Terminal Voltage and Load Frequency Control of Self-Excited Induction Generators for Isolated Wind Power System using Battery Energy Storage

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Abstract – **This paper presents an investigation of active and reactive power controller to control voltage and frequency for an isolated induction generator driven by a wind turbine, supplying 3-phase 4-wire loads. The control strategy is based on the indirect current control of the VSC (voltage source converter) using a frequency PI controller. The proposed controller consists of three single-phase IGBT (Insulated Gate Bipolar Junction Transistor) based VSC, which are connected to each phase of the induction generator through zig-zag transformer and a battery at their DC link. The controller has the capability of controlling reactive and active powers to regulate the magnitude and frequency of the generated voltage. The proposed isolated system is modeled and simulated in MATLAB using Simulink and Power System Block-set toolboxes to verify the performance of the controller.**

Index Terms – **Battery Energy storage system (BESS), squirrel-cage induction generator (SCIG), wind energy conversion system (WECS).**

I. INTRODUCTION

Isolated asynchronous generators, which are also known as self excited induction generators (SEIG), appear to be an effective solution for isolated wind power applications where grid supply is not accessible and where areas are rich in renewable energy[1-2]. The increasing interest in renewable energy sources, power quality improvement, uncertainty in power output, isolated system integration, induction generator poor voltage regulation, induction generator reactive power requirement, and uncertainty in consumer load give attention to power engineer about the maximum power tracking, reactive power supply of generator, interconnection of network, voltage and frequency control of load and storage of power[3]. When SCIG is used for wind power applications, its reactive power requirement is met by a capacitor bank at its stator terminals [4].

The SCIG has advantages like simplicity, low cost, rugged, maintenance free, absence of DC, brushless etc. as compared to the conventional synchronous generator for hydro applications [5]. In this paper an effort is made to investigate a controller for the wind turbine driven generator to feed 3-phase 4-wire loads in remote communities where grid supply is not accessible. An investigation of such a system is necessary because most of the loads in such communities are single phase distributed loads [6-8].

The proposed controller consists of three single-phase IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter (VSC), which are connected to each phase of induction generator through zig-zag transformers [9-10] and a battery at its DC link [12-14]. In addition to controlling the magnitude and frequency of the generated voltage it also has the capability of harmonic elimination, load balancing, load leveling and neutral current compensation under any dynamic condition like variation of consumer load.

II. PRINCIPLE OF OPERATION

Fig 1 shows the schematic diagram of the proposed electro-mechanical system along-with its controller, excitation capacitor and consumer loads. A star connected excitation capacitor bank is used to generate the rated voltage at no-load, while additional demand of excitation to regulate the voltage is met by the controller. The proposed controller is realized using three single-phase IGBT based voltage source converters (VSCs) with a battery at its DC bus. All three phases of voltage source convertor is connected to three phase asynchronous generator through transformer.

The proposed controller is having a bi-directional flow capability of active and reactive powers by which it can control the magnitude and frequency of the generator voltage during different dynamic condition like variation in consumer loads and non linear loads. For maintaining constant frequency which is directly proportional to active power, total generated power should be consumed by the applied load (consumer load + battery). Here a frequency controller is used for extracting the active component the source current. When load is less than the generated power, it starts charging the battery and consumes additional generated power which is not consumed by the consumer loads. should be consumed by the applied load (consumer load + battery). Here a frequency controller is used for extracting the active component the source current. When load is less than the generated power, it starts charging the battery and consumes additional generated power which is not consumed by the consumer loads.

A zigzag transformer is connected in parallel to the load for filtering zero-sequence components of the load currents. Further, the zigzag windings trap triplen harmonic (third, ninth, fifteenth etc.) currents. The zigzag transformer consists of three single phase transformers with the turn ratio of 1:1. The zigzag transformer is to be located as near to the load as possible. The neutral terminal of the consumer loads is connected to the neutral terminal of the zigzag transformer.

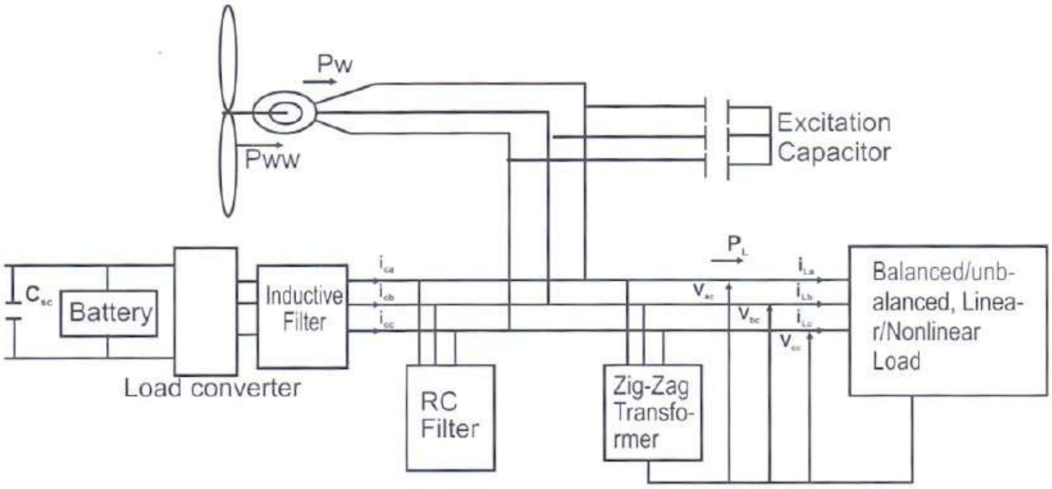

Fig.1. Schematic diagram of voltage and frequency control

III. CONTROL SCHEME

Fig. 2 shows the control scheme of BESS based VF controller to provide constant voltage and frequency along with constant excitation capacitor of induction generator. The control scheme is based on the generation of reference source currents (have two components in-phase and quadrature with AC voltage). The in-phase unity amplitude templates (u_a,u_b and u_c) are three-phase sinusoidal functions, which are derived by dividing the AC voltages v_a, v_b and v_c by their amplitude V_t. Another set of quadrature unity amplitude templates (w_a, w_b and w_c) is sinusoidal function obtained from in-phase vectors (u_a, u_b and u_c). To regulate AC terminal voltage (V_t), it is sensed and compared with the reference voltage (V_{tref}). The voltage error is processed in the PI voltage controller. The output of the PI controller for AC voltage control loop decides the amplitude of reactive current (I_{smq}*) to be generated by the BESS based VFC. Multiplication of quadrature unity amplitude templates (w_a, w_b and w_c) with the output of PI based AC voltage controller (I_{smq}*) yields the quadrature component of the reference source currents (i_{saq}*, i_{sbq}* and i_{scq}*). For a constant power generation and load leveling, the active power component of the source current is fixed at a rated value, which is the amplitude of in-phase component of source current (I_{smd}*). Multiplication of in-phase unit amplitude templates (u_a,u_b and u_c) with in phase component of source current (I_{smd}*) yields the in-phase component of the reference source currents (i_{sad}*, i_{sbd}* and i_{scd}*). The sum of instantaneous quadrature and in-phase components of these currents is the reference source currents (i_{sa}*, i_{sb}*, and i_{sc}*), and these are compared with the sensed source currents (i_{sa}, i_{sb} and i_{sc}). These current error signals are amplified and compared using PWM hysteresis controller for generating the PWM signals for switching of the devices of CC-VSC [9].

IV. CONTROL ALGORITHM

Computation of active component of reference source current:

For the constant power application, induction generator should generate constant active power. For the constant power, in-phase component of reference source currents is set equal to the rated amplitude of active power component of the current which is calculated as:

$$Ismd^* = \sqrt{2}(P\_rated)/(\sqrt{3}V\_rated)$$

Where Prated and Vrated are total rated power of generator and rated voltage.

$$V_t = \left\{\left(\tfrac{2}{3}\right)\left(V_a^2 + V_b^2 + V_c^2\right)\right\}^{1/2}$$

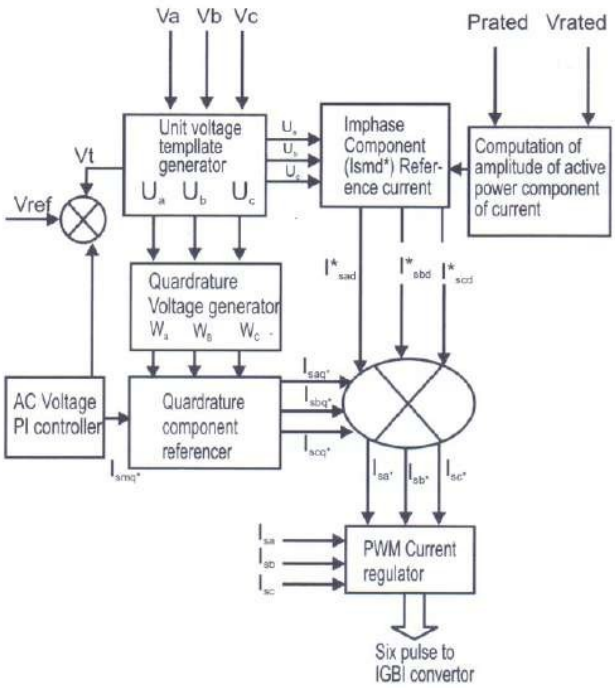

Fig.2. Schematic diagram of control scheme of BESS based VF controller.

The unity amplitude templates having instantaneous value in phase with instantaneous voltage (va, vb and vc), which are derived as

$$u_a = V_a/V_t \qquad u_b = V_b/V_t \qquad u_c = V_c/V_t$$

Instantaneous values of in-phase components of reference source currents are estimated as:

$$i_{sad}^* = I_{smd}^* . u_a ; \qquad i_{sbd}^* = I_{smd}^* . u_b ; \qquad i_{scd}^* = I_{smd}^* . u_c$$

Computation of reactive component of reference source current:

The a.c voltage error V_{err} at n^{th} sampling instant as

$$V_{err}(n) = V_{tref}(n) - V_t(n)$$

where $V_{tref}(n)$ is an amplitude of the reference AC terminal voltage and $V_t(n)$ is the amplitude of the sensed three-phase a.c voltage at the generator terminals at nth instant. The output of the PI controller ($I^*_{smq}(n)$) for maintaining constant a.c terminal voltage at the nth sampling instant is expressed as:

$$I^*_{smq}(n) = I^*_{smq}(n-1) + K_{pa}\{V_{err}(n) - V_{err}(n-1)\} + K_{ia} V_{err}(n)$$

Where K_{pa} and K_{ia} are the proportional and integral gain Constants of the proportional integral (PI) controller. V_{err} (n) and V_{err}(n-1) are the voltage errors in n^{th} and $(n-1)^{th}$ instant and $I^*_{smq}(n-1)$ is the amplitude of quadrature component of the reference source current at $(n-1)^{th}$ instant.

The instantaneous quadrature components of the refer source currents are estimated as:

$$i^*_{saq} = I^*_{smq} w_a ; \quad i^*_{sbq} = I^*_{smq} w_b ; \quad i^*_{scq} = I^*_{smq} w_c$$

Where w_a, w_b and w_c are another set of unit vectors having a phase shift of 90° leading the corresponding unit vectors u_a, u_b and u_c which are given as follows:

$$W_a = -u_b/\sqrt{3} + u_c/\sqrt{3}$$
$$W_b = \sqrt{3}\,u_a/2 + (u_b - u_c)/2\sqrt{3}$$
$$W_c = -\sqrt{3}\,u_a/2 + (u_b - u_c)/2\sqrt{3}$$

Total reference source currents are sum of in-phase and quadrature components of the reference source currents as:

$$i^*_{sa} = i^*_{saq} + i^*_{sad}$$

$$i^*_{bs} = i^*_{sbq} + i^*_{sbd}$$

$$i^*_{sc} = i^*_{scq} + i^*_{scd}$$

The reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with the sensed source currents (i_{sa}, i_{sb} and i_{sc}). The current errors are computed as:

$$I_{saerr} = I^*_{sa} - I_{sa}$$

$$I_{sberr} = I^*_{sb} - I_{sb}$$

$$I_{scerr} = I^*_{sc} - I_{sc}$$

Using above value of current error, the pulses of PWM are generated for IGBT convertor.

Parameters of Lead acid storage battery:

In this study, the capacity of battery is fixed. The design storage capacity of the battery bank is taken as 600 kWh. The commercially available battery bank consists of cells of 12 V. The nominal capacity of each cell is taken as 150 Ah.

To achieve a dc bus voltage of 700 V through series connected cells of 12 V, the battery bank should have (700/12) = 59 number of cells in series. Since the storage capacity of this combination is 150 Ah, and the total ampere hour required is (600 kWh/700 V) = 857 Ah, the number of such sets required to be connected in parallel would be (857 Ah/150 Ah)=5.71 or 6 (selected). Thus the battery bank consists of 6 parallel connected sets of 59 series connected battery cells.

Thevenin's model is used to describe the energy storage of the battery. In which, the parallel combination of capacitance (C_b) and resistance (R_b) in series with internal resistance (R_{in}) and an ideal voltage source of voltage 700V are used for modeling the battery, in which the equivalent capacitance C_b is given as

$$C_b = \frac{(kWh * 3600 * 1000)}{0.5(V_{ocmax}^2 - V_{ocmin}^2)}$$

Taking the values of V_{ocmax} = 750 V, V_{ocmin} = 680 V and kWh= 600, the value of C_b obtained is 43156 F [14]

V. EXCITATION CAPACITANCE

On the basis of the no-load motoring test it was calculated that the value of the capacitance should be 15 mF per phase. This value provides full compensation of induction machine's reactive power need and it should yield rated voltage of 240 V at rated synchronous speed of 1500 rpm (i.e. at 50 Hz) but experimentally it is 23mF at 1300 rpm[15].

An inductor is used on the ac side of the converter for boost function. For 5% ripple in the current through the inductive filter, inductance (Lf) of the inductive filter can be calculated as [4]

$$L_f = \left\{(\sqrt{3}/2)m_a V_{dc}/(6af_s I_{r(p-pLSC)})\right\}$$

here f_s is the switching frequency and is equal to 10 kHz $I_{r(p-p)LSC}$ and is the peak-to-peak ripple current in the converter and inductive filter. During transients, the current in the inductive filter is likely to be more than the steady-state values. For calculation of inductance, current rating of 120% (a = 1.2) of steady-state current is taken; modulation index is taken as one. Thus, the value of inductance of the filter is

$$L_f = \left\{(\sqrt{3}/2)700/(6^* \ 1.2^*10000^*11.1)\right\} = 0.76mH$$

The rounded-off value of 0.8 mH is selected for investigation

VI. RESULTS AND DISCUSSION

The performance of the proposed controller is demonstrated under different electrical dynamic conditions. Figs 3 and 4 show the performance of the controller for supplying balanced/ unbalanced, linear/ non-linear loads and it is observed that in all conditions, the controller responds in a desired manner. Simulated transient waveforms of the generator voltage (V_{abc}), generator current(I_{abc}), load currents (I_{Labc}), controller current (I_{Cabc}), terminal voltage (V_m), frequency (f), speed of the wind (vw), battery current (I_b), battery voltage (V_b) are given under different dynamic (variation of consumer load) conditions.

Performance of wind genrator System with Constant Balanced Linear Load at wind speed 9 m/s:

Performance of wind generator system is shown under balance linear load at 9 m/s wind speed , at wind speed 9 n fig.3.

m/s turbine torque is 0.7 pu and power output of SCIG is 0.75 kW at 50 Hz frequency. Now applied RL load is single three phase of total active power 0.4 kW. In this situation surplus power charges the battery, so that system frequency and voltage remain constant. Under these condition stator currents, load voltage and current excitation current is constant as shown in fig.3.

Performance of wind generator system is shown (Fig. 4) under unbalance, linear load at 9 m/s wind speed. At wind speed 9 m/s turbine torque is 0.7 pu and power output of *SCIG* is 0.75 KW at 50 Hz frequency. Now applied nonlinear load (consist of diode and resistive load with LC filter) is single three phase of total active power 0.4 KW. Now unbalancing created by changing value of each loads at different time interval. Let at time 0.5 s phase a is half loaded, under this situation load voltage and current are balance as shown in characteristics obtain. Now phase b is reduced to one half at time 1 s, system is balanced as shown with high content of harmonics. Also battery current and voltage increasing which shows that battery is charging to maintain the frequency and voltage of load. Due to nonlinear elements Harmonics introduced in stator current of SCIG, load current and excitation current but system is in balance condition.

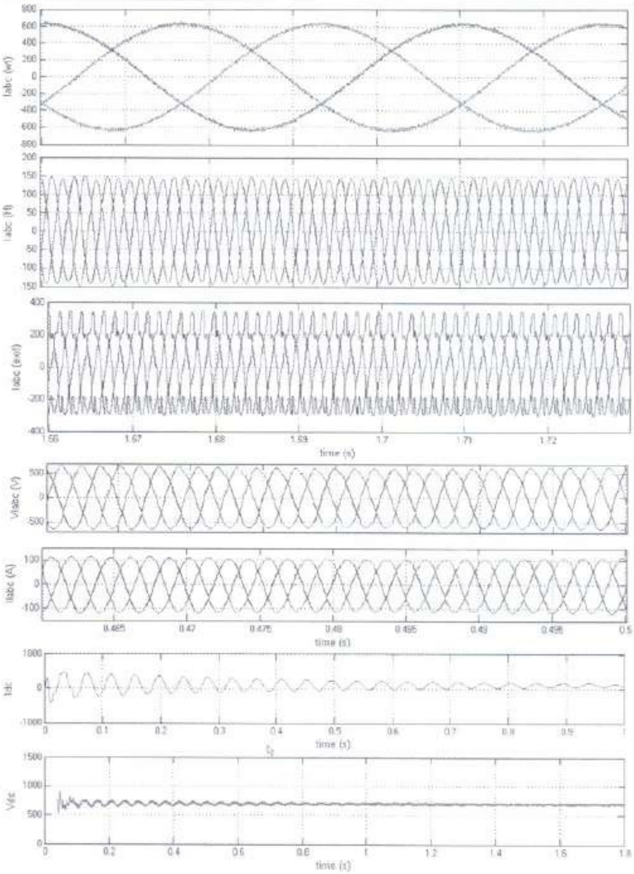

Fig.3. Characteristics of stator currents of wind generator, Load current and voltage, battery current and voltage characteristics at wind speed 9(m/s) and at constant .75 KW balanced load.

VII. CONCLUSION

The performance of the VF controller has been demonstrated under the conditions of varying balanced/unbalanced linear and non-linear consumer loads. It has been observed that the controller responds in a desired manner and maintains the magnitude and frequency of the generated voltage along with functioning as a harmonic eliminator, a load balancer and a neutral current compensator.

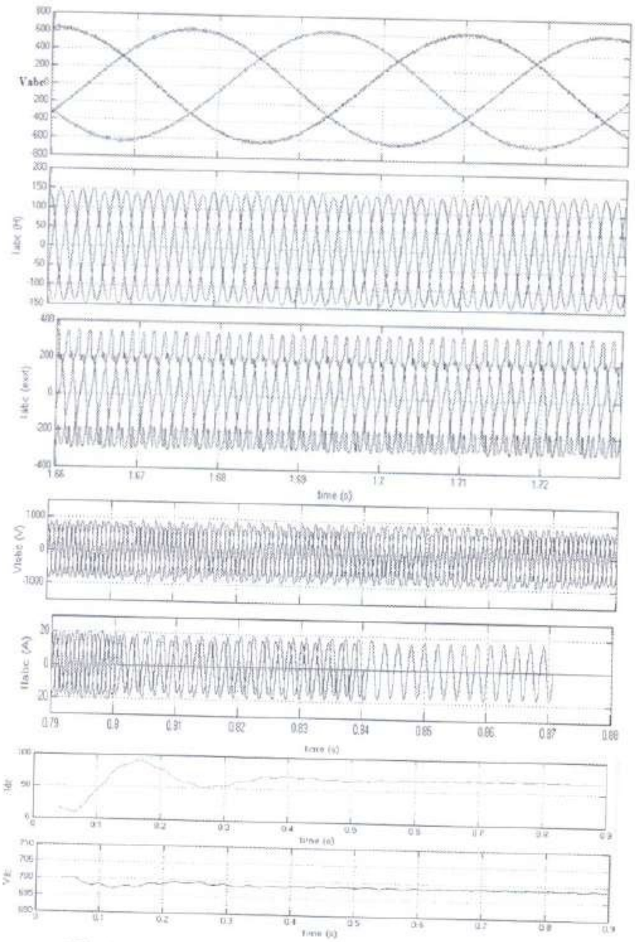

Fig.4: Performance characteristics of Wind generator with Unbalanced Linear Load at wind speed 9 m/s.

Appendix

The parameters of 0.75kW, 415V, 50Hz, Y-connected, 4-pole asynchronous machine are given below.

Battery specification

$C_b = 40000F$, $R_b = 10k\Omega$, $R_s = 0.01\Omega$, $V_{oc} = 450V$

Controller parameters

$L_f = 3mH$, $R_f = 0.1\Omega$, and $C_{dc} = 8000\mu F$, N1:N2 = 1:1

$K_{pa} = 0.18$, $K_{ia} = 0.01$; $K_{pf} = 43$, $K_{if} = 3250$.

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