# VOLTAGE AND FREQUENCY CONTROL OF AN ASYNCHRONOUS GENERATOR FOR A STAND-ALONE WIND ENERGY CONVERSION SYSTEM

**Article history**
Received
*06 September 2016*
Received in revised form
*10 October 2016*
Accepted
*02 November 2016*

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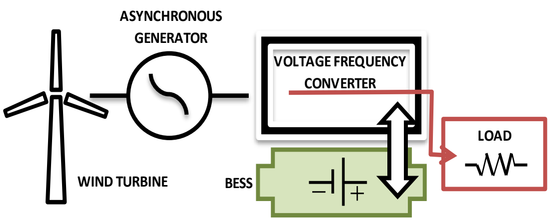
## GRAPHICAL ABSTRACT




## ABSTRACT

This paper proposes the voltage and frequency control for standalone wind energy conversion system, driven by isolated asynchronous generator with voltage source converter and battery energy storage system. The controller is a combination of voltage source converter made up of insulated gate bipolar junction transistor and battery storage system at the dc-link. Bidirectional active and reactive power flow capability of the controller function to ensure the voltage and frequency control of the system during variation in consumer load and wind turbine speed. The proposed system has been tested through MATLAB using Simulink.

## KEYWORDS

Voltage source converter; battery energy storage system; isolated asynchronous generator.

## INTRODUCTION

The human population levels is now six billion [1] and the resources of the planet are under pressure. Human existence has always shown a proclivity towards natural resources, and with depletion of conventional energy resources, research for other energy options is intense. Among the natural elements, wind is the earliest source to power man's mechanical innovations and inventions. Use of wind power for sail ships, grinding mills and water pumps dates back to almost 3000 years [2]. The dependence then tapered down as fossil fuel usage increased and rural electrification spread [3]. The earliest effort to produce electricity from wind turbines can be traced to nineteenth century, and in the twentieth century, the employment was largely for charging batteries rather than generating voltages in good range.

Table 1 shows the notable developments in the wind turbine technology for electricity generation. As referred from Table 1, interest in wind turbines as a tangible option came about after the peak of oil prices in 1973. The concerns on climate change and need for low $CO_2$ emissions have contributed to sustained interest and wind turbines seen as a 'clean energy' source. The global power sector contributes to about 25% of the overall greenhouse gas emissions and about 40% of the energy related $CO_2$ emissions [4]. In the efforts, hydro and wind energy sectors are expected to be the major contributors towards emission reductions. There are paradigm shifts in policies, with some countries actively pushing for renewable energy resources. Wind energy is potential to be the largest contributor among the renewables.

Table 1: Wind turbines: Developments [2]

| Year | Development |
|---|---|
| **1931-1987** | 100 kW-2.5 MW Turbines |
| **1980-1990** | Development of small turbines (<100 kW); Hydraulic transmission; Horizontal turbines with 1, 2 or 3 blades; Fixed speed, induction generators |
| **1991** | First offshore wind farm; 11 turbines, 450 kW |
| **2002** | 160 MW wind farm |

## Wind Energy Conversion Systems

Wind based energy harnessing systems are generally referred to as wind energy conversion systems (WECS). There are basically two applications, one is grid-connected WECS and another is stand-alone (off-grid) turbines. The stand-alone arrangements are well suited for remote clusters of populace and limited demands. Smaller size turbines can reduce the stress on the grid and reduce pollution [5]. Due to their capacities, if employment of diesel generators (DG) could be eliminated, there would be substantial saving in costs (fuel, operation and maintenance, fuel transportation costs etc.) [6]. Where wind energy potential is present but grid access is absent (connections are difficult and expensive), stand-alone wind turbines are viable to be installed. Since the arrangement is off-grid, some forms of storage system will be required. When complementary systems are employed, they are integrated with a micro-grid [7], thus power management requires complicated control systems [8].

The WECS can be classified either as a fixed speed or a variable speed system, based on turbine operation. Between these, the fixed speed wind turbine is relatively the simplest and most robust. Nevertheless, most wind turbine manufactures are increasingly shifting towards variable speed concepts due to the advantages of easy and simple pitch control, mechanical load reduction and high energy yield. Further reduction of fluctuations in output and extensive controllability of both active and reactive power are achievable with the variable speed turbines.

On the electrical part, induction generators (IG) and synchronous generator (SG) are generally employed in WECS. Although considerable recent research focused on SGs, their cost and installation requirements are major impediments. The squirrel cage induction generator (SCIG) has advantages of low cost, ruggedness, requires less maintenance, absence of dc, brushless, etc., as compared with the conventional SG [9]. The primary limitations of IG systems are poor voltage and frequency regulation, which can be controlled using a variable frequency control (VFC).

When an IG is coupled with a wind turbine, input power also varies depending on the wind speeds, which leads to variation in the terminal voltage and frequency [10]. This ac power can be used directly for certain frequency insensitive loads on practical applications, which require conversion into constant ac voltage of desired frequency and magnitude [11]. The regulation of the output voltage and frequency in stand-alone operation of a SCIG based WECS requires external schemes and the development of static power converters [12].

Some proposed schemes require a frequency converter [13] or a matrix converter [14]. Lin et al., [15] proposed a voltage source inverter (VSI) with a battery bank on the dc side to maintain the voltage and frequency of the SCIG. Use of batteries besides the VSI increases the efficiency of the system, relative to the use of dump-load. In addition, it can provide reactive power to the SCIG and supply active power to the load when the power produced by this generator increases during the variation of wind speed [16]. Hazra and Sensarma [17] suggested a noble control strategy, where the control signals for switching of the load-side converter are generated from the error of the reference and the sensed stator currents of SCIG, rather than by the errors of the load-side converter currents.

In the absence of the grid in a SCIG based system, the regulation of voltage and frequency has become even more challenging. This paper discusses a control strategy for effective voltage and frequency control of a stand-alone WECS based on squirrel cage induction machine, using voltage source converter and battery energy storage system (BESS) for varying the load conditions. The performance of the controller has been then analysed using the MATLAB simulation software.

## System Configuration

Figure 1 shows the schematic layout of a complete stand-alone wind energy system. The proposed controller consists of an IGBT based voltage source converter and a battery connected through a dc link. The controller is connected at the common coupling point through an inductor ($L_f$, $R_f$) interfacing the supply line and converter. The additional excitation capacitor connected to the machine helps in maintaining the rated voltage at no-load, and the additional demand is met by the controller.

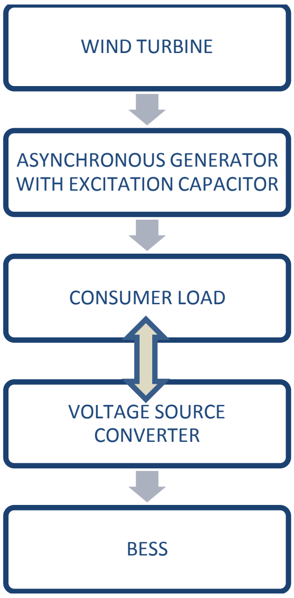



**Figure 1: Schematic diagram of the proposed WECS**

The controller has bidirectional power flow capability, which helps in maintaining constant magnitude of voltage and frequency under different electrical and mechanical conditions. To maintain constant frequency, the total power produced should be consumed completely by the load. When additional power is produced, it gets stored in the revolving component of the machine, which increases the machine speed and thus increases the system frequency. This is avoided in the proposed system by absorbing the extra power by the battery. Similarly, when the system is deficient of power, the battery will supply the power. Thus, constant frequency is maintained by the controller.

## Methodology

Figure 2 depicts the control strategy used in the WECS system. Here, the generated reference source current has been compared with the generator current to obtain the PWM signal for the VSC, using the dq0 transformation technique. The dq0 transform reduces the three phase (a,b,c) quantities to two phase (d-q) quantities, which simplifies the calculations. It is often used to simplify the analysis of three-phase machines or to simplify calculations for the control of three-phase inverters. Herein, it is used to simplify the control of three phase inverter. The PWM controls the VSC output, which in turn controls the voltage and frequency of the system. The control strategy consists of two blocks, namely voltage control block and frequency control block.

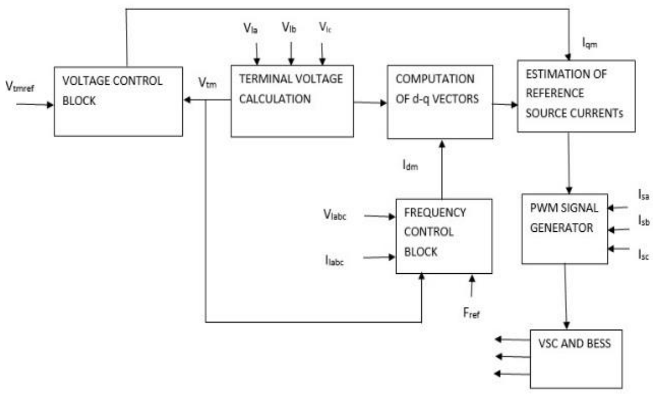



**Figure 2: Control strategy for the proposed system**

The control scheme is explained as the following steps:

Step 1: Calculate $V_{tm}$ using the load voltage and current values by,

$$V_{tm}=\left\{\left(\frac{2}{3}\right)\left(v_{la}^2+v_{lb}^2+v_{lc}^2\right)\right\}^{1/2} \qquad (1)$$

Step 2: Calculated $V_{tm}$ is compared with the $V_{tmref}$ and send to the PI controller to obtain the $I_{qm}$. This part contributes to the voltage control block of the scheme.

Step 3: Similarly, $I_{dm}$ is calculated in the frequency control block using the load voltage and current values, as depicted in Figure 3.

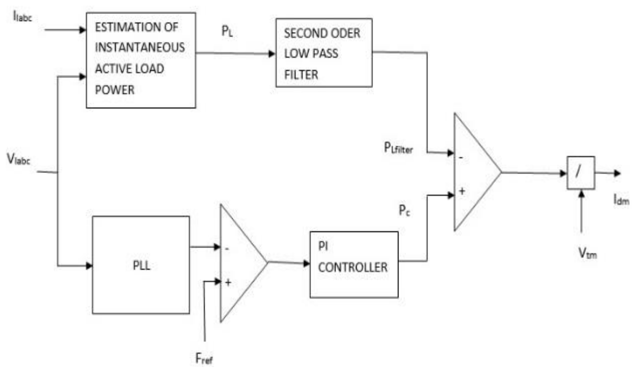



**Figure 3: Frequency control block**

The instantaneous active load power ($P_L$) is calculated using $v_\alpha$, $v_\beta$, $i_\alpha$, $i_\beta$. i.e.

$$P_L = v_\alpha i_\alpha + v_\beta i_\beta \quad (2)$$

where $v_\alpha$, $v_\beta$, $i_\alpha$, $i_\beta$ can be computed as:

$$v_\alpha = \left(\frac{\sqrt{2}}{3}\right)\left(v_{la} - \frac{1}{2}v_{lb} - \frac{1}{2}v_{lc}\right) \quad (3)$$

$$v_\beta = \left(\frac{\sqrt{2}}{3}\right)\left(\frac{\sqrt{3}}{2}v_{lb} - \frac{\sqrt{3}}{2}v_{lc}\right) \quad (4)$$

$$i_\alpha = \left(\frac{\sqrt{2}}{3}\right)\left(i_{la} - \frac{1}{2}i_{lb} - \frac{1}{2}i_{lc}\right) \quad (5)$$

$$i_\beta = \left(\frac{\sqrt{2}}{3}\right)\left(\frac{\sqrt{3}}{2}i_{lb} - \frac{\sqrt{3}}{2}i_{lc}\right) \quad (6)$$

The instantaneous load power is then filtered using 2nd order low pass filter to obtain $P_{Lfilter}$ output. The frequency of the output voltage is obtained using the phase locked loop (PLL), which is then compared with the reference frequency value. The error signal that is obtained from the comparison is sent to the PI controller to get the Pc value. The $P_{Lfilter}$ is then compared with the Pc to acquire the $I_{qm}$ value. The overall operation of the frequency control block can be represented as:

$$I_{dm} = \frac{2(P_{Lfilter} - P_c)}{(V_{tm})} \quad (7)$$

Step 4: The direct component and quadrature component unit vector are computed in the d-q unit vector computation block.

Step 5: The direct component reference source current is obtained by multiplying the direct component unit vector and amplitude of the active power component of the source current ($I_{dm}$). Similarly, the quadrature component of the reference source current is obtained by multiplying the reactive power component of the source current ($I_{qm}$) and quadrature component of the unit vector.

Step 6: The reference generator currents are obtained by adding the direct and quadrature reference current values.

$$i_{sa}^r = i_{qa}^r + i_{da}^r \quad (8)$$

$$i_{sb}^r = i_{qb}^r + i_{db}^r \quad (9)$$

$$i_{sc}^r = i_{qc}^r + i_{dc}^r \quad (10)$$

Step 7: The reference obtained current is compared with the sensed source current to obtain the error input to send to the PWM generator.

$$i_{saerr} = i_{sa}^r - i_{sa} \quad (11)$$

$$i_{sberr} = i_{sb}^r - i_{sb} \quad (12)$$

$$i_{scerr} = i_{sc}^r - i_{sc} \quad (13)$$

The generated PWM pulses will produce the voltage at the required frequency and magnitude, and then deliver them to the consumer even if the load and wind speed are varied. The parameters and data used in the exercises are tabulated in Table 2.

## SIMULATION RESULTS AND DISCUSSION

The torque, stator current and rotor speed waveforms obtained using Simulink for the proposed system are shown in Figure 4. It can be seen from the waveform that the rotor speed ($W_m$) slowly increased from zero and then stabilized at roughly 1s. The machine was run as a motor until 0.5s, which was visible by positive electromagnetic torque ($T_e$). After 0.5s, $T_e$ became negative, hence it is understood that the machine was running as a generator. When the machine was operated as a generator, it produced sufficient reactive power to meet the load. The stator current remained constant at 50Hz frequency, as shown in Figure 5. The load current and voltage waveforms showed a constant voltage and current for varying load conditions but not for a constant frequency.

**Table 2: System parameters and data for simulation**

| |
|---|
| **Squirrel cage induction machine:** |
| 20KW, 415V, 50Hz, Y-connected 4-pole<br>$R_s$ 0.15Ω<br>$R_r$ 0.01909Ω<br>$L_{lr}$ , $L_{ls}$ 1.65mH<br>$L_m$ 0.075mH<br>Inertia constant 0.05926<br>Friction factor 0.05479pu<br>Excitation capacitive reactive power ($Q_c$) 12KVAR |
| **Wind Turbine data:** |
| Rating 22KW<br>Base wind speed 8m/s<br>Maximum power at base wind speed 0.73pu<br>Base rotational speed 1..2pu<br>Pitch angle 0 |
| **Battery data:** |
| $C_B$ 30000F<br>$R_B$ 10KΩ<br>$V_{OC}$ 800V |
| **Frequency PI controller data** |
| $K_{pf}$ 2.3<br>$K_{if}$ 60 |
| **Voltage PI controller:** |
| $K_{pa}$ 0.03<br>$K_{ia}$ 0.002 |

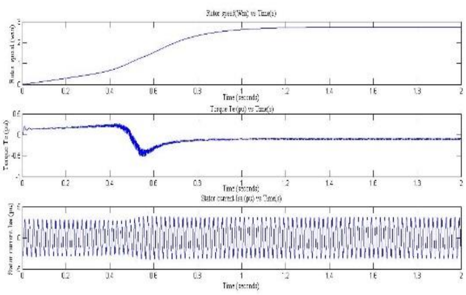


**Figure 4: Output waveforms for the machine**

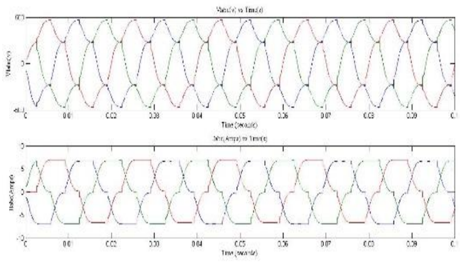


**Figure 5: Output waveforms of the load voltage and current**

## CONCLUSION

The proposed voltage and frequency controller are made to operate for a stand-alone wind energy system run by asynchronous machine. The simulation results for the system with the proposed controller demonstrate that the proposed controller is indeed capable to maintain constant frequency and voltage during operation.

## ACKNOWLEDGEMENTS

The authors acknowledge the guidance and help extended by Dr Jamuna of VIT University, Chennai, India.

## NOMENCLATURE

| | |
|---|---|
| $i^r_{da}, i^r_{db}, i^r_{dc}$ | Instantaneous value of quadrature component of reference source currents of the generator |
| $i_{la}, i_{lb}, i_{lc}$ | Instantaneous line current of an asynchronous generator |
| $i^r_{qa}, i^r_{qb}, i^r_{qc}$ | Instantaneous value of direct component of reference source currents of the generator |
| $i_{sa}, i_{sb}, i_{sc}$ | Sensed source current of the generator |
| $i^r_{sa}, i^r_{sb}, i^r_{sc}$ | Instantaneous value of reference source currents of the generator |
| $i_{saerr}, i_{sberr}, i_{scerr}$ | Current error of the generator |
| $v_{la}, v_{lb}, v_{lc}$ | Instantaneous line voltages at the terminal of an asynchronous generator |
| $V_\alpha$ | Instantaneous voltage of α component |
| $V_\beta$ | Instantaneous voltage of β component |

| | |
|---|---|
| $I_\alpha$ | Instantaneous current of α component |
| $I_\beta$ | Instantaneous current of β component |
| $C_B$ | Battery capacitance |
| $P_L$ | Instantaneous active power |
| $P_{Lfilter}$ | Filtered output of the instantaneous active power |
| $P_c$ | Power error signal |
| $R_B$ | Battery resistance |
| $R_s$ | Stator resistance |
| $R_r$ | Rotor resistance |
| $V_{tm}$ | Amplitude of the terminal voltage |
| $V_{tmref}$ | Amplitude of reference ac voltage terminal |
| $I_{dm}$ | Active component of reference source current |
| $I_{qm}$ | Quadrature component of reference source current |
| $K_{pf}$ | Proportional coefficient of frequency PI controller |
| $K_{If}$ | Integral coefficient of frequency PI controller |
| $K_{pa}$ | Proportional coefficient of voltage PI controller |
| $K_{ia}$ | Integral coefficient of voltage PI controller |
| $L_{lr}$ | Rotor side inductance of the generator |
| $L_{ls}$ | Stator side inductance of the generator |
| $L_m$ | Mutual inductance of the generator |
| $F_{ref}$ | Reference frequency |
| $V_{oc}$ | Battery open circuit voltage |

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