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A PWM Controlled IGBT based VSCS with a Battery Energy Storage System for an Isolated Wind-Hydro Hybrid System Using Cage Generators

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Abstract: — This paper presents a Pulse Width Modulation (PWM) controlled Insulated Gate Bi-polar Transistor (IGBT) based Voltage Source Converters (VSCs) with a battery energy storage system (BESS) for an isolated wind-hydro hybrid system using two squirrel cage induction generators (SCIG) or simply two cage generators, one driven by a variable speed wind turbine and another driven by a constant power hydro turbine. The proposed system has a battery energy storage system (BESS) at the middle of two back –to-back connected pulse width modulation (PWM) controlled insulated-gate-bipolar –transistor (IGBT) based voltage source converters (VSCs).The main objectives of the control algorithm for the VSCs are to achieve the maximum power point tracking (MPPT) through rotor speed control of a wind turbine driven SCIG at machine side (or generation side) and to control the magnitude and frequency of the load voltage at load side(or hydro power generation side). The proposed system has a facility to bidirectional real and reactive power flow, by which it controls the magnitude and frequency of the load voltage. The control techniques with wind-hydro hybrid power is modeled and simulated in MATLAB 2009a environment using Simulink and Sim Power System set tool boxes. The proposed system studied under various load conditions with different input wind speeds.

Keywords: Pulse Width Modulation (PWM) , Hybrid system , Maximum Power Point Tracking (MPPT), Battery Energy Storage System (BESS)

I. INTRODUCTION

From the last few decades many countries are aware with global warning problems. One of the main problems is the pollution from burning fossil fuels to produce energy. Then the solution of this problem is to produce the clean energy .So more attention and interest have been paid to the utilization renewable energy sources, like solar, hydro, wind, biomass etc... Wind energy is the fastest growing and most promising renewable source among them due to economically variable. In India total installed capability of wind power generation is 8754M.W in the year 2008. India now ranks 5^{th} in the world with an installed capacity of 11807MW as on 31-3-2010 according to Ministry of New and Renewable energy (MNRE), India. According to MNRE, in India the total installed capacity as on May 2014, the energy scenario status is given in bellow Table.1 [2]

Source	Total Installed Capacity (MW)
Wind Power	21,262.23
Solar Power (SPV)	2,647.00
Small Hydro Power	3,803.65
Biomass Power	1,365.20
Bagasse Cogeneration	2,512.88
Waste to Power	106.58
Total	**31,833.01**

Table.1. Total Renewable Energy Installed Capacity (May 2014) in India

Among the renewable energy sources, small hydro and wind energy have the ability to complement each other [5].For power generation by small hydro or micro hydro as well as wind systems, the use of squirrel cage induction generators (SCIG) has been reported in literature. [1],[3]

There are two important parameters in the hydro power generation, i.e., discharge and head of the water level for the determination of generating voltage for a hydro electric power generation [3]. When SCIG is used for small or micro hydro applications, its reactive power is met by a bank of capacitors at its stator terminal. In recent years, wind-turbine technology has switched from fixed speed to variable speeds. The variable speed machines have several speeds advantages has been reported.[4].Natural energy based power generation systems are generally equipped with storage batteries to balance the total power [6].In this paper, the subscript $'w'$ is used to denote the parameters and variables of wind turbine generator and subscript $'h'$ is used to denote the parameters and variables of hydro turbine generator.

A schematic diagram of three phase four wire proposed system is shown in Fig.1.The two back-to-back connected PWM controlled IGBT based VSCs are connected between the stator windings of $SCIG_w$ and the stator windings of $SCIG_h$ to give a path for active and reactive power flow in the proposed wind hydro hybrid system.

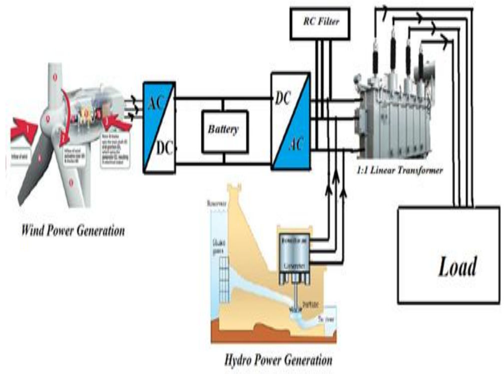

Fig.1.Schematic diagram of the proposed wind-hydro hybrid system

The stator windings of the $SCIG_h$ are connected to the load terminals. The two VSCs may be called as the machine side converter at $SCIG_w$ and the load side converter at $SCIG_h$. An inductor is connected in series with the BESS to remove the ripples from the battery current. A zigzag transformer is in parallel to the load for filtering zero sequence components of the load currents. Further, the zigzag transformer windings trap triple harmonics [8]. As shown in Fig.1 the transformer consists of three single phase transformers with a turn's ratio of 1:1. The neutral wire of the transformer is connected to the neutral wire of the load.

II. Operating Principle of Proposed System

A. *Machine Side Converter Control Technique :*

To achieve MPPT, the $SCIG_w$ is required to be operated at optimal tip speed ratio (TSR) as shown in Fig.2. The TSR determines the $SCIG_w$ rotor speed set point for a given wind speed, and the mechanical power generated at this speed lies on the maximum power points of the wind turbine as shown in Fig.3.[1]

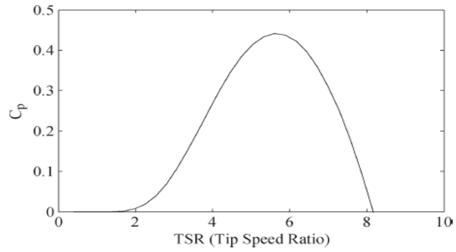

Fig.2. Power coefficient (c_p) versus tip speed ratio (λ) for wind turbine

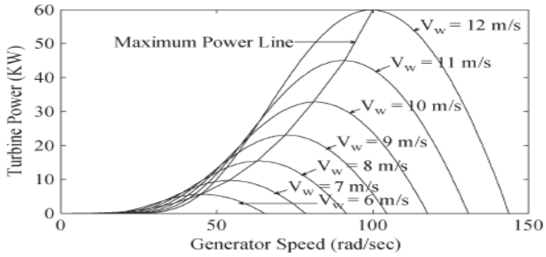

Fig.3.Mechanical output power of the wind turbine versus generator ($SCIG_w$) speed for different wind speeds.

The operating principle of the machine side converter is based on the decouple control of d-and q-axis stator currents of the SCIG with the d-axis aligned to rotor flux axis[3].

In the proposed system, the tip speed ratio (λ_w) for a wind turbine of radius (r_w) and gear ratio (η_w) at a wind speed of (v_w) is given by equation (1). For MPPT in the wind turbine generator system, the $SCIG_w$ must be operate at the optimum tip speed ratio (λ_w^*) as shown in Fig. (2). Thus the reference rotor speed (w_{rw}^*) and the optimal tip speed ratio (λ_w^*) for MPPT is

$$\lambda_w^* = \frac{\omega *_{rw}\ r_w}{\eta_w\ v_w} \tag{1}$$

At the n^{th} sampling instant, the resultant rotor error is fed to the Proportional Integral (PI) controller, gives the reference q-axis stator current (I_{qsw}^*).

The reference d-axis $SCIG_w$ stator current I_{dsw}^* is determined from the rotor flux set point ($\varphi^* drw$) at the n^{th} sampling instant is given by

$$I_{dsw\,(n)}^* = \frac{\varphi_{drw}^*}{L_{mw}} \tag{2}$$

Where L_{mw} is the magnetizing inductance of $SCIGw$

For generating the three phase reference $SCIG_w$ stator currents (i^*_{swa} , i^*_{swb} and i^*_{swc}), the transformation angle is given by

$$\theta_{rotor\ flux\ w} = \theta_{slip\ w} + \left(\frac{pw}{2}\right)\theta_{rw} \qquad (3)$$

The references for d-q components of $SCIG_w$ stator currents are converted to three phase reference $SCIG_w$ stator currents by $d-q$ to abc transformation using angle $\theta_{rotor\ flux\ w}$ is given by equations (4),(5) and (6)[1]

$$i^*_{swa} = I^*_{dsw}\sin(\theta_{rotor\ flux\ w}) + I^*_{qsw}\cos(\theta_{rotor\ flux\ w}) \qquad (4)$$

$$i^*_{swb} = I^*_{dsw}\sin\left(\theta_{rotor\ flux\ w} - {2\pi}/{3}\right) + I^*_{qsw}\cos\left(\theta_{rotor\ flux\ w} - {2\pi}/{3}\right) \qquad (5)$$

$$i^*_{swc} = I^*_{dsw}\sin\left(\theta_{rotor\ flux\ w} + {2\pi}/{3}\right) + I^*_{qsw}\cos\left(\theta_{rotor\ flux\ w} + {2\pi}/{3}\right) \qquad (6)$$

Then the above reference currents are compare with sensed $SCIG_w$ stator currents to compute the $SCIG_w$ stator current errors, and those are amplified with gain (k=5) and the amplified signals are compared with a frequency (10 kHz) triangular carrier wave of unity amplitude to generate the required gating signals for the IGBTs of the machine side VSCs.

B. Load Side Converter Control Technique :

The aim of the load side ($SCIG_h$) side converter is voltage frequency control at the load terminals by maintaining active and reactive power balance.[3]

The reference voltages (v^*_{an} ,v^*_{bn} and v^*_{cn}) for control of the load voltages at time't' given by

$$v^*_{an} = \sqrt{2}\ v_t\ \sin(2\pi f t) \qquad (7)$$

$$v^*_{bn} = \sqrt{2}\ v_t\ \sin\left(2\pi f t - \frac{2\pi}{3}\right) \qquad (8)$$

$$v^*_{cn} = \sqrt{2} v_t \sin\left(2\pi f t + \frac{2\pi}{3}\right) \qquad (9)$$

Where f is the nominal frequency (50Hz) and v_t is the phase-neutral load voltage, which is 240 V

The measured load voltages (v_{an} , v_{bn} and v_{cn}) are compared with the reference voltages at n^{th} sampling instant to compute the error voltage signals and these are fed to a PI voltage controller to obtain the three phase $SCIG_h$ reference currents (i^*_{sha} , i^*_{shb} and i^*_{shc}).

Now the above reference currents are compared with the sensed three phase currents of $SCIG_h$ and these error signals are amplified with gain (k=5) , and amplified signals are compared with a fixed frequency (10KHz) triangular carrier wave of unity amplitude to generate gate pulses for IGBTs of the load side converter.

BESS used in the system is designed by Thevinen's equivalent model and its ratings are given in Appendix section. The proposed hybrid system with BESS being considered has a wind turbine of 55kW and a hydro turbine of 35kW. The ratings of the SCIGs are equal to the ratings of its turbine ratings and the ratings of the reaming devices calculated values are given in the Appendix.

III. MATLAB BASED SIMULATION RESULTS & DISCUSSIONS

MATLAB based simulation diagram of proposed wind-hydro hybrid system is shown in Fig.4

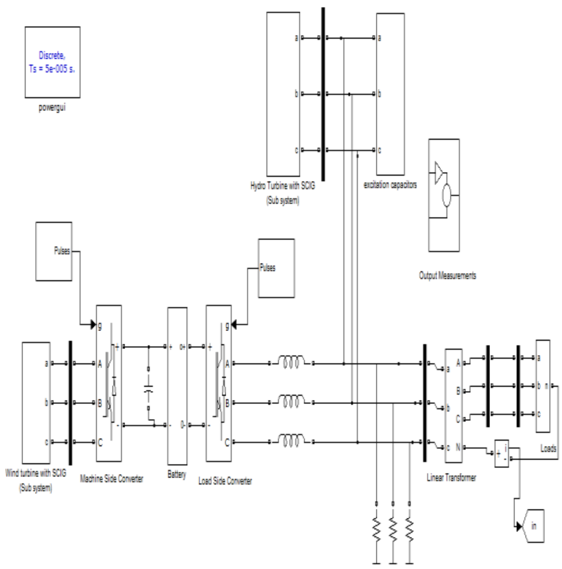

Fig.4. MATLAB based simulation diagram of proposed wind-hydro hybrid system.

The simulated transient wave forms of stator $SCIG_w$ current(i_{sw}) $SCIG_h$ stator current(i_{sh}),load side converter current (i_C),load frequency(fL) , wind frequency(fw),three phase load voltage(v_L)

,three phase load current (i_L) , single phase load currents (i_{La} , i_{Lb} ,and i_{Lc}) , zigzag transformer currents (i_{ta} , i_{tb} , and i_{tc}),load frequency (f_L) ,battery current (i_b) ,battery voltage (v_{dc}) ,SCIG$_w$ stator power (P_w) , SCIG$_w$ stator power (P_w) ,SCIG$_h$ stator power(P_h) , load power (P_L),battery power (P_b), power coefficient (C_P),SCIG$_W$ rotor speed (ω_{rw}) , and wind velocity(V$_w$) are shown in graphs for different operating conditions in this section.

The system is designed for an isolated location with the load varying from 30 to 90 kW at lagging power factor of 0.8

A .MATLAB based simulation results with balanced linear loads

At wind speed of 10.1 m/s the corresponding rotor speed of SCIG$_w$ is 102 rad/s and the generated power from the SCIG$_w$ is 52.3 kW at power coefficient of 0.45 and the generated power from SCIG$_h$ is 33.3 kW, which is constant in all the conditions in this project. The system is feeding electrically balanced three single phases linear loads of total rating 60kW and 30 kvar. The total generated power is more than the load power so the battery observes the excess generation power to maintain frequency of the load voltage constant. The load side converter supplies the load reactive power to maintain the magnitude and frequency of the load voltages are constant. The resultant MATLAB based graphs are shown in Fig.5.

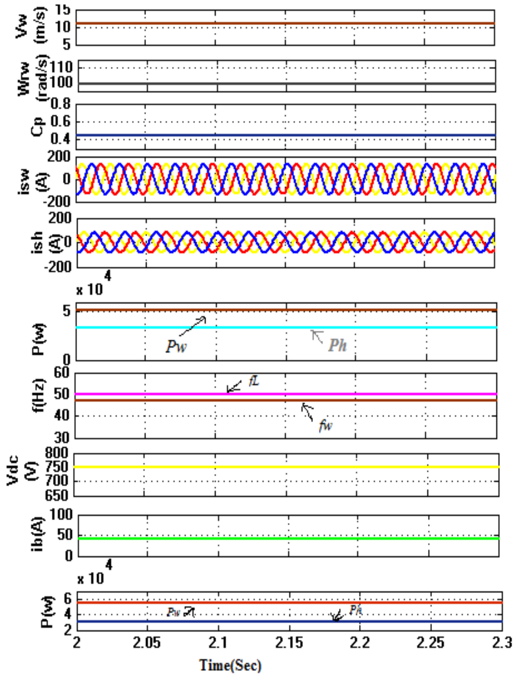

Fig.5: MATLAB based simulation results of the hybrid system at wind speed of 10.1 m/s with balanced linear loads.

B. MATLAB based simulation results with un balanced linear loads:

At wind speed of 8.2m/s the corresponding rotor speed of SCIG$_w$ is at 75 rad/s and its generated power is 20.1 kW. The system is feeding electrically the same as the before case and here an unbalance in load is created by using a timer circuit at 2.1 and 2.5 seconds, the resultant MATLAB results are shown in fig6.From the Fig.6.Under the unbalanced condition the currents in the zigzag transformer is non zero, but the currents in all the three phase windings are the same, that means that the zero sequence currents flowing through these windings. It is clear that from Fig.6, magnitude of load voltage and load frequencies are maintained constant even if the unbalance is created in the system.

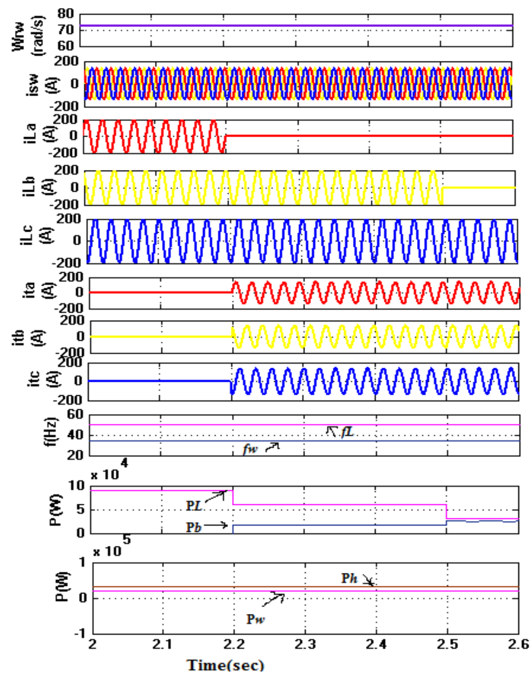

Fig.6. MATLAB based simulation results of the hybrid system at wind speed at of 8.2 m/s with unbalanced linear loads.

C. MATLAB simulation results under mixed load consisting of Linear, Nonlinear and Dynamic loads at wind speed of 9 m/s :

Fig.7. shows the performance of the wind-hydro hybrid system is shown with balanced mixed load with a wind speed of 9.1 m/s. The corresponding rotor-speed set point for $SCIG_w$ is at 82 rad/s, and the stator frequency is 38.38 Hz. At this speed, the mechanical power corresponding to the maximum coefficient of performance is 30 kW. The input mechanical power to the $SCIG_h$ is taken as 35 kW, and the power generated through $SCIG_h$ is 33.3 kW. Thus, the total power generated is (30 + 33.3) kW = 63.3 kW. The system is feeding electrically balanced three single-phase linear loads (each of 3.3 kW) and balanced three single-phase nonlinear loads (each of 8 kW). Because the power generated by the system is more than the required active power for the electrical loads (33.9 kW), the battery is absorbing the surplus power to maintain the frequency of the load voltage constant. At 3.05 s, an induction motor of 15 kW is started, which takes large starting current. As a result, the battery charging current reduces to maintain the frequency of the load voltage constant.

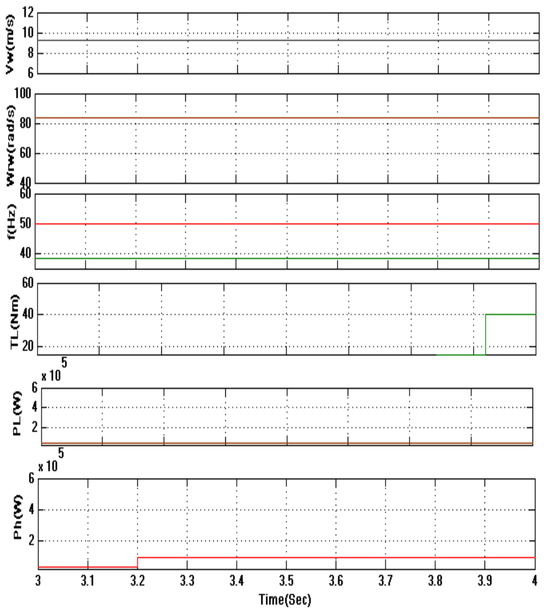

Fig.7. MATLAB based simulation results of the hybrid system under mixed load consisting of Linear, Nonlinear and Dynamic loads at wind speed of 9.1 m/s.

D. MATLAB based simulation results under varying wind speeds with linear balanced load

As shown in Fig.8, the wind-hydro hybrid system is started with a three single phase linear loads of totaling 45kW at wind speed of 7m/s .At this condition, the output power from the $SCIG_w$ 13kW and the total power is (13+33.3) = 46kW.Since the generated power is almost equal to the active power of the load, the battery power is zero. At 3.5 m/s, the wind speed is increased from 7 to 8m/s and its generated power is 20kW, hence the excess power is used for charging of battery. At 3.4 s, the wind is decreased from 8.1 to 6.1 m/s and its generated power is 7.5kW, here the total generated power is less than the active load power, so the deficit power is delivered by the BESS. From the MATLAB simulation resultant graph of Fig.8, it is clear that in all the conditions frequency and voltage at side is constant.

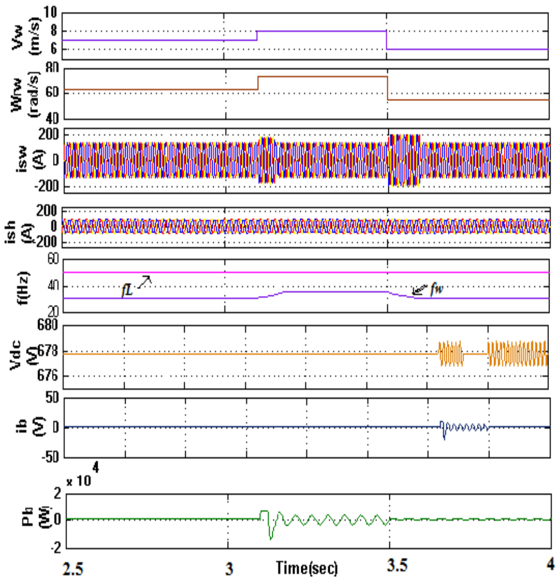

Fig.8.MATLAB based simulation results of the hybrid system at variable wind speeds with linear balanced loads

IV.CONCLUSION

A three phase four wire isolated load driven by wind –hydro hybrid system with two squirrel cage induction generators has been designed and simulated in MATLAB 2009a environment using Simulink and Sim Power System tool boxes. It has been demonstrated that the proposed hybrid system performs dynamically under different aspects while maintains constant voltage and frequency at load side by means of load side converter. Moreover, it has shown capability of MPPT at wind turbine side (Machine side converter side).

Scope for Future work:

In order to increase reliability few more sources such as solar and biomass can be added.

An AI technique can be adopted in the fine tuning of system variables to get optimal performance of the proposed model.

APPENDIX

1. *Parameter of 37.3-kW 415-V 50-Hz Y-connected* $SCIG_h$ *:* R_s=0.09962Ω , R_r=0.059 Ω, L_s=0.870 mH , L_r=0.030370 H , and Inertia=0.4 kg.m^2
2. *Parameters of 55-kW 415-V 50-Hz, Y-connected six-pole SCIGw:* R_s=0.060 Ω, Ls=0.690 mH, $R_{r=}$0.0513Ω, L_m=0.0298 H, and Inertia =1.5 kg.m^2.
3. *Parameters of 55-kW wind turbine:* wind speed range = 5.0-12m/s, speed range = 42-82 r/min, I=13.5 kg.m^{2,} r = 7.5 m, C_{pmax}=0.04412, and λ^*=5.66
4. *Machine side converter:* Active power (Psw) = 55kW, Reactive power (Qsw) =18.4kvar.
5. *Load side converter:* Reactive power (QL) = 67.5 kvar, KVA rating =112.5kVA.
6. *RC Filter and AC inductor:* R=5.0Ω, C=5.0µF, $L_{f=}$ 0.76 mH.
7. *BESS specifications:* C_b=43157 F, R_b=10kΩ, R_{in}=0.2Ω, Voc max = 750V, Voc min= 680V, Storage = 600 kW.h, L= 1 mH.
8. *PI controllers:* K_{pv}=15 and K_{iv}=0.05.
9. *1:1 Zig Zag Transformer Specifications:* three single phase transformer of 15 kVA 138/138 V

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