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To cite this article: Ratnam Kamala Sarojini and K Palanisamy 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **937** 012018

IOP Conf. Series: Materials Science and Engineering **937** (2020) 012018 doi:10.1088/1757-899X/937/1/012018

Comparison of Emulated Inertia controller with Synchronous Generator

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Abstract. The emulated inertia controller (EIC) is designed to emulate the inertia to the power electronic inverter. The EIC helps to integrate the large-scale PV into the grid without affecting the stability. This paper demonstrates the design of EIC control. This paper the highlights the comparison of EIC with the traditional synchronous generator (SG). The frequency response of both EIC and SG are compared for different scenarios.

1. Introduction

The usage of renewable energy sources (RES) in the power generation sector is tremendously increasing due to concern on carbon emissions. The renewable power generation such as PV and wind are integrated to the grid though the power electronic converters. The power electronic based renewable power generators decouple the load from the source. The more penetration of RES in the power generation affects the frequency stability of the system. In general, the SG deals with frequency stability issues in the traditional power system. Whenever there is a change in the system frequency the kinetic energy stored in the rotor of the SG injects to balance the system in the inertial response. As the power generation from the RES is increasing, the inertia constant of the grid is decreasing. The less inertia constant results in more frequency deviation and large rate of change of frequency. To mitigate the inertia related issues, the virtual inertia concept is proposed in the literature. The main idea behind the virtual inertia is to emulate the inertial characteristics of the SG to the power electronic inverter. Several emulated inertia control (EIC) techniques are developed in the literature to address the issue [1].

In [2], the complete mathematical model of the SG is taken to design the inertia emulation algorithm, and it results in numerical instability. In [3], the second-order model of SG is considered to design the control algorithm; here, the calculation of ROCOF leads to complexity in the algorithm. The EIC control scheme is an appropriate solution to the low inertia power system. The EIC mimics the SG characteristics, by regulating the switching pattern of the inverter to offer the virtual inertia and to decrease frequency nadir during disturbances. In [4], the small-signal modelling of EIC with ideal grid-connected inverter is analysed. The implementation of the EIC algorithm in the power system is reported in [5]. The use of inertia emulation in the microgrid is analysed in [6]. Inertia emulation using hybrid energy storage consists of battery and supercapacitor for the single-phase rooftop system is proposed in [7-20]. However, earlier investigation on EIC only emphasis on the controller design, grid-connected applications and hardly compares inverter with EIC and SG. The objective of this paper is to compare the physical structure and performance of the EIC with power electronic inverter with SG [21-30].

The rest of this paper is organized as follows. Section 2 explains the structure of RES based power generation and traditional SG. Section 3 describes the control strategy of EIC. Section 4 presents fundamental comparison of the SG and EIC with inverter. Section 5 deals with the results and discussions. Finally, section 6 gives the conclusion.

2. Structure of Power Generation from RES with Grid-tied Inverters and traditional SG

The general structure of power generation from the renewable and conventional sources is detailed in Figure 1. The Figure 1 consists of the primary energy source, prime mover, energy conversion unit and grid [31]. The primary energy source for the RES based system might be solar, wind, battery, fuel cell etc. whereas in case of traditional energy storage system for the primary energy storage system is Hydraulic, coal etc. The prime mover for the RES based system is DC-DC convertors, for the Conventional system the prime mover is turbine [32-34]. The next stage is the energy conversion unit. The energy conversion unit for the RES based system consists of DC bus capacitor, grid-tied inverter, and a filter. The energy conversion unit for the conventional system consists of the rotor and a synchronous generator.

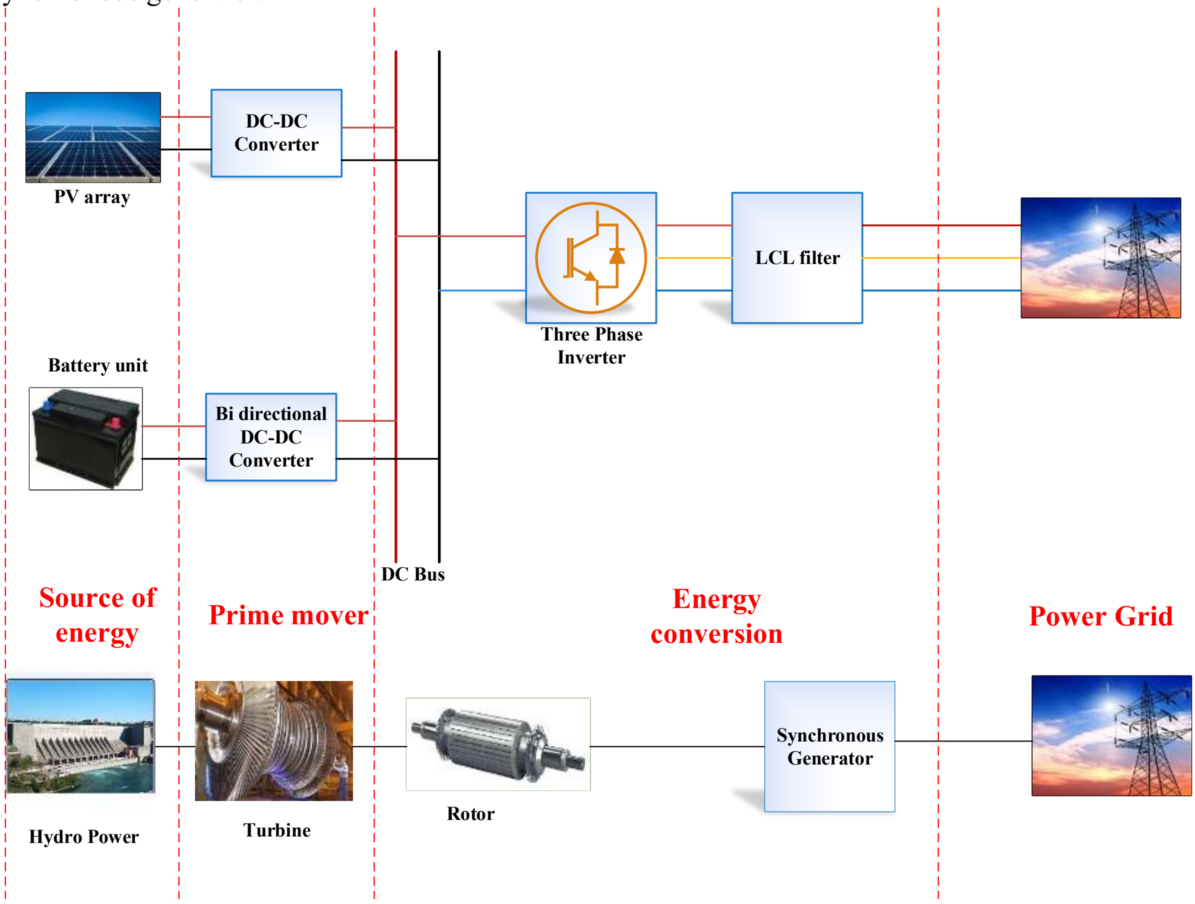

Figure 1 structure of RES and traditional power generation system

3. Control strategy of EIC

EIC enhances frequency stability of the power system and allows more power generation from renewables into the system [8]. EIC uses the swing equation to emulate the inertia. EIC resembles the

IOP Conf. Series: Materials Science and Engineering **937** (2020) 012018 doi:10.1088/1757-899X/937/1/012018

SG characteristics to enhance the frequency stability. Moreover, it emulates inertia to the power electronic inverter like SG to support frequency stability of stand-alone microgrid. The control diagram for the EIC is illustrated in Figure 2. The main concept of EIC is to calculate the extra power required for the frequency deviation and to add this extra power to set point. The EIC responds to frequency variations and alters the load angle. The electrical appearance of both EIC and SG mathematically equivalent. Hence, the inertial response of the EIC is similar to the SG.

The EIC developed based on the swing equation to alter the load angle of the inverter θ. The fundamental concept of EIC is shown in (1)-(3).

$$(P_{Set} - P_{Cal}) / \omega - D_P(\omega - \omega_r) = J\frac{d\omega}{dt} \quad (1)$$

$$\frac{d\theta}{dt} = \omega \quad (2)$$

$$\frac{1}{k}\int (Q_{Set} - Q_{Cal}) + D_q(V_m^* - V_m)dt = E \quad (3)$$

The EIC is divided into two control parts. The first part of EIC is used to alters the load angle based on the frequency deviation. The damping term for the given frequency deviation is included to the difference in the set torque (calculated with set power) to the torque output (calculated with output power). The integrator, along with inertia term alters the load angle based on the difference in torque terms. Whereas in the second part of EIC regulates the voltage amplitude. Depends on the reactive power variation, the voltage amplitude can be altered. The voltage amplitude and the load angle are combined to get the reference voltage for the inverter. The reference voltage generated by the EIC is fed to PWM to produce the pulses for the inverter. Whenever there is a change in the demand, the EIC alters the load angle to inject/absorb the power with the help of energy stored in the battery. Implementation of EIC in a stand-alone microgrid reduces the frequency deviations and ROCOF.

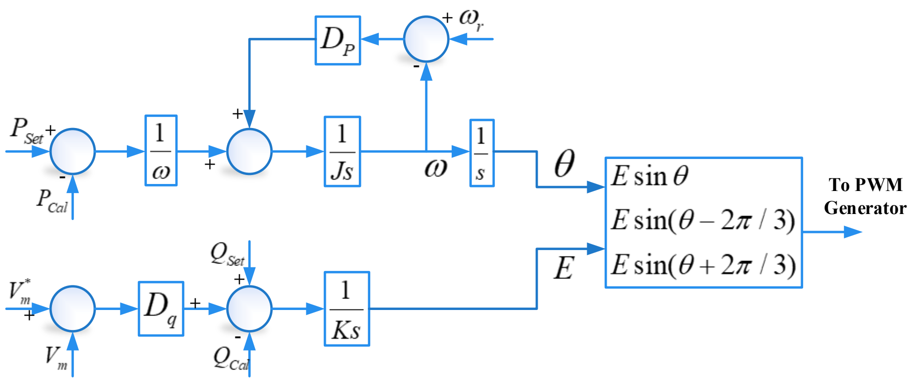

Figure 2. Emulated inertia control

4. Fundamental correlation between EIC with inverter and SG

The inverter with EIC control and SG shows the close resemblances in physical structures, parameter characteristics, mechanism of energy transmission and mathematical models.

4.1. Fundamental comparison in physical structure and parameter

The physical structures for both RES based generation and traditional generation are shown in Figure 1. The detailed physical structure for both the generation is clearly discussed in Section 2. The summary of the relevance of the EIC with inverter and the SG is tabulated in Table 1.

Table I – Relevance of EIC with inverter and SG elements

	Inverter with EIC	**SG**
Source of energy	RES, Battery, SC	Hydraulic, Coal. nuclear
Prime mover	Power electronic converters	Turbines
Energy conversion device	Capacitor	Rotor

The parameters of the EIC with inverter and SG are logically related. The inertia of the rotor of SG is related to the capacitance of the capacitor of the power electronic inverter. The energy stored in the rotor of SG is used in inertial response to compress the frequency deviations in traditional power system. Whereas the energy stored in capacitor/ energy in storage element is used to reduce the frequency deviations. The relevance of the different parameters, EIC with inverter and SG is summarised in Table 2.

Table 2- Relevance of EIC with inverter and SG parameters

Inertia with EIC	**Traditional SG**
Capacitance of capacitor	Inertia of rotor
Filter	Stator of the SG
DC capacitor voltage	Rotor angle
Output voltage of the inverter	SG internal voltage
Output voltage of the filter	Terminal voltage of SG
Energy stored in capacitor	Energy stored in rotor

4.2. Similarity of the mechanism of energy transmission and Its mathematical model

There is a similarity in the mechanism of the energy transmission in the EIC with inverter and in SG is shown in (1). From (1) the dynamic behaviour of rotor of SG and capacitor of the inverter are first order differential equations. Hence, the energy transfer mechanism for the both systems in frequency deviations are similar to maintain the system in equilibrium. The control mechanism of the EIC is to attain power balance and to maintain the stability. The simulation parameters are shown in Table 3.

5. Results and discussions

The simulations are carried out using the Matlab/Simulink environment. The simulations are performed in order to compare the performance of EIC and SG model. The ratings of Power electronic inverter with EIC and SG are considered to be of same rating. To exhibit the similarity of the EIC with inverter and SG several cases were tested. The simulation parameters are shown in Table 3.

Table 3: Simulation parameters

Parameters	Values
Reference frequency (f)	50 Hz
Reference Voltage (V^*)	220 V
Rated DC bus voltage (V_{DC})	500 V
PV cell	$V_{OC} = 37.3$ V, $I_{SC} = 8.2$ A, $V_m = 30.3$, $I_m = 7.5$, $N_S = 15$, $N_P = 2$.
DC bus Capacitor	3300 μF
Inverter side inductance (L_1)	2.1 mH

Load side inductance (L_2)	0.8 mH
Filter capacitance (C)	12 μF
Frequency Drooping Coefficient (D_P)	50
Inertia coefficient (J)	0.058 Kg.m^2
Voltage drooping coefficient (D_q)	120
Gain (k)	1000 A. s
SG capacity	10 KVA

5.1. Response to sudden load increase
In this case the frequency response of the inverter with EIC control and SG are compared under sudden increase in load. Initially the system is running in steady state and the frequency is maintained at 50 Hz. At t =2 s the sudden 10% increasing of load demand is simulated. The frequency response of inverter is replicating the frequency response of the SG as shown in Figure 3.

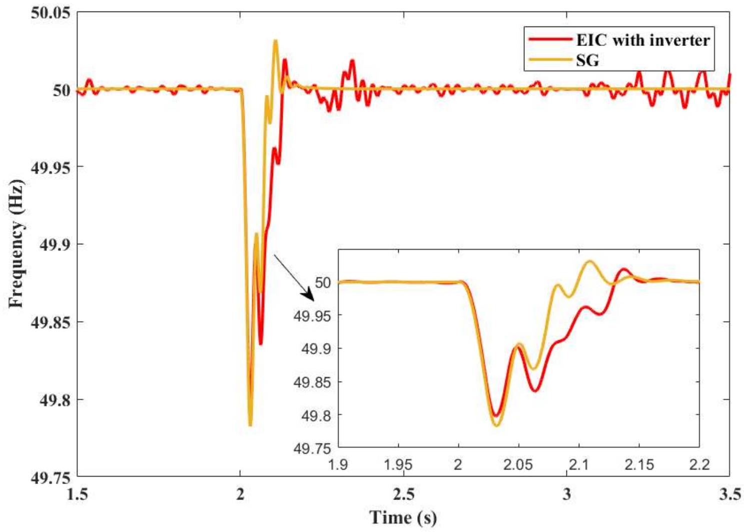

Figure 3. Frequency response under sudden load increase

5.2. Response to sudden load decrease
In this case the frequency response of the inverter with EIC control and SG are compared under sudden decrease in load. The system reaches to steady state after sudden increasing of demand and the frequency is maintained at 50 Hz. At t = 4 s the sudden 10% increasing of load demand is simulated. The frequency response of inverter is replicating the frequency response of the SG as shown in Figure 3.

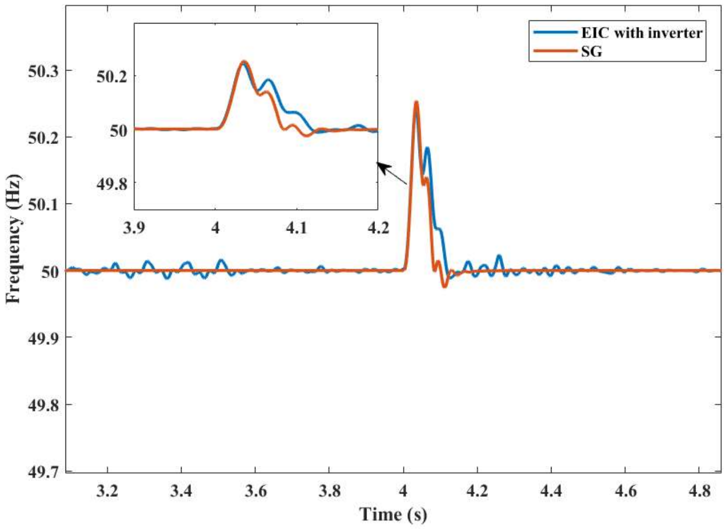

Figure 4. Frequency response under sudden load decrease

From simulation results it was concluded that inverter with EIC control is able to emulate the frequency response like SG. Hence, low inertia in power grids can addressed by using the EIC along with power electronic inverters.

6. Conclusion

In this paper, an EIC was modelled to emulate the inertial response of the SG. The transient behaviour of the grid connected inverter with EIC is compared with SG. It can be concluded that the VSG is showing similar characteristics of SG and can be used in the large penetration of RES system to maintain the stability. On the other hand, power rating of the inverter needs to be increased. This paper summaries the comparison of EIC with inverter and SG in terms of the physical structure and parameters. This paper proved that the EIC controlled inverter exhibit the relevant dynamic response same as of SG.

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