Comparison Analysis of Virtual Inertia Control Methods for Smoothing Power Production of Grid Connected Wind Farm on a Power System

1st Marwan Rosyadi
Dept. of Electrical Engineering
Universitas Muhammadiyah Surabaya
Surabaya, Indonesia
rosyadi@um-surabaya.ac.id

2nd Agus Siswanto
Dept. of Electrical Engineering
17 Agustus 1945 of University
Cirebon, Indonesia
asiswanto.untagcrb@gmail.com

3rd Rudi Irmawanto
Dept. of Electrical Engineering
Universitas Muhammadiyah Surabaya
Surabaya, Indonesia
rudi.irmawanto@ft.um-surabaya.ac.id

Abstract—**This paper presents comparison analysis of the methods of Virtual Inertia Control System (VICS) for smoothing power production of large-scale wind farm which connected to a power system. Four commonly used VICS methods, synchronous generator model-based, swing equation based, droop-based approach, and frequency-power response-based, are compared in terms of effectiveness in smoothing wind farm power production and damping frequency fluctuation of the power system. The VICS is applied on the inverter based STATCOM/BESS which connected to 9-Bus power system model. Simulation analyses have been performed by using PSCAD/EMTDC. The results show that the frequency-power response-based VICS is more effective for reducing wind farm power fluctuation.**

Keywords—virtual inertia control system, STATCOM/BESS, wind farm, frequency control.

I. INTRODUCTION

Along with the increasing rate of demand for electrical energy, the use of primary energy sources derived from fossil fuels is also increasing. As a result, the supply of fossil energy sources is depleted. Wind energy is the most popular forms of renewable energy today, and it is widely used all over the world. Wind energy, on the other hand, has a weakness because it is classified as a variable renewable energy source with non-dispatchable and intermittent characteristics. Wind turbine generators are pieces of machinery that convert wind energy into electrical energy. Wind turbine generators have the advantage of being able to be installed in distribution networks, reducing energy imports without the need for long-distance transmission networks [1]. However, the widespread deployment of wind turbine generators reduces the inertia in the electric power system. This is due to power converters used in wind turbine generators replacing the functions of fossil power plants that use synchronous generators. [2]. When inertia is lost, the system becomes more susceptible to interference and loses reliability. High-level wind farm power fluctuations can cause excessive frequency and voltage oscillations. Even if the oscillation exceeds a critical threshold, the wind farm must be removed from the system.. Disconnecting large-capacity generators from the system abruptly can cause serious problems with system stability and safety [3, 4].

In electric power systems, Inertia is the amount of energy stored in the generator shaft, which causes it to continue rotating. When large generators fail, this stored energy is very useful because it provides temporary time to replace the power lost due to failure. This transient response, which is usually only for a few seconds, allows most power generation mechanical systems to recognize and respond to failures [2]. As a result, replacing the lost inertia through a virtual inertial system concept is critical to maintaining the system's stability and reliability. Inverter equipment that mimics synchronous generators to provide synthetic inertia for auxiliary services in electric power systems is known as a virtual inertial system [5].

Several research papers [5-8] have reported the applications of VICS on power systems that incorporate renewable energy plants. These papers describe the success of a power converter connected to a grid system and capable of being converted into a virtual synchronous generator. The inverter can mimic the inertial characteristics of rotor rotation of the synchronous generator, and the resulting frequency response is also similar. The basic concept of VICS has been presented in the findings of other studies [9-11] using various approaches. The VICS concept here is nearly identical to the previous one, namely through inverter control engineering that can imitate the synchronous generator inertia characteristic but with different control methods. Literacy [12] expresses VICS operational characteristics in terms of the correlation between active power and frequency, reactive power and rotor angle, allowing for comparisons between synchronous generators and virtual inertial systems. The VICS technique aims to enhance the frequency stability of the electric power system by imitating the synchronous generator's rotor inertial characteristics and frequency in frequency control [13,14]. Furthermore, [15, 16] demonstrate several techniques for developing models and controls to emulate various synchronous generator control dynamics. This control model and technique performs admirably and can perform automatic synchronization without a Phase Lock Loop (PLL). The VICS control method, however, requires further development in theoretical and practical applications, as well as validation with conventional synchronous generators [17]. All the VICS techniques described in the literatures can be broadly divided into four categories: 1) synchronous generator-based, 2) swing equation-based, 3) drop-based approach, and 4) frequency power response-based.

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In this study, a comparative study of the four basic methods of VICS control mentioned above is applied to an inverter based STATCOM/BESS that is used to smooth fluctuations in energy production from a wind farm. The inverter system is configured by the Modular Multilevel Converter (MMC) system which has advantages over conventional converters.

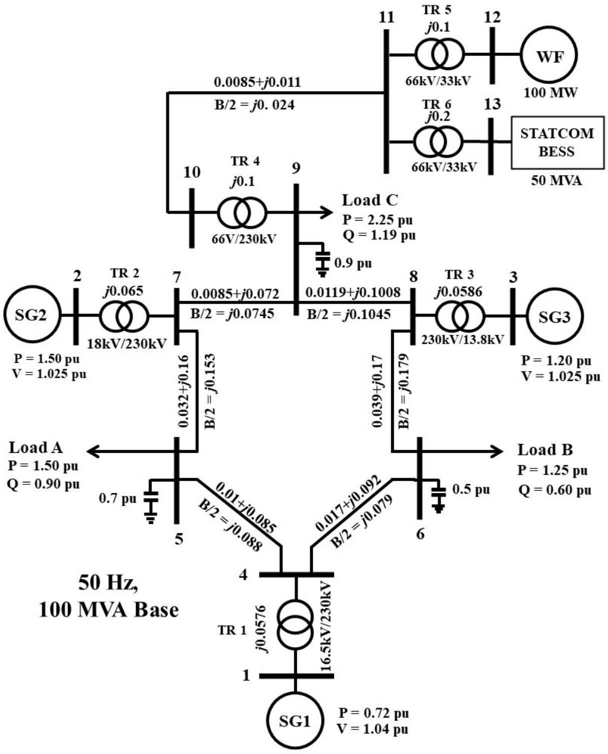

Fig. 1. The power system model

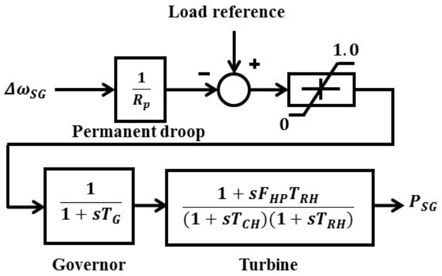

Fig. 2. The governor model for steam turbine

II. MODEL OF POWER SYSTEM

The single line diagram of the power system model considered in this study is shown in Fig. 1. A 100 MW Wind Farm (WF) is linked to the 9-Bus of power system model via 66 kV of single circuit transmission line. The wind farm is represented by an aggregate model of variable speed wind turbine based permanent magnet synchronous generator. A detailed model of the wind farm in aggregate representation can be founded in [18]. The parameters of the wind farm are shown in Table I. A 50 MVA STATCOM/BESS is installed close to the wind farm, which has a Virtual Inertia Control System (VICS). The 9-Bus power system is made up of two thermal power plants (SG1 and SG2), as well as a hydro power plant (SG3). SG1 is operated by Automatic Generation Control (AGC), SG2 by Load Limit (LL), and SG3 by Governor Free (GF). The governor model for thermal and hydro power plants are shown in Figs. 2 and 3, respectively [19]. The AGC system as depicted in Fig. 4 is represented by integral controller with gain *Ki*. Automatic Voltage Regulator (AVR) used by all conventional power plants is based on an IEEE type SCRX solid state exciter available in the PSCAD/EMTDC master library [20]. Table I presents the synchronous generator parameters of the conventional power plants. Table II presents the typical values of turbine parameters.

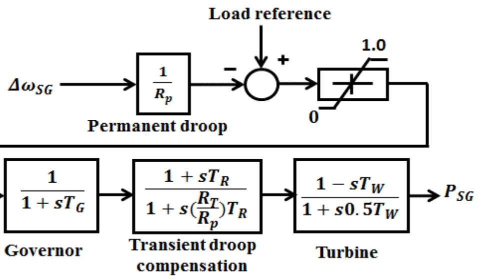

Fig. 3. The governor model for hydro turbine

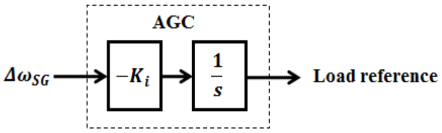

Fig. 4. Integral controller for AGC

TABLE I. PARAMETER OF GENERATOR

Parameters	Synchrounous Generators		
	SG1	SG2	SG3
Power	150 MVA	250 MVA	200 MVA
Voltage	16.5 kV	18 kV	13.8 kV
Ra	0.003 pu	0.003 pu	0.003 pu
Xd	1.220 pu	1.220 pu	1.200 pu
X`d	0.258 pu	0.258 pu	0.314 pu
X``d	0.207 pu	0.207 pu	0.22 pu
T`do	8.710 sec	8.710 sec	5.2 sec
T``do	0.033 sec	0.033 sec	0.029 sec
Xq	1.160 pu	1.160 pu	0.700 pu
X``q	0.207 pu	0.207 pu	0.29 pu
T``qo	0.141 sec	0.141 sec	0.034 sec
H	3.0 sec	5.4 sec	4.6 sec

TABLE II. PARAMETERS OF TURBINE AND GOVERNOR

Steam Turbine		Hydro Turbine	
Parameter	value	Parameter	value
T_G	0.2 sec	T_G	0.2 sec
F_{HP}	0.3 sec	T_W	1.0 sec
T_{RH}	7.0 sec	T_R	5.0 sec
T_{CH}	0.3 sec	R_T	0.38
R_p	0.05	R_p	0.05

III. STATCOM/BESS TOPOLOGY

The combination of Static Synchronous Compensator (STATCOM) and Battery Energy Storage (BESS) creates a one-of-a-kind configuration that enhances the benefits of STATCOM technology. The integration of STATCOM and BESS aims to enhance the robustness and efficiency of delivery power using advanced controls, analytics, and communications [21]. In this study, the VICS is implemented on the STATCOM/ BESS inverter system for smoothing the power output of the wind farm.

Fig. 5 shows the STATCOM/BESS topology with VICS mechanism. The STATCOM/BESS is formed from two main components, Static Synchronous Compensator (STATCOM) and Battery Energy Storage System (BESS). The STATCOM consists of voltage source inverter based Modular Multilevel Converter (MMC) with two DC capacitors. On the DC side of the STATCOM, the BESS is connected in parallel with the series capacitor (C_{dc}). The AC side of STATCOM is linked to the grid via filter inductance (L_f), filter resistance (R_f), and a coupling transformer (TR). The VICS receives feedback three phase voltage (v_{abc}) and three phase current (i_{abc}) from grid system. The VICS mimics the characteristic of the synchronous generator in response to voltage and frequency deviations in the grid system by adjusting the magnitude (e_v) and phase (θ_v) of the reference voltage that is fed to the Pulse Width Modulation (PWM) circuit. The PWM circuit compares the carrier signal to the reference voltage to generate width pulses as a switch command for the power electronic IGBT on the inverter circuit.

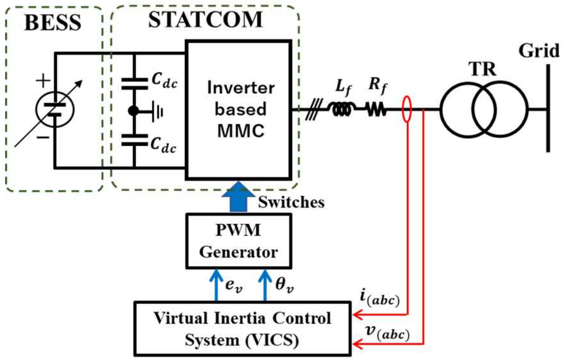

Fig. 5. Schemetic diagram of STATCOM/BESS with VICS mechanism

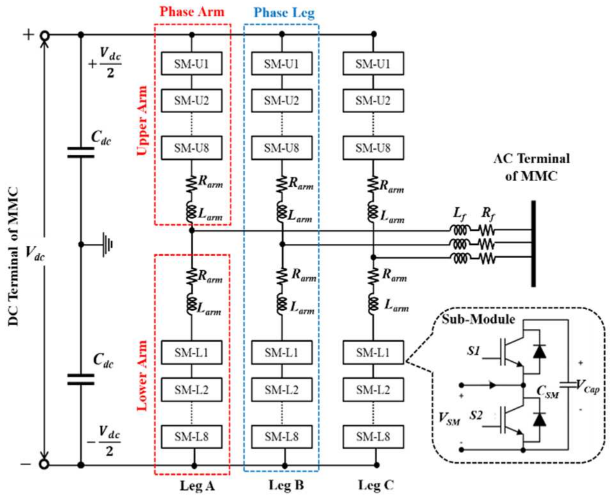

Fig. 6. Detailed configuration of inverter based MMC

Fig. 6 shows detailed configuration of the inverter based MMC. The MMC consists of three phase legs. Each leg has upper and lower arms. Each arm is made up of series identical sub-modules (SM), as well as an arm inductor (L_{arm}) and arm parasitic resistor (R_{arm}). The arm inductor is employed to reduce the flow of arm current between three phase legs [22]. The sub-module is configured as a two-level half-bridge arranged by two IGBTs, two diodes, and a capacitor (C_{SM}). Two identical DC capacitors (C_{dc}) are installed at DC terminal output of the MMC. The common point connection between the upper and lower arms are connected to AC terminal voltage through phase inductor (L_f) and phase resistor (R_f). The phase inductor can be used as a harmonic filter [22].

The three most common modulation techniques for multilevel converters such as MMCs can be summarized as follows: Space Vector Modulation (SVM), Multi Carrier Pulse Wave Modulation (MC-PWM), and Nearest Level Modulation (NLM) [23]. Because of its advantages, the Phase Shifted Pulse Wave Modulation (PS-PWM) technique [24] is being considered in this study.

IV. VIRTUAL INERTIA CONTROL SYSTEM

The integration of power plants that use large amounts of renewable energy to replace the functions of traditional power plants results in a loss of inertia in the electric power system. As a result, the electric power system's ability to respond to the rate of change in frequency deteriorates. In the worst case scenario the frequency becomes unstable and can even cause blackouts. To prevent frequency instability, STATCOM/ BESS-based inverter control through the Virtual Inertia Control System (VICS) mechanism can replace the role of conventional generators which offer virtually additional inertia to the power system. VICS can control the terminal voltage of the inverter output by imitating the characteristics of a synchronous generator in a conventional generator.

In imitating the behavior of synchronous generators, VICS can be controlled by various methods as has been reported by the researchers [25]. In this study, only four basic methods are discussed in the VICS.

A. Synchronous Generator Model Based (VICS1)

Topology of the synchronous generator model based or synchronverter and its detailed control are shown in Figs. 7 and 8. Feedback current (i_{abc}) and voltage (v_{abc}) from output of inverter is used to obtain the differential equations within the controller. P^*_m and Q^*_m are set point of active and reactive powers, respectively. J_v and D_v are respectively virtual moment inertia and virtual damping factor which can be set as desired.

The drooping frequency control mechanism, similar to that used by synchronous generators, regulates the magnitude and phase of the inverter terminal voltage [26]. The capture dynamic behavior of synchronous generator can be calculated by basic equations as follow:

$$T_e = L_m i_f \, (i, sin\theta_v) \tag{1}$$

$$e_v = \dot{\theta}_v L_f i_f sin\theta_v \tag{2}$$

$$Q_m = -\dot{\theta}_v L_f i_f (i, cos\theta_v) \tag{3}$$

where, T_e is the electromagnetic torque, L_m is the mutual inductance between the rotor field winding and the stator winding, i_f is the filed excitation current, θ_v is the electrical rotor angle. e_v is the generate voltage at the stator winding terminal. Q_m is the reactive power output.

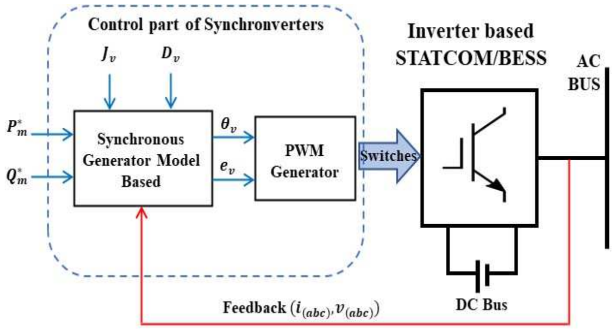

Fig. 7. Topology of the synchronous generator model based

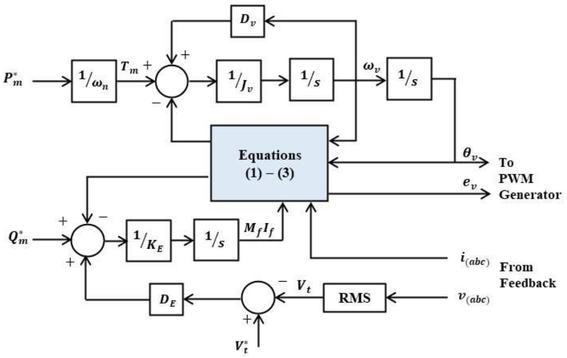

Fig. 8. Control diagram of the synchronous generator model based

B. Swing Equation Based (VICS2)

Fig. 9 depicts the topology of a swing equation-based VICS. The working principle is almost the same as the synchronverter. The power output (P_{out}) and grid angular frequency (ω_g) are calculated from feedback three phase current (i_{acb}) and voltage (v_{abc}) measured at the inverter terminal output. P_{in} represents the prime over set point power output obtained from the governor model shown in Fig. 10 [27]. The first order of transfer function with gain K_G and time constant T_G represents the governor model. P_0 is initial power reference of the synchronous generator. The magnitude virtual voltage (e_v) can be calculated using the *Q-v* droop method.

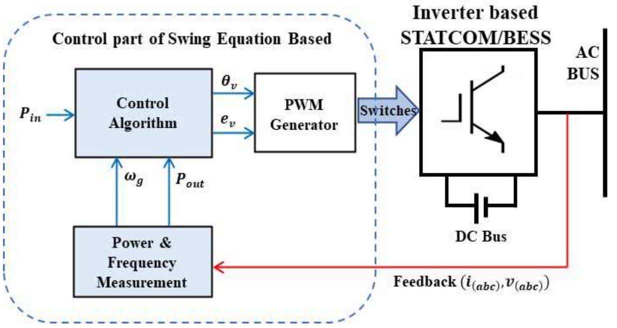

Fig. 9. Topology of the swing based equation of VICS

The swing equation of the synchronous generator generate the virtual phase command (θ_v) for the inverter. The swing equation is written as follow:

$$P_{out} - P_{in} = J_v\omega_m\left(\frac{d\omega_m}{dt}\right) + D_v\Delta\omega \tag{4}$$

$$\Delta\omega = \omega_m - \omega_g \tag{5}$$

where ω_m is virtual angular frequency.

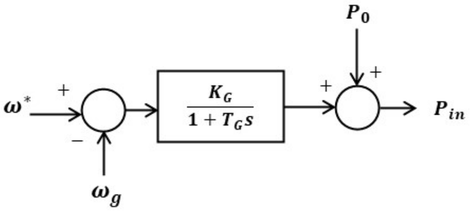

Fig. 10. Governor model for the synchronous generator model based VICS

C. Droop Based Approach (VICS3)

The droop-based approach controller of VICS is implemented as primary frequency control of synchronous generator. The VICS proportionally can share the load to the power rating by precisely adjusting the individual droop factors using only local measurements. The characteristic of frequency standard droop is as follows:

$$\omega_g = \omega^* + D_p(P^* - P_F) \tag{6}$$

where, ω^* is set point of the frequency, ω_g is the grid frequency, *Dp* is the droop slope, P^* is power set point, and P_F is the inverter filtering power output. The inverter filtering power output (P_{inv}) obtained by using first order lowpass filter with T_F time constant [28]. Fig. 11 shows the VICS with droop-based approach controller.

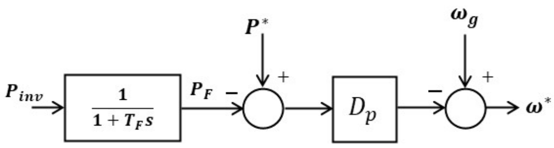

Fig. 11. Control system of frequency-droop approach based VICS

D. Frequency-Power Response Based (VICS4)

The dynamic control of frequency-power response-based VICS is based on frequency measurements and the generator's behavior in releasing/absorbing inertial power in case of power imbalance. As a result, the VICS mechanism allows the inverter to control its output power in response to changes in frequency [29]. Topology of frequency-power response based VICS is shown in Fig. 12. The Phase Lock Loop (PLL) circuit is used to calculate frequency deviations ($\Delta\omega_g$) in the grid system. The current loop controller adjusts magnitude (e_v) and the phase (θ_v) of the inverter reference voltage through the *q*-axis and the *d*-axis currents, respectively.

The power output of the STATCOM/BESS inverter (P_{INV}) can be controlled by Eq. (6):

$$P_{INV} = K_D\Delta\omega_g + K_I\frac{d\omega_g}{dt} \tag{7}$$

where, K_I and K_{ID} are the inertia constant and damping constant gains, respectively. The damping constant aids in restoring the frequency to its original value. Based on the frequency derivative, the inertia constant provides a fast dynamic frequency response. For current loop controller, the reference of the *d*-axis current (I^*_d) is calculated by using Eq.

(8) and reference of the q-axis current (I^*_q) can be set to zero for maintaining the reactive power output (Q_{INV}) in unity power factor operation.

$$I_d^* = \frac{2}{3}\left(\frac{V_d P_{INV} - V_q Q_{INV}}{V_d^2+V_q^2}\right) \qquad (8)$$

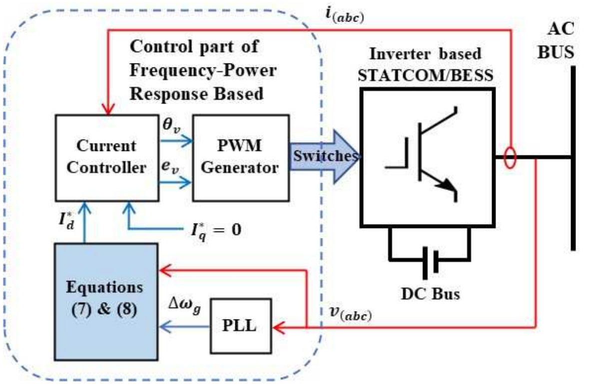

Fig. 12. Topology of frequency-power response based VICS

V. SIMULATION RESULTS

A comparison analysis of the VICS methods for smoothing the power production of wind farms connected to the power grid system was investigated through simulation studies performed with PSCAD/EMTDC. The simulation study was carried out in four scenarios as follows: without VICS (No VICS), synchronous generator model Based (VICS1), swing equation based (VICS2), droop based approach (VICS3), and frequency-power response based (VICS4). The actual wind speed variations data used on the wind farm are depicted in Fig. 13.

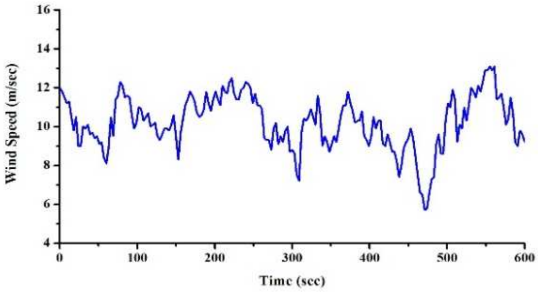

Fig. 13. Wind speed variation data

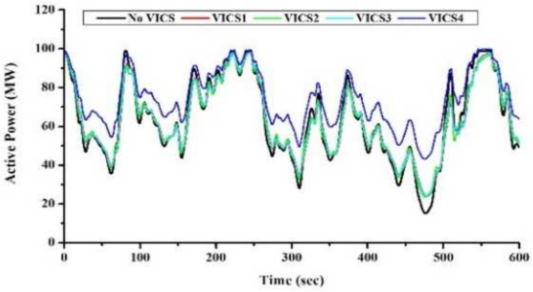

Fig. 14. Active power output of the wind farm

Fig. 14 depicts the active power output of the wind farm for each method. The figure shows that there is almost no difference in the responses obtained by the VICS1, VICS2, and VICS3 methods. The VICS4 method, on the other hand, demonstrated a significant difference. This is because the VICS4 method mimics the Automatic Generation Control (AGC) governor operation of synchronous generator.

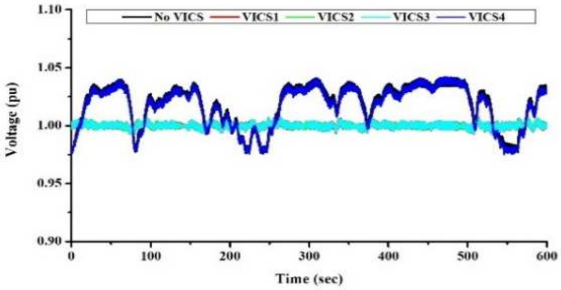

Fig. 15. Voltage profile on the Bus 11

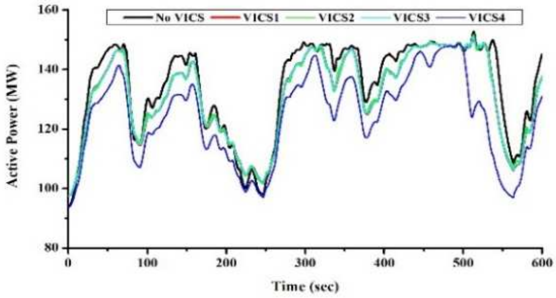

Fig. 16. Active power output of SG1

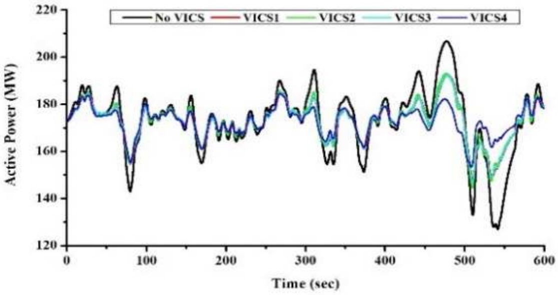

Fig. 17. Active power output of SG2

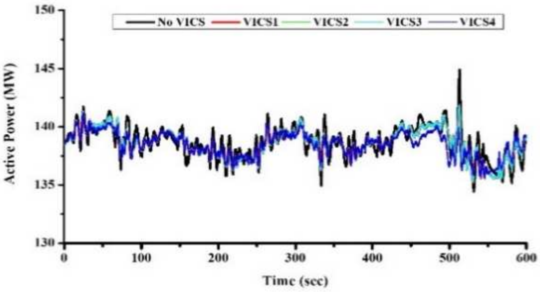

Fig. 18. Active power output of SG3

The voltage profile on Bus 11 is depicted in Fig. 15. The VICS1, VICS2, and VICS 3 methods can keep the wind farm's terminal voltage at its nominal value. While the VICS4 method is not used to control the wind farm's output terminal voltage, the voltage fluctuates.

Figs. 16, 17, and 18 depict the active power output of SG1, SG2, and SG3. The results show that the four VICS methods can reduce fluctuations in the output power of each synchronous generator. The VICS4 method, on the other hand, can achieve significant attenuation. Finally, Fig. 19 depicts the power system's frequency response. The VICS's four methods can reduce frequency fluctuation. However, when compared to the other methods, the VICS4 method can significantly reduce frequency fluctuation.

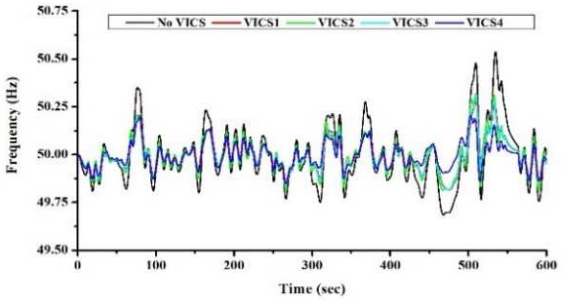

Fig. 19. Frequency response of the power system

VI. CONCLUSION

A comparison of Virtual Inertia Control System (VICS) methods was carried out. The simulation results show that the synchronous generator model-based, swing equation-based, and droop-based approach methods reduce wind farm power fluctuations in the same way. The frequency-power response-based method reduces wind farm power output fluctuations more effectively than the other methods.

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