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Static Voltage and Frequency Regulation of Standalone Wind Energy Conversion System

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Abstract

Background/Objective: This paper presents regulation of Self Excited Induction Generator (SEIG) as asynchronous generator in standalone mode for wind energy conversion system (WECS). **Methods/Statistical Analysis:** The proposed controller consists of Voltage Source Converter (VSC) having bidirectional active & reactive power flow control, integrated with Battery Storage Unit (BSU), connected in shunt. It compensates for variable reactive power with variable active power. Rating of induction machine has been obtained by short circuit test, open circuit test and synchronous speed test. **Findings:** SEIG have relative advantage over conventional synchronous generator. However, vo1ltage and frequency regulation are among prime challenges in its practical application as standalone generator. Voltage and frequency of SEIG depends upon speed of rotor, shunt capacitor and load. A suitable control scheme needs to be developed to ensure minimum variation in voltage and frequency for variable input and electrical load. Voltage regulation has been achieved by adjusting reactive power provided by static compensator consisting of inductor a VSC and dc bus capacitor. **Conclusion/Improvement:** The simulation results show that voltage and frequency of SEIG-WECS have negligible variation for resistive, reactive, balanced, unbalanced and nonlinear load under varying wind speed and consumer load. It eliminates harmonic contents and balances the connected electrical load.

Keywords: Battery Storage Unit, Standalone Generator, Self Excited Asynchronous Generator, Voltage Source Converter, Voltage and Frequency Regulation

1. Introduction

Squirrel cage asynchronous motor can be used to make SEIG by connecting appropriate value of capacitor at its stator terminals[1] and driving the rotor by suitable speed prime mover. It has relative advantages over traditional synchronous generators in terms of rugged construction, lower maintenance, simple operation and brushless construction[2]. However, voltage and frequency regulation are among inherent obstacle in its practical application as asynchronous generator in variable speed drive application. Voltage and frequency of SEIG, count on rotor speed, connected load and power factor (*p.f.*) of load[3].

Synchronous generators have better efficiency in fixed speed drive applications[4], but induction generators are preferred for variable drive applications. Literature includes application of induction machine as doubly fed induction generator[5,6], SEIG[7] and associated controllers[8,9] to work under stochastic nature of wind energy[10]. Voltage and frequency of generator can be regulated by connecting fixed shunt capacitors and electronically switched inductances3. Series connected capacitors provide additional VARs with increasing load while shunt capacitors supply reactive power demand of SEIG[11]. Series connected capacitors can generate sub-synchronous resonance whereas the parallel connected capacitors can cause poor voltage regulation for constant[12,13] and variable[14,15] load applications.

The output frequency of SEIG-Wind Energy Conversion System (WECS) in standalone mode can be regulated by asynchronous ac-dc-ac link power converter incorporating matrix converter[16]. Controlled Pulse Width Modulated (PWM) gate signal is connected toVSC with BSU can be used to regulate voltage and frequency[17]. This

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scheme presents low frequency harmonics at low rotor speeds. VSC based controller can be used with variable speed prime mover prime mover to meet dynamically varying real and reactive[18] load power demand connected by the side of SEIG stator to regulate fixed supply frequency. A series capacitor has been used to reduce usage of static compensator (STATCOM) for regulating voltage in3-phase SEIG[19]. SEIG conned to variable speed prime mover and a VSC based controller can maintain active power at generator end for reducing burden of supplied reactive power to load[20].

Generation from SEIG is substantially depends on *p.f.* of connected load due to its dependence on reactive current[21]. Load control unit doesn't balance large reactive power requirement variation. STATCOM balances the phase current and thus works as a load balancer[22]. The controller regulates active and reactive power to regulate frequency and voltage respectively. STATCOM can be used to work as reactive power compensator. It can also regulate voltage and frequency with increase in load current and significantly eliminateharmonics[23].

Standalone WECS using a squirrel cage SEIG could be one of the attractive options for small power generation system. A bidirectional VS-PWM with a capacitor and switched resistor at dc bus provides a reference voltage and frequency for the induction generator[24,25]. The converter can compensate for reactive power to regulate the terminal voltage[26,27]. However, it can only absorb the active power.

This paper presents bidirectional real and reactive power flow management scheme to govern system voltage and frequency for variable generator speed drive and connected load. Proposed bidirectional converter compensates variable reactive power to regulate the terminal voltage. It absorbs active power during light load or higher wind speed and delivers the active power during high load or lower wind speed with BSU for SEIG-WECS in order to obtain frequency and voltage regulation for variable mechanical power as well as varying load conditions.

2. System Description

System configuration and control scheme of SEIG- WECS has been shown in Figure 1 and Figure 2 respectively. The wind turbine has been connected to SEIG rotor through gearing and coupling arrangement. Stator side of SEIG consists of delta connected capacitor bank, to meet reactive power demand, in parallel with VSC and the consumer load. Capacitor bank provides necessary excitation to generate electrical power at rated voltage under no load condition. VSC controller meets additional excitation required for regulating voltage. VSC absorbs or injects the active power depending upon frequency error (e_f). VSC absorbs active power conserved in BSU, when frequency of the system is more than reference value. Conversely, VSC injects active power when system frequency decreases due to increase in load or decrease in wind speed. Reactive power is also compensated from VSC as a function of terminal voltage error. As the terminal voltage drops, the terminal voltage error makes the VSC converter to inject reactive power. Thus VSC provides real and reactive power flow in both rectifier and inverter mode. DC bus capacitor is connected in parallel with BSU, which suppresses the ripples appearing at the DC side of VSC.

3. Mathematical Modeling

The proposed control scheme has been shown in Figure 2. Three phase reference current (i_a^*,i_b^* and i_c^*) consists of two components viz. direct axis or active component (i_{ad}^*,

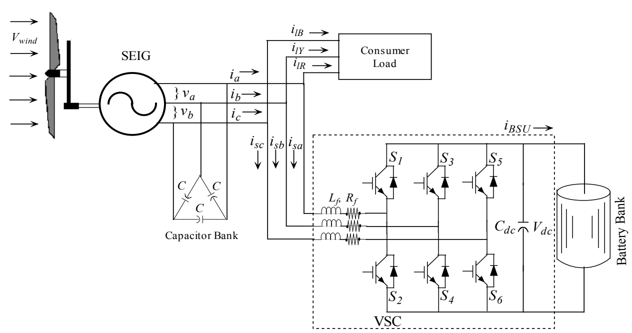

Figure 1. Schematic diagram of 3-Φ SEIG-WECS.

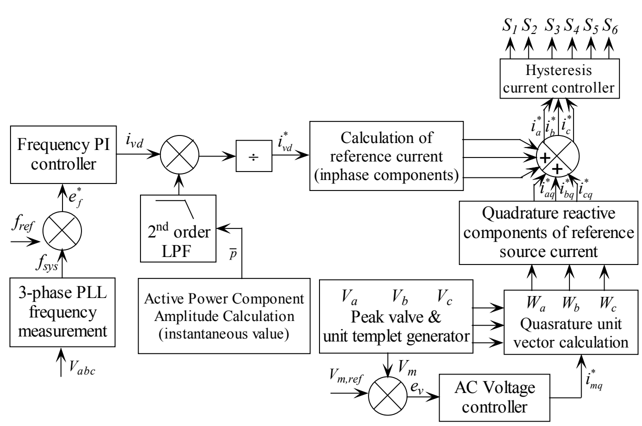

Figure 2. MATLAB based Controller subsystem of SEIG-wind energy conversion system

i_{bd}^* and i_{cd}^*) to control frequency and quadrature axis or reactive component (i_{aq}^*, i_{bq}^* and i_{cq}^*) to control terminal voltage. Control scheme has been designed to regulate terminal voltage, frequency, reactive power retention, load reconciliation, harmonic eradication and battery current. Voltage error e_v has been calculated by comparing peak voltage amplitude (v_m) and amplitude of reference AC voltage ($v_{m,ref}$). Error e_v is processed through voltage PI controller to obtain quadrature current reference (i_q^*) as reactive component of reference current.

Unit templates (u_a, u_b and u_c) and quadrature unit template (w_a, w_b and w_c) are computed by three phase AC line voltages (v_a, v_b and v_c) and their peak amplitude (v_m). Instantaneous magnitude of frequency (*f*) is calculated by phase locked loop control.

Frequency error (e_f) is estimated by subtracting estimated frequency (*f*) from reference frequency (f_{ref}). Frequency error is processed through frequency PI controller. Maximum generator current ($I_{G,max.}$) is calculated by division of rated power output of SEIG to rated terminal voltage. In order to generate real part of reference current component (i_d^*), obtained outcome of frequency PI controller is subtracted from maximum generator current. The product of output references (i_d^* and i_q^*) and unit templates is algebraically summed to attain reference source currents (i_a^*, i_b^* and i_c^*). Obtained reference source current is compared with actual line currents (i_a, i_b and i_c) and passed in hysteresis current controller to get PWM switching pulses to feed VSC.

3.1 Unit Template Generator

The peak amplitude of voltages (V_m) is calculated as

$$V_m = \{(2/3)(v_a^2 + v_b^2 + v_c^2)\}^{1/2} \tag{1}$$

Where, v_a, v_b and v_c are terminal line voltages of SEIG.

The unit vectors in phase with v_a, v_b and v_c are computed as

$$\begin{aligned} u_a &= v_a/V_m \\ u_b &= v_b/V_m \\ u_c &= v_c/V_m \end{aligned} \tag{2}$$

Unit vector in quadrature with v_a, v_b and v_c is:

$$\begin{aligned} w_a &= (-u_b + u_c)/\sqrt{3} \\ w_b &= \sqrt{3}u_a/2 + (u_b - u_c)/2\sqrt{3} \\ w_c &= -\sqrt{3}u_a/2 + (u_b - u_c)/2\sqrt{3} \end{aligned} \tag{3}$$

AC voltage error at nth sampling time is calculated as:

$$e_v(n) = V_{m,ref}(n) - V_m(n) \tag{4}$$

Where, $V_{m,ref}(n)$ is reference peak amplitude of AC voltage.

3.2 Reference Source Current

The outcome of voltage PI controller to regulate AC voltage at stator terminals of SEIG at n^{th} sampling time is:

$$i_q(n) = i_q(n-1) + K_P[e_v(n) - e_v(n-1)] + K_I e_v(n) \tag{5}$$

Where, K_P and K_I are gain constants of voltage PI controller; $e_v(n)$ and $e_v(n-1)$ are AC peak voltage errors at n^{th} and $(n-1)^{th}$ sampling time; $i_q(n-1)$ is magnitude of reference source current at $(n-1)^{th}$ sampling time.

Quadrature reactive component of the reference source current is estimated by:

$$\begin{aligned} i_{aq}^* &= i_q w_a \\ i_{bq}^* &= i_q w_b \\ i_{cq}^* &= i_q w_c \end{aligned} \tag{6}$$

Frequency error $e_f(n)$ is given by:

$$e_f(n) = f(n) - f_{ref}(n) \tag{7}$$

Where, $f(n)$ and $f_{ref}(n)$ are system frequency and the reference frequency respectively at n^{th} sampling time.

Frequency error is passed by frequency PI controller and output at n^{th} sampling time t is given by:

$$i_d(n) = i_d(n-1) + K_P[e_f(n) - e_f(n-1)] + K_I e_f(n) \tag{8}$$

Where, K_P and K_I are gain constants of the frequency PI controller; $e_f(n)$ and $e_f(n-1)$ are frequency errors at the n^{th} and $(n-1)^{th}$ sampling time; $i_d(n-1)$ is output of frequency PI controller at $(n-1)^{th}$ sampling time.

Active component of reference is obtained by subtracting output of frequency PI controller from maximum generator current i.e.

$$I_d^*(n) = I_{G,Max.}(n) - I_d(n) \tag{9}$$

The instantaneous in phase active reference source current component is calculated by:

$$\begin{aligned} i_{ad}^* &= i_d u_a \\ i_{bd}^* &= i_d u_b \\ i_{cd}^* &= i_d u_c \end{aligned} \tag{10}$$

Thus from equation (6) and equation (10), reference source current can be obtained as:

$$\begin{aligned} i_a^* &= i_{ad}^* + i_{aq}^* \\ i_b^* &= i_{bd}^* + i_{bq}^* \\ i_c^* &= i_{cd}^* + i_{cq}^* \end{aligned} \quad (11)$$

Required PWM pulses for VSC is calculated by comparing reference source current and obtained load current; and passing error in hysteresis current controller.

$$\begin{aligned} i_{a,error} &= i_a^* - i_a \\ i_{b,error} &= i_b^* - i_b \\ i_{c,error} &= i_c^* - i_c \end{aligned} \quad (12)$$

Hysteresis current controller generates PWM pulses for VSC using these error values of current.

4. Modeling of Wind Turbine Generator

WTGS consists of asynchronous SEIG as generator unit. The synchronous speed test data for air gap voltage and magnetizing current is experimentally estimated for simulation of saturation in SEIG. MATLAB based model of SEIG-wind energy conversion system has been considered. 7.5 kW, 400 V, 50 Hz, delta connected induction machine has been used as SEIG. Capacitor bank of 36 μF per phase connected in delta has been used at stator end of machine for obtaining a 6 kW power output at rated voltage and rated speed.

The power output of SEIG-WECS can be given as:

$$P = 0.5\rho A K_P v_{wind}^3 \quad (13)$$

Where, ρ is specific density of air, A is swept area of the blades, K_p is power coefficient and v_{wind} is wind speed in m/s.

Power coefficient K_p is the function of tip speed ratio (TSR, λ). For a constant pitch angle (β), it may be given as:

$$K_P = K_1\{(K_2/\lambda_i) - K_3\beta - K_4\}e^{-(K_5/\lambda_i)} + K_6\lambda \quad (14)$$

Where,

$$1/\lambda_i = [1/(\lambda + K_7\beta)\} - \{K_8/(\beta^3+1)\} \text{ and } \beta = 0^0 \quad (15)$$

For the constants K_1 = 0.5176, K_2= 116, K_3 = 0.4, K_4 = 5, K_5 = 21, K_6 = 0.0068, K_7 = 0.08, K_8 = 0.035; polynomial relationship curve for K_p and λ at fixed degree pitch angle (β = 0), provides utmost value of K_P as 0.48 for a maximum TSR. This gives highest mechanical power available for wind turbine.

5. Results and Discussion

The SEIG-WECS with energy storage system for variable electrical load and input wind speed has been simulated and results have been analyzed. Figure 3 shows the SEIG-WECS supplying balanced 3-phase resistance load. Transient waveform from in figures 3 to 6 includes SEIG line voltage (V_{abc}), line current (I_{abc}), load current ($I_{L,abc}$), VSC current ($I_{s,abc}$), peak terminal voltage (V_m), frequency (f), wind velocity (v_{wind}), battery current (I_{BSU}), DC bus voltage (V_{dc}) and generator, load & battery power (P). The SEIG has been connected with excitation capacitor to generate 6 kW at rated speed. At time t=1.55 sec., a resistive load of 4 kW has been connected. On incorporating resistance load, voltage and frequency remain constant and current supplying to BSU reduces VSC current subsequently. At time t=1.7 sec., an additional resistive load of 4 kW has been connected i.e. total load connected to SEIG-WECS system becomes 8 kW. Then after an additional 2 kW load is supplied from BSU and battery bank current becomes negative. The power curve relation shows that the generated power remains constant at 6 kW while power to battery bank becomes positive when load is less than 6 kW and become negative when load power is more than 6 kW.

Figure 4 shows transient waveform of SEIG-WECS for unbalanced reactive load. A 3 kW, 0.8 lagging *p.f.* balanced reactive load has been applied at t=1.55 sec. At t=1.65 sec., a single phase resistance load is added and total load becomes unbalanced. Application of reactive unbalanced load, the voltage and frequency remains constant. The SEIG

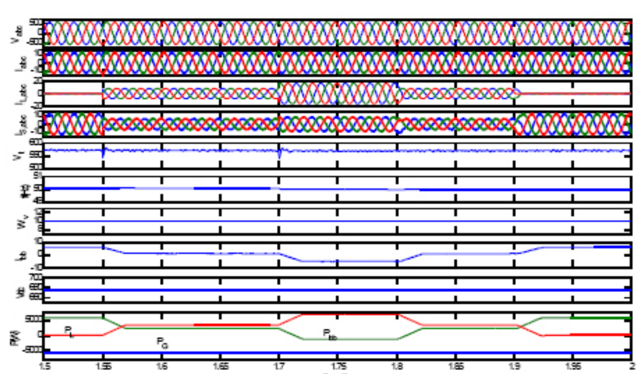

Figure 3. Transient waveform of SEIG-WECS for application of 8kW resistive load application.

currents also remain balanced. VSC compensates reactive power demand of load. It also works as load balancer.

Figure 5 represents transient waveform for nonlinear diode rectifier load with 100 ohms and 100 mH at DC side. Another 3-phase balanced resistance load of 4 kW has been added at time t=1.7 sec. With application of nonlinear load, voltage and frequency of SEIG-WECS remains constant, as obtained in case of linear and unbalanced load application. SEIG voltage and current remains sinusoidal and VSC eliminates the harmonic components generated by the nonlinear load. The generated output power remains constant and the additional active power demand is supplied form BSU.

The harmonic analysis shows that the total harmonic distortion (THD) of SEIG voltage and current is obtained as 1.6% and 2.2% respectively while the load current THD is 26.2%.

Figure 6 revels performance of system under variable wind speed and constant resistive load. At time t=1.55 sec., balanced 3-phase resistive load of 4 kW is applied. At time t=1.65 sec., wind velocity is changed from 10 m/s

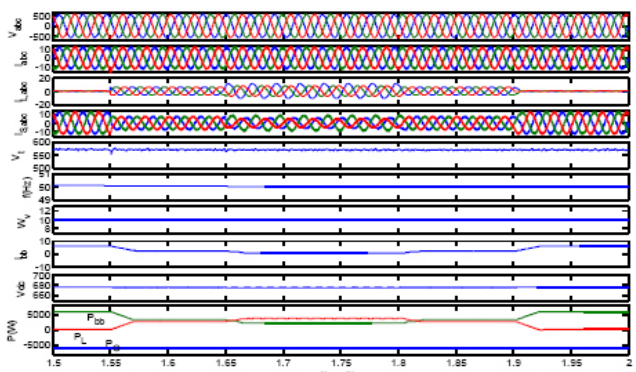

Figure 4. Transient waveform of SEIG-WECS for application of unbalanced reactive load.

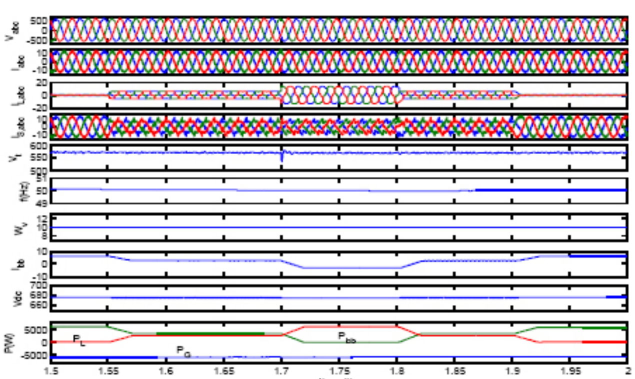

Figure 5. Transient waveform of SEIG-WECS for application of nonlinear load.

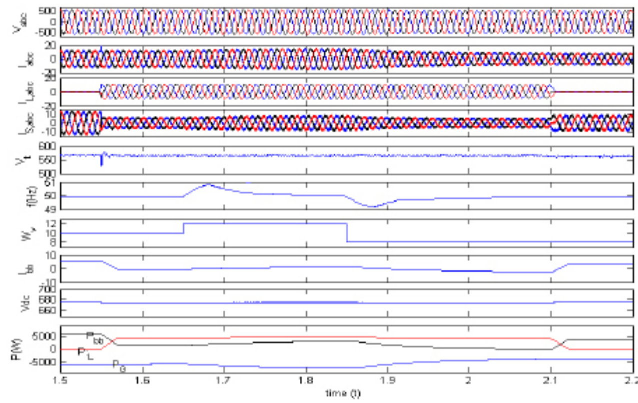

Figure 6. Transient waveform of SEIG-WECS for variable wind speed and resistive load.

to 12 m/s. Increase in wind speed increases the power output of the generator while voltage and frequency remains constant. Generator current also increases. At time t=1.85 sec. wind speed reduces from 12 m/s to 8 m/s, which is below the base speed. Reduction in wind speed reduces power output of SEIG. The generator current also reduces accordingly. At time t=2.1 sec., load is fully removed. Voltage and frequency remains constant with change in wind speed and with change in consumer load. BSU absorbs additional active power and delivers when load demand is increased from rated generation.

6. Conclusion

The application of AWECS as standalone system has been designed and analyzed under varying consumer load and wind speed. A VSC based voltage and frequency regulation has been proposed and validated with simulation for WECS with SEIG in standalone mode for frequency control incorporating BSU. Proposed controller has bidirectional power flow capability of real and reactive power compensation. It regulates voltage and frequency of SEIG-WECS unit under variable electrical load and wind speed. VSC works as voltage regulator, harmonics remover and load equalizer for varying consumer load. Thus for the proposed system the voltage and frequency remains constant for resistive, reactive, balanced, unbalanced, nonlinear loads under varying wind speed and consumer load. Hence the system will be beneficial for feeding isolated loads.

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