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

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***Abstract*—This paper presents comparative study of Virtual Inertia Control System (VICS) techniques for smoothing power production of enormous wind farm which connected to the electric grid 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. The PSCAD/EMTDC has been used to perform the simulation analyses. The simulation study demonstrates that the frequency-power response-based VICS is superior for minimizing power fluctuation from the wind farm.**

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 generator is used to convert energy from wind to electricity. Wind turbine generators has 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 can reduce rotating mass (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. A virtual inertial system is an inverter device that simulates a conventional generator to serve artificial inertia for supplementary services in electric power systems [5].

Several research papers [5-8] have reported the applications of VICS on power systems that incorporate renewable energy plants. The success of a power converter connected to a grid system that resembles a synchronous generator is described in these papers. The inverter emulates the rotating mass characteristics 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] conducted a comparative study between synchronous generators and virtual inertial systems wherein the operational characteristics of the VICS revealed that changes in the frequency and rotor angle of the system have a correlation with the active power and reactive power generated by the inverter. The VICS technique aims to improve the power system frequency stability 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.

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

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Converter (MMC) system which has advantages over conventional converters.

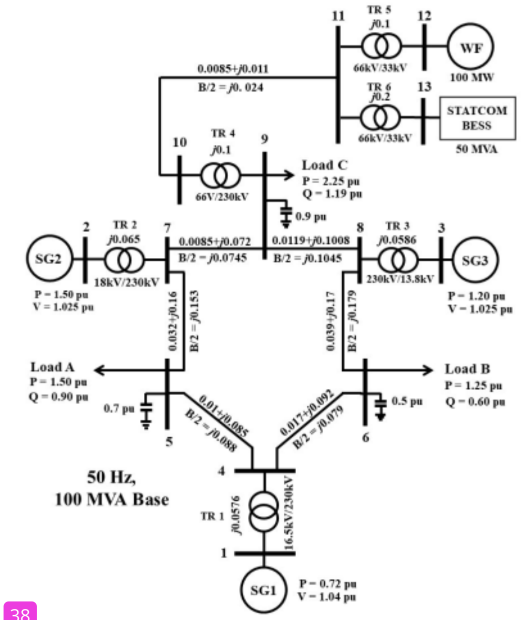

Fig. 1. The power system model

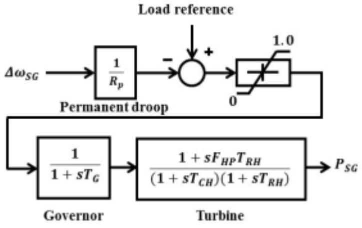

Fig. 2. The governor model for steam turbine

II. MODEL OF POWER SYSTEM

The power system model taken into consideration for this study is displayed in Fig. 1. A 66 kV transmission line connects the 9-Bus power system model to a 100 MW wind farm (WF). The WF is represented by an aggregate model of the wind turbine permanent magnet generator. A detailed model of the WF in aggregate representation can be founded in [18]. Table I displays the specifications of the WF. A 50 MVA STATCOM/BESS is installed close to the wind farm, which has a Virtual Inertia Control System (VICS). Three conventional generators are used in the 9-Bus power system. SG1 is operated by Automatic Generation Control (AGC), SG2 by Load Limit (LL), and SG3 by Governor Free (GF). Figures 2 and 3 show the governor models for steam and hydroelectric power plants, 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]. The parameters for the generators shown in Table I, and those for the turbine and governor are shown in Table II.

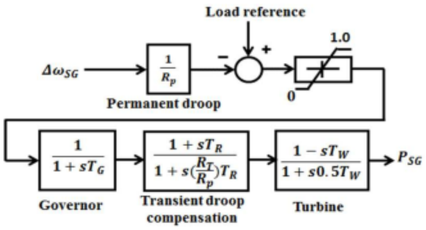

Fig. 3. The governor model for hydro turbine

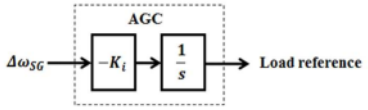

Fig. 4. Integral controller for AGC

TABLE I. GENERATOR PARAMETER

Parameters	Synchrounous Generators		
	SG1 Steam unit	SG2 Steam unit	SG3 Hydro unit
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. TURBINE AND GOVERNOR PARAMETER

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 wind farm power output.

The STATCOM/BESS topology with the VICS mechanism is depicted in Fig. 5. The STATCOM/BESS is formed from two main components, STATCOM and 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 linked 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 deviation of voltage and frequency by adjusting the magnitude (e_v) and phase (θ_v) of the reference voltage. The Pulse Width Modulation (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.

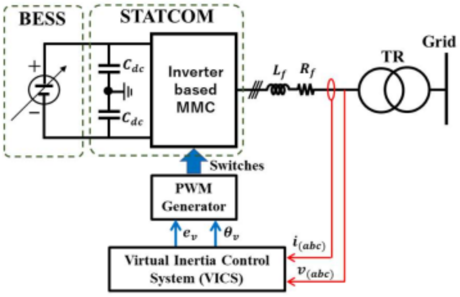

Fig. 5. Schemetic diagram of STATCOM/BESS with VICS mechanism

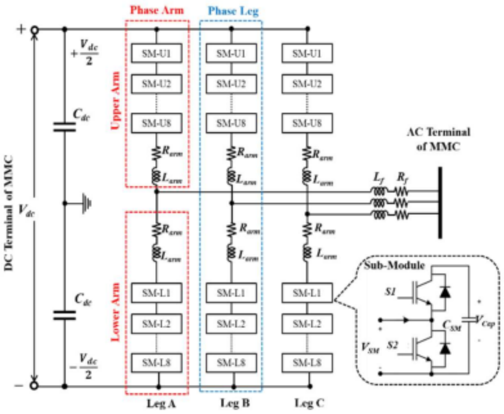

Fig. 6. Detailed configuration of inverter based MMC

Fig. 6 shows detailed configuration of the inverter based MMC. There are three phase legs in the MMC. Upper and lower arms are present on each leg. Each arm is constructed from a set of symmetrical sub-modules (SM), as well as an arm inductor (L_{arm}) and parasitic arm resistor (R_{arm}). The inductor is used to decrease the flow of circulation current between the phase legs [22]. The sub-module is configured as a half-bridge in two level which arranged by IGBTs, diodes, and a capacitor (C_{SM}). Two identical DC capacitors (C_{dc}) are installed at DC terminal output of the MMC. Through a phase inductor (L_f) and a phase resistor (R_f), the phase leg is connected to an AC terminal. The phase inductor can be used as a harmonic filter [22].

Following is a summary of the three most popular modulation methods for MMC: Space Vector Modulation (SVM), Multi Carrier Pulse Wave Modulation (MC-PWM), and Nearest Level Modulation (NLM) [23]. The Phase Shifted Pulse Wave Modulation (PS-PWM) method [24] is being taken into consideration in this study due to its benefits.

IV. VICS METHODS

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. The power system capability to adapt to the rate of frequency deviation consequently declines. 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 output voltage characteristics of 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. Real power is set at P^*_m, and reactive power is set at Q^*_m. J_v stands for virtual moment inertia, and D_v is a movable virtual damping factor.

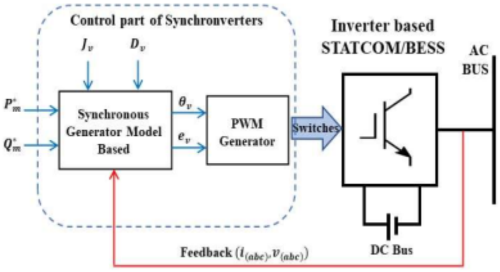

Fig. 7. Topology of VICS1

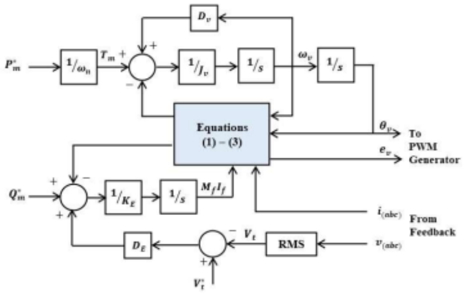

Fig. 8. Control diagram of the VICS1

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

$$T_e = L_m i_f\,(i, sin\theta_v) \qquad (1)$$

$$e_v = \dot{\theta}_v L_f i_f sin\theta_v \quad (2)$$

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

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.

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 transfer function in first order 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.

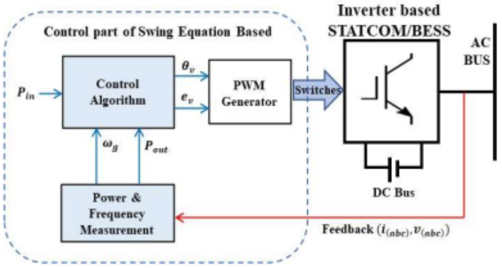

Fig. 9. Topology of the swing based equation of VICS

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

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

$$\Delta\omega = \omega_m - \omega_g \quad (5)$$

where ω_m is virtual angular frequency.

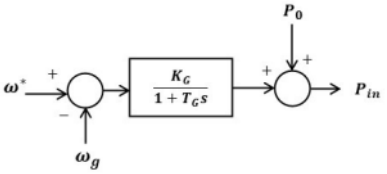

Fig. 10. Governor model for the VICS2

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:

$$\omega_g = \omega^* + D_p(P^* - P_F) \quad (6)$$

where, ω^* is set point of the frequency, ω_g is the frequency measured from the network, *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.

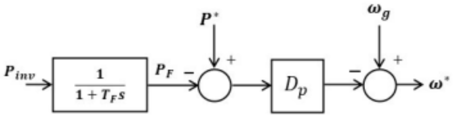

Fig. 11. Control system of VICS3

D. Frequency-Power Response Based (VICS4)

The dynamic control of the VICS4 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 presented 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 respectively the *q*-axis and the *d*-axis currents.

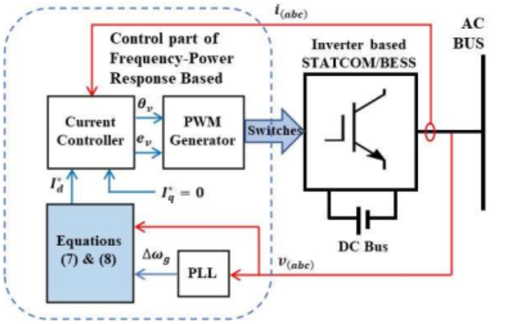

Fig. 12. Topology of frequency-power response based VICS

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

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

where, K_I is gain for the inertia constant and K_D is gain for damping constant. The damping constant aids in restoring the frequency deviation. Based on the frequency derivative, the inertia constant provides a fast dynamic frequency response. For current loop controller, the reference current in the *d*-axis (I^*_d) is calculated by using Eq. (8) and reference current for the *q*-axis (I^*_q) can be selected for maintaining the reactive power output (Q_{INV}) in unity power factor operation.

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

V. SIMULATION RESULTS

Through simulation studies using PSCAD/EMTDC, a comparative study of the VICS methods for smoothing the power production of grid-connected wind farms was investigated. The simulation study was carried out in four scenarios as follows: No VICS, VICS1, VICS2, VICS3, and VICS4. The actual wind speed data applied to the wind generator is depicted in Fig. 13.

Fig. 14 depicts the real power profile 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.

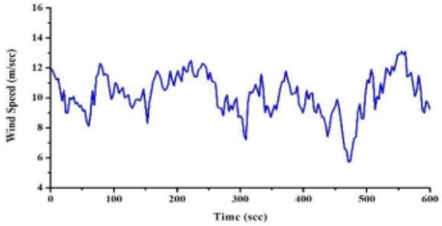

Fig. 13. Wind speed variation data

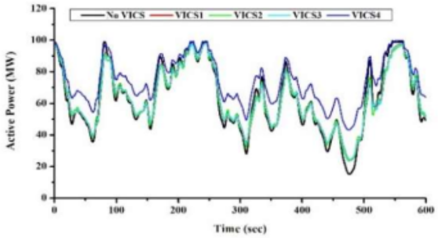

Fig. 14. Real power profile of the wind farm

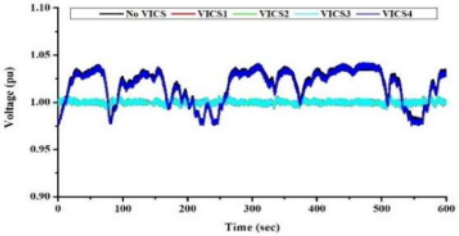

Fig. 15. Voltage profile on the Bus 11

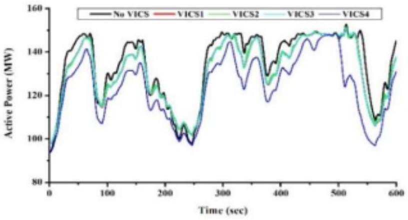

Fig. 16. Real power profile of SG1

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. Because the VICS4 method does not use to regulate the wind farm's terminal voltage, its voltage profile fluctuates.

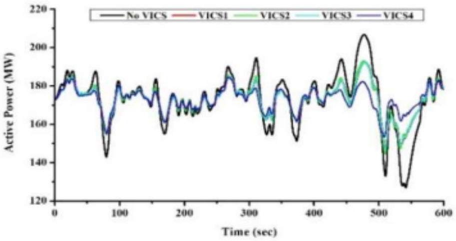

Fig. 17. Real power profile of SG2

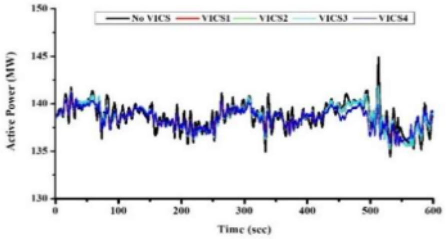

Fig. 18. Real power profile of SG3

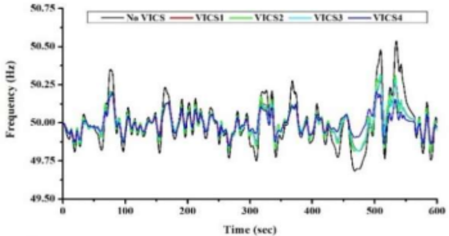

Fig. 19. Frequency response of the power system

Figs. 16, 17, and 18 depict the real power profile of SG1, SG2, and SG3, respectively. 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.

VI. CONCLUSION

A comparative analysis of Virtual Inertia Control System (VICS) methods for smoothing wind farm power fluctuation was carried out through simulation study. Synchronous generator model-based, swing equation-based, and droop-based approach methods have same response in reducing wind farm power fluctuations. Whereas, the frequency-power response-based method is more effective than the other methods.

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