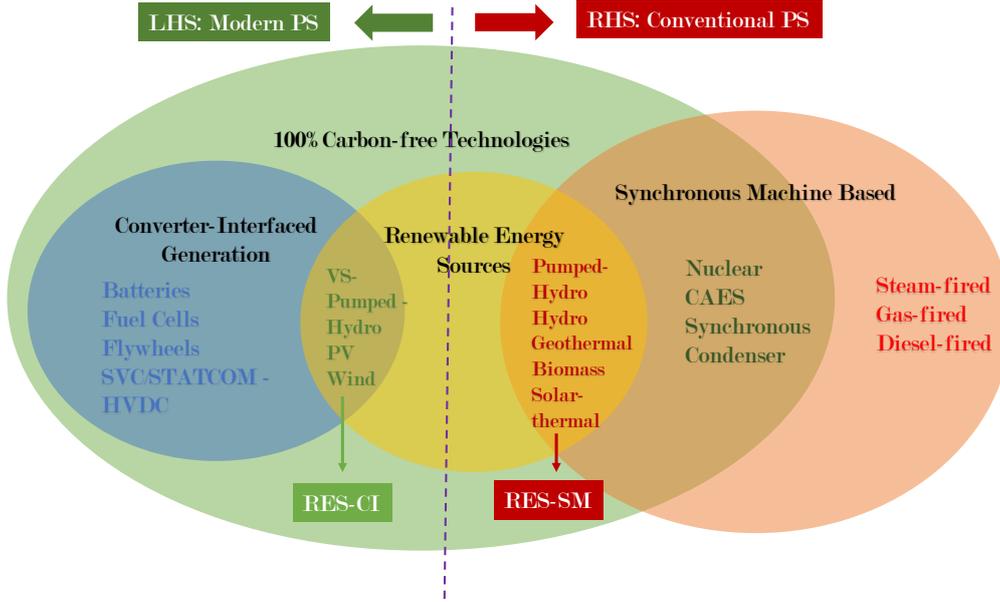


Figure 1: Different power generation plant types. (SVC:Static Var Compensator, STATCOM:Static synchronous compensator, VS: Variable Speed, CAES: Compressed Air Energy Storage, PS: Power System) [5]

SG's inertial response in the active power control loop of the converter. Additionally, future research directions are proposed to further investigate the issue of low-inertia in the future power systems.

The remainder of this paper is organised as follows. Section 2 explores the concept of inertia and the relation between inertia and frequency regulation and control in conventional power systems. Section 3 first explains the effect of CIG integration on the previous inertia concept and then assesses the proposed inertia emulation technique using such converters as a solution to the issue. Finally section 4 concludes with the manuscript most important key-takeaways and propositions for future steps.

2. The low inertia challenge

Inertia is the term coined to describe the physical behavior of a system to continue in its initial state of motion when an exterior force acts upon it. A car for example, tends to continue motion in its initial direction when the driver presses the break pedal. The car doesn't stop instantaneously, but continues in its initial trajectory for a certain distance until the friction with the ground dissipates all its Kinetic Energy (KE) and then finally stops. A power plant utilizing an SG directly connected to the rest of the grid is physically analogous to the previous concept. The famous SG's swing equation derived from newton's second law of motion for rotating objects is shown in equation (1).

$$\sum P = \frac{J \cdot \omega_e}{p^2} \cdot \frac{d^2 \theta_e}{dt^2} \quad (1)$$

where $\sum P$ is the sum of all active power produced by the generator, e.g., $P_e - P_m - P_f$ for instance. J is the moment of inertia which physically represents the resistance to the change in the rotational speed of the SG. θ_e and ω_e are respectively the rotor electrical angular position and the electrical rotational speed. p is the number of rotor field winding pole pairs.

To further simplify the above second order differential swing equation, first, an important term is introduced, which is the inertia constant H , which is defined as the the time period in seconds when the system can produce the nominal power only through the stored KE in its rotor. Thus, the inertia constant H can be expressed as:

$$H = \frac{E_k}{S} = \frac{J \cdot \omega_{e,0}}{2 \cdot p^2} \quad (2)$$

Further more, the second order swing equation (1) can be expressed in per unit (\tilde{P}) and rewritten as two first order equations. Considering the rated machine power and nominal frequency as base values and assuming only small deviations from rated frequency ($\omega_e \approx \omega_{e,0}$) and by substituting by equation (2), we can express the swing equation simply as:

$$\sum \tilde{P} = 2H \cdot \frac{d\tilde{\omega}_e}{dt} \quad (3)$$

The previous swing equation is derived for a single machine. For a power system of (n) SGs, the following generalization is used. First, the inertia constant for the whole network is calculated as in equation (4). Then, as the frequency at the different generators' terminals is not the same at the event of a certain imbalance in the network, the generalized swing equation represents the aggregated average fluctuations of the electrical frequency at a virtual point in the network called the "Center of Inertia" (COI) and is expressed in equation (5) for a certain power imbalance ΔP_{dist} .

$$H_{total} = \frac{\sum_{i=1}^n E_{k,i}}{S_{total}} = \frac{\sum_{i=1}^n H_i \cdot S_i}{\sum_{i=1}^n S_i} \quad (4)$$

$$\Delta \tilde{P}_{dist} = 2H_{total} \cdot \frac{d\tilde{\omega}_{e,COI}}{dt} \quad (5)$$

The total inertia H_{total} in a conventional power system can be described as a resistance in the form of KE exchange from rotating machines, to compensate for the fluctuations in frequency arising from power imbalances. Thus, instantaneous, short-term energy support under load fluctuations is called Synchronous Inertia (SI). Consequently, increased value of the total network inertia constant H_{total} means that the network exhibits a large amount of KE stored in its rotating masses and hence, can compensate *momentarily* for larger power imbalances and result in less severe frequency fluctuations and drops until the generating units equipped with frequency control governors start reacting to arrest such frequency fluctuations (primary control) and return the frequency to its nominal value (secondary control).

Frequency ROCOF and nadir are indicators of how severe a frequency fluctuation is following an imbalance event. The former is an indication of how rapidly the frequency changes after a sudden imbalance and is calculated from equation (6). The latter determines the lowest frequency reached following the imbalance after the primary frequency control started acting to prevent further frequency drop. The frequency ROCOF and nadir values are very important, as they determine the set points of the safe operation relays such as the load shedding relays (UFLS) pre-configured by the network operators to maintain the safe and reliable operation of the network by arresting increased and further drop of frequency below limits of operation.

$$ROCOF = \frac{\Delta P_{dist} \cdot f_b}{2S_{total} \cdot H_{total}} \quad (6)$$

3. Power converters contribution to network inertia

Power converters don't intrinsically inherent enough energy storage to provide inertia response such as that provided by synchronous machines and discussed above. Additionally, power converters interfacing wind energy for instance, prevent the physical coupling between the KE in the blades and the grid [12], [13]. Thus, the decrease of synchronous based units and an increase of penetration of such RES-CI units imposes the following challenges to network operators [7], [8]:

- 1) Very limited inertial response following an imbalance,
- 2) Decreased frequency regulation reserves such as Primary Frequency Curtailment Reserves (P-FCR),
- 3) Increased ROCOF and decreased nadir values,
- 4) Resulting in triggering of ROCOF relays, activating network security thresholds such as UFLS,
- 5) Consequently, the overall network frequency stability is jeopardized.

To be able to face these challenges, current research is undergoing in the field of power converters control to compensate for the previous challenges without jeopardizing the overall grid stability. For that purpose, the classification of power converters based on control technique has been undergoing a continuous development and adjustment to be more representative of the requirements of the continuously developing and evolving power system [14]–[16]. Classically in literature, power converters controls are classified into three distinct categories namely "Grid-forming", "Grid-feeding", and "Grid-supporting". Grid-forming (GFM) control aims to create the network's nominal frequency and voltage references, while Grid-feeding/following (GFL) control is most commonly used with PV and wind converters, since they are designed to work at maximum power point (MPP) and synchronize their output with the network frequency and voltage. Grid-supporting main objective on the other hand is to participate in the regulation of the ac grid voltage amplitude and frequency references by controlling the active and reactive power delivered to the grid [17].

In recent literature, GFM technology has grown beyond the simple need to create and maintain the reference network frequency and voltage to being a generic inverter control that can be tuned and designed to provide a wide variety of network requirement needed by the network operator, while maintaining its base role as creating and maintaining the network base frequency and voltage reference. GFM inverter can thus be defined based on its capability and the grid services it provides to the network [18], [19]. One of these classifications is shown in table I according to [19], [20]. It can be seen how the distinctive limit between GFL and GFM technologies fades when only classifying the converter

Table I: Classification of power converters according to their contribution to network support and stability [19], [20]

Strategy/Contribution	Strategy A	Strategy B	Strategy C
Active Power tracking	✓✓	✓✓	X
Active Power saturation	✓✓	✓✓	X
Frequency support	✓✓	✓✓	✓✓
Inertia contribution	X	✓✓	✓✓
Robustness	✓✓	✓	✓

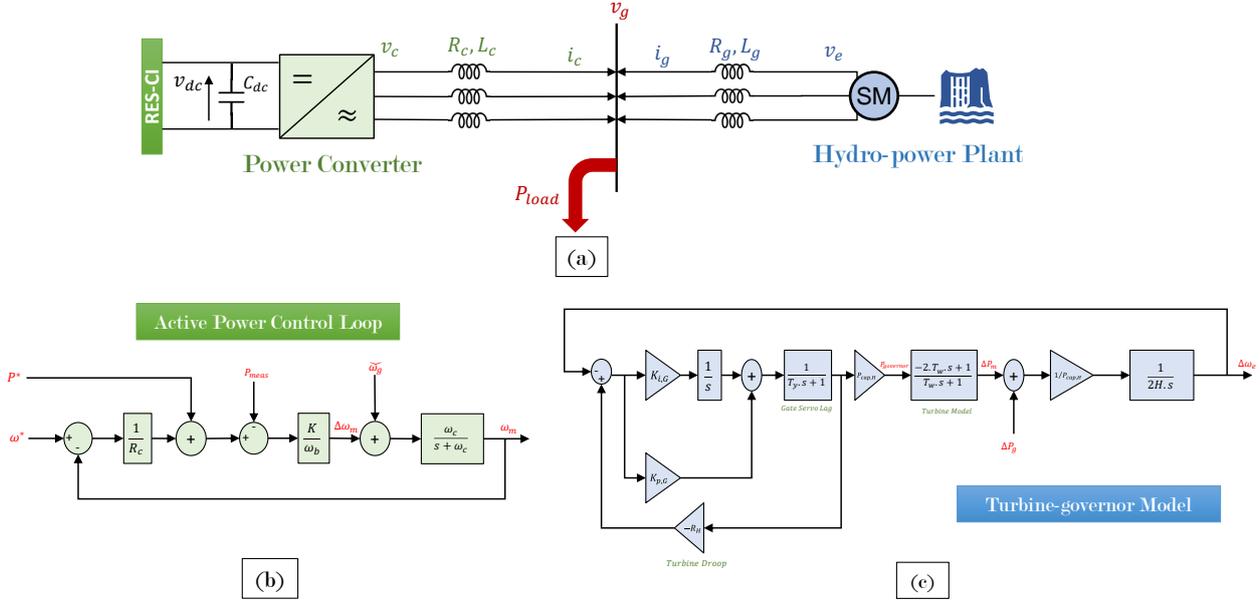


Figure 2: (a) The network under study, (b) Converter's active power control loop, (c) Hydro's turbine-governor model

control according to the contribution it makes to the grid. It can also be noted how converters can be controlled to contribute to the network inertia instead of decreasing it.

In order to understand how converters can be controlled to provide inertial response and increase network inertia constant, let us consider the following network proposed in this paper and shown in Fig. 2a. The network consists of a power converter connected to a large synchronous machine representing a large hydro-power plant. In order to analyze the active power and frequency dynamics accompanying the inertial response under study and following a certain power imbalance, the active power control loop of the converter as well as the hydro turbine-governor models are considered only in this study. The former and latter models are shown in Fig. 2b-2c respectively. The transfer function of the converter active power loop (after the droop constant) shown in Fig. 2b is shown in equation (7). The use of the low pass filter (LPF) with cut-off frequency ω_c results in a lag between the grid measured frequency ω_g and synchronizing angle used in the control ω_m , which emulates the inertial effect.

$$p^* - p_{meas} = \frac{\omega_b}{K \cdot \omega_c} \cdot \frac{d\omega_m}{dt} + \frac{\omega_b}{K} \cdot (\omega_m - \omega_g) \quad (7)$$

Equation (7) is analogous to that of virtual synchronous generator (VSG) control concept. It can be reformulated into:

$$p^* - p_{meas} = 2H_v \cdot \frac{d\omega_m}{dt} + \frac{\omega_b}{K} \cdot (\omega_m - \omega_g) \quad (8)$$

Thus, by comparing equation (7) to equation (8), the emulated inertia constant can be tuned as:

$$H_v = \frac{\omega_b}{2K \cdot \omega_c} \quad (9)$$

Developing the small-signal model of the power converter control loop in Fig. 2b would result in a fourth order transfer function model. Assuming all frequencies are approximately equal, an equivalent decomposition of the fourth order model in two-second-order model can be deduced [20]. The resulted small-signal model describing the grid frequency dynamics in response to an imbalance is shown in Fig. 3. An illustration of the effect of the emulated inertia by the

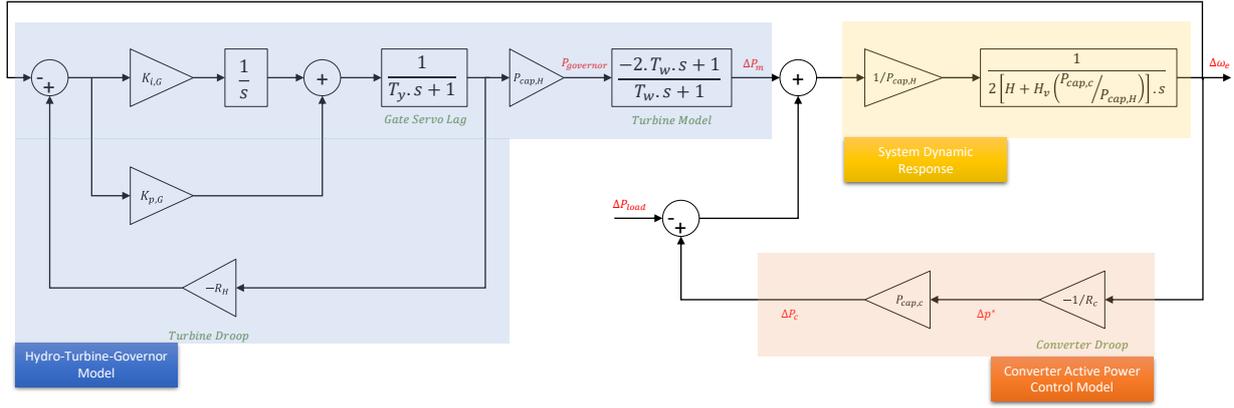


Figure 3: Small-signal dynamic model

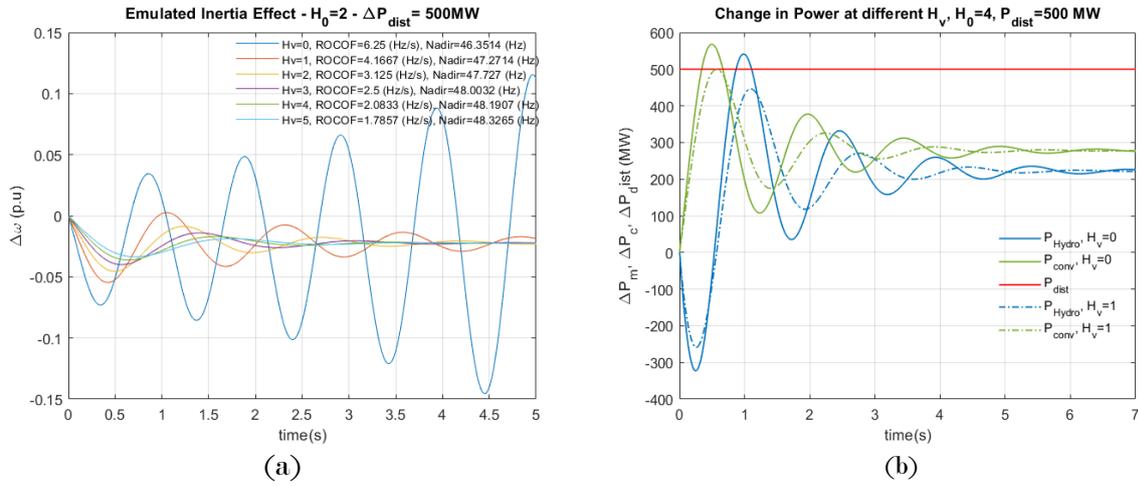


Figure 4: (a) Effect of emulated inertia, (b) converter versus turbine-governor system in regulating active power

converter in supporting the network stability and robustness to ROCOF and nadir is simulated and some insights are shown in Fig. 4.

It can be concluded from Fig. 4a that a disturbance of 500MW could result in very high ROCOF (6.25 Hz/s) and jeopardize the network frequency stability in a system with base synchronous inertia constant of 2s (the blue curve). The contribution of the converter in providing emulated inertial response can result in lower ROCOF and higher frequency nadir as shown. Additionally, in contrary to conventional synchronous inertia which depends of the generator parameters as shown from equation (2), the emulated inertia by the converter is tunable as shown from equation (9).

Fig. 4b shows how the turbine-governor model reacts versus the converter active power control loop to this disturbance of 500MW both at the case where the converter emulates the inertial response and without it. It can be noticed how the converter control is hundreds of magnitudes faster than the turbine-governor model which is considered a key advantage for providing frequency regulation support using power converters. It should also be noted that during the transient period, active power of the converter increased above 500MW which is also his rated maximum power. A limiter should thus be added to the control to prevent over-loading.

4. Conclusions and future directions

In this paper, we demonstrated the contribution of power converter in the grid robustness and frequency stability through emulating inertial response using a small-signal dynamic model of a network supplied by a synchronous generator and a power converter. The validity of the proposed model controllers in response to a certain imbalance was tested and their inertial response was simulated. The shown configuration appears to be stable in the regime of small-signals and the inertial response emulated by the power converter's controls is proven to be effective in arresting high ROCOF values and limiting the frequency nadir. Another insight brought to the surface by this manuscript is the effectiveness of the novel power converter classification reported in literature, where power converters are classified according to their contribution to the network which removes the ambiguity accompanying the previous classification

into grid-following/forming and supporting. The authors believe that the recent classification is more representative of the control architectures.

Recently, many techniques for inertia emulation and frequency regulation using power converters are proposed in the literature. Evaluating such techniques within different and complex network topologies and investigating the inertia placement homogeneity across the network is reported to be the next step in assessing potential solutions for the challenges of low-inertia networks. Time-domain simulations could be handy in evaluating the different controls on the overall network stability of complex and large networks to analyze the effect of network topology and inertia placement on the frequency stability of complex and huge power systems and the similarities/differences between such systems and very small ones such as Microgrids. Possible future investigation of the network's stability assessment using Lyapunov's energy functions could provide interesting insight of the network overall stability. However, the former despite being a good candidate for evaluating stability of non-linear systems, it requires the good selection of the energy function which might be a challenging task to perform.

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