HYBRID SYSTEMS: WIND SOLAR AND WIND HYDRO HYBRID SYSTEMS WITH BATTERY STORAGE

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Abstract- This paper deals with a novel isolated wind solar and wind hydro hybrid generation system. The wind solar hybrid generation system employs squirrel cage induction generator (SCIG) driven by a variable speed wind turbine and a high power photovoltaic system. The wind hydro hybrid generation system is designed with SCIG driven by a variable speed wind turbine and another squirrel cage induction generator driven by a constant power hydro turbine. The system utilizes two back to back connected voltage source converters (VSCs) with a battery energy storage system at their dc link. The main objectives of the control algorithm for the VSCs are to achieve maximum power tracking (MPT) through rotor speed control of a wind turbine driven SCIG under varying wind speeds and control of the magnitude and the frequency of the load voltage. The above mentioned hybrid systems have the ability of bidirectional active and reactive power flow by which it controls the magnitude and frequency of the load voltage. The two electromechanical systems are modeled and simulated in MATLAB using Simulink and Sim Power System set tool boxes and different aspects of the proposed systems are studied for various loads under varying wind speed conditions.

Keywords- Battery energy storage system (BESS), Squirrel cage induction-generator (SCIG), Synchronous generator wind energy conversion system (WECS), Voltage source converter (VSC).

I. INTRODUCTION

The renewable energy resources have attracted a large attention worldwide due to soaring prices of fossil fuels.

Renewable energy resources are thought-about to be vital in rising the security of energy supplies by decreasing the dependence on fossil fuels and in reducing the emissions of greenhouse gases. The viability of isolated systems exploiting renewable energy resources depends mostly on rules and stimulation measures.

Renewable energy resources are the natural energy resources that are inexhaustible, example solar, geothermal, biomass and small hydro generation. Among the renewable energy sources, small hydro and wind energy have the ability to complement each other.

Hybrid power systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in one another. System efficiencies are usually more than that of the individual technologies used separately and higher dependability is accomplished with redundant technologies and/or energy storage. Some hybrid systems include both, which simultaneously improve the standard and availability of power. In general, well-designed hybrid systems considerably scale back the fuel consumption while improving system dependability. In addition to the diesel generator and the renewable energy generator, hybrid systems consist of a battery bank for energy storage, a control system and a particular system architecture that allows optimal use of all elements. Hybrid systems assure potentially very affordable solutions to rural electricity needs.

For low and medium load applications, (<10kWh/day), wind or hybrid systems are considerably enticing. For higher applications, wind/solar hybrid system are very attractive as long as a wind resource is available.

Bilateral, multilateral finance and market stimulation programs ought to be based on best service at least cost. There exists a large assortment of literatures on the modelling of WECS, specifically on the modeling of individual parts in the system which is comprised of two subsystems, specifically a wind turbine part and an electric generator part.

DC machines were common until 1980s in smaller installations below 100 kW, because of its high and easy speed control. The presence of commutators in DC machines has low reliability and high maintenance. The second kind of electrical generators are synchronous generators suitable for constant speed systems. Another selection for the electric generator in a WECS may be a synchronous generator. But synchronous generators have the weakness of uncontrollable flux decaying over a period of time, whereas induction generators have many benefits like absence of dc field current, low maintenance needs, low price simplicity and wide range of applications.
Many wind power systems for economy and reliability reasons used induction machines driven by a turbine through a gear box as an electrical generator. On the basis of rotor construction induction machine can be either squirrel cage type or wound rotor type. Squirrel-cage rotor construction is common because of its rigidity, lower price and ease of construction. Hence, these days it is mostly used.

In the case of stand-alone or autonomous systems, the problems of voltage and frequency control (VFC) are very vital. In references [16]–[17], the problems of VFC for standalone systems using SCIGs have been stated. However, maximum power tracking (MPT) could not be attained in this battery-based isolated system using SCIG operated at constant speed. Reference [4] proposes an electronic load controller for VFC at the stator terminals, and the controller delivers excess power from the hydropower generator to a dump load, when the load is less than the generated power.

In this paper, a three-phase four-wire autonomous (or isolated) wind-solar hybrid system and a wind small hydro system are proposed for isolated locations, which can't be connected to the grid and where ever the wind potential and hydro potential exist simultaneously. One such location in India is the Andaman and Nicobar group of islands. Wind and micro-hydro perform well during stormy periods, while photovoltaics work best in dry summer conditions with long sunny days. The wind hydro system utilizes variable speed wind turbine driven SCIG and constant-speed, constant power small hydro turbine-driven synchronous generator. Schematic diagram of a three-phase four-wire autonomous system is shown in Fig. 2. Two back-to-back-connected pulse width modulation (PWM)-controlled insulated gate bipolar transistor (IGBTs)-based voltage source converters (VSCs) are connected between the stator windings of SCIG and the stator windings of the PMSG to allow bi-directional power flow. The stator coils of the induction generator are connected to the load terminals. The two VSCs can be referred as the machine side converter and the load side converter. The system employs a battery energy storage system (BESS), which performs the load levelling in the case of uncertainty in the wind velocity and variable loads. The BESS is connected at the dc bus of the PWM converters.

The benefit of using BESS on the dc bus of the PWM converters is that no extra converter is needed for delivery of power to or from the battery. Also, the battery maintains the dc bus voltage constant during load disturbances or load fluctuations. An inductor is connected in series with the BESS to reduce ripples from the battery current.

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) currents. It is a vital element in the hybrid system.

In the conventional control of variable-speed SCIGs, the objective of the load-side converter (called as grid-side converter in the grid-connected systems) is to keep the dc-bus voltage steady at the dc link of two back-to-back connected VSCs. Because in the projected system the dc-bus voltage is kept constant by the battery, the control objective of the load-side converter is different, i.e., to maintain an active power balance in the system by delivering the extra power to the battery or for transferring deficit power from the battery. Further, the load-side converter gives the requisite reactive power for the load. A novel control strategy using indirect current control is planned for the load-side converter. 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 instead of the errors of the load-side converter currents. With this control strategy, the switching of the load-side converter is controlled to make the SCIG currents balanced and sinusoidal at the nominal frequency. Any unbalance and harmonics in the load currents are compensated by the zigzag transformer and the load-side converter.

The proposed control algorithm for the load-side converter needs sensing of the load voltage and stator currents of SCIG. For the control purpose, sensing of load-side converter currents and load currents is not required, thus reducing the requirement of current sensors for the control of load side converter.

Figure 1: Schematic diagram of wind-solar hybrid system

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Figure 2: Schematic diagram of wind-hydro hybrid system

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II. PRINCIPLE OF OPERATION

The planned system uses two back-to-back-connected VSCs. These VSCs are named as the machine side converter and load-side converter. The objective of the load-side converter is VFC at the load terminals by maintaining active- and reactive-power balance. To realize MPT, the SCIG is needed to be operated at optimal tip speed ratio. The tip speed ratio determines the SCIGw rotor-speed set point for a given wind speed, and also the mechanical power generated at this speed lies on the maximum power line of the turbine. The load-side converter is controlled for the regulation of load-voltage magnitude and load frequency. Further, for maintaining the load-frequency constant, it is also essential that any surplus active power in the system is diverted to the battery. As an alternative, the battery system ought to be able to provide any deficit within the generated power. Similarly, the magnitude of the load voltage is maintained constant within the system by balancing the reactive-power demand of the load through the load side converter.

For the proposed system, there are three modes of operation. In the initial mode, the required active power of the load is less than the power generated by the synchronous generator and the excess power generated by the PMSG is transferred to the BESS through the load-side converter. Moreover, the power generated by the SCIG is transferred to the BESS. In the second mode, the required active power of the load is more than the power generated by the hydro and wind generation. Then the portion of the power generated by the wind is transferred to the load and the remaining is stored in the battery. In the third mode, the active power of the load is more than the power generated by both the wind and hydro generation. The deficit is supplied by the battery.

A: Control of load side converter

The objectives of the load-side converter are to keep the rated voltage and frequency at the load terminals constant whatever be the connected load. The power balance in the system is maintained by diverting the excess power generated to the battery or by supplying power from the battery in case of deficit between generated power and load demand. Similarly, the desired reactive power for the load is provided by the load-side converter to keep constant value of the load voltage. The control strategy is explained below.

1) Generation of Reference Three-Phase SCIGw Currents:

The reference voltages (V*an, V*bn, and V*cn) for the control of the load voltages at time t are given as

\[ V_{an}^* = \sqrt{2} V_s \sin(2\pi ft) \]

\[ V_{bn}^* = \sqrt{2} V_s \sin(2\pi ft - 120) \tag{2} \]

\[ V_{cn}^* = \sqrt{2} V_s \sin(2\pi ft + 120) \tag{3} \]

where \( f \) is the nominal frequency, which is taken into account as as 50 Hz, and \( V_s \) is the rms phase-to-neutral load voltage, which is 240 V. The load voltages \( (V_{an}, V_{bn}, \text{ and } V_{cn}) \) are detected and compared with the reference voltages. The error voltages \( (v_{an}, v_{bn}, \text{ and } v_{cn}) \) at the nth sampling instant are calculated as

\[ v_{an}(n) = V_{an}(n) - V_{an} \tag{4} \]

\[ v_{bn}(n) = V_{bn}(n) - V_{bn} \tag{5} \]

\[ v_{cn}(n) = V_{cn}(n) - V_{cn} \tag{6} \]

The reference three-phase SCIGw currents \( (i_{swa}, i_{sub}, i_{swc}) \) are generated by feeding the voltage error signals to PI voltage voltage controller with proportionate gain \( K_p \) and integral gain \( K_i \). The reference three-phase SCIGw currents are then compared with the detected SCIGw currents \( (i_{swa}, i_{sub}, \text{ and } i_{swc}) \) to calculate the SCIGw current errors as:

\[ i_{swa} = i_{swa} - i_{swa} \tag{7} \]

\[ i_{sub} = i_{sub} - i_{swb} \tag{8} \]

\[ i_{swc} = i_{swc} - i_{swc} \tag{9} \]

These current errors are amplified with gain \( K=5 \), and the amplified signals are compared with a fixed-frequency (10 kHz) triangular carrier wave of unity amplitude to produce gating signals for IGBTs of the load-side converter. The sampling time of the controller is taken as 50\( \mu \)s, as this time is sufficient for calculations in a typical DSP controller.

B: Control of machine side converter

1) Speed-Control Loop for MPT and Reference q-axis SCIGw Stator-Current Generation: In the proposed algorithm, the rotor position \( (\theta_{rw}) \) of SCIGw and therefore the wind speed are detected. The rotor speed \( (\omega_{sw}) \) of SCIGw is determined from its rotor position \( (\theta_{rw}) \). The tip speed ratio \( (\lambda_{sw}) \) for a wind turbine of radius \( r_w \) and gear ratio \( \eta_w \) at a wind speed of \( V_w \) is outlined as:

\[ \lambda_{sw} = \frac{\omega_{sw} r_w}{\eta_w V_w} \tag{10} \]

For MPT within the wind-turbine-generator system, the SCIGw should operate at the optimum tip speed ratio. Thus, the reference rotor speed \( (\omega_{otw}) \) for MPT is generated using (10) as:

\[ \omega_{otw} = \lambda_{sw} V_w \eta_w r_w \tag{11} \]
The reference rotor speed of SCIG\textsubscript{W} is compared with \( w_{roc} \) to calculate the rotor-speed error \( (w_{roc}) \) at the nth sampling instant. The aforesaid error is fed to the speed proportional integral (PI) controller. At the nth sampling instant, the output of the speed PI controller with proportional gain \( K_{p,o} \) and integral gain \( K_{i,o} \) provides the reference q-axis SCIG\textsubscript{W} stator coil current \( (I^*_{qsw}) \).

2) Reference d-axis SCIG\textsubscript{W} Stator-Current Generation:

The reference d-axis SCIG\textsubscript{W} stator current \((I_{dsw})\) is determined from the rotor flux set point as

\[
I_{dsw(n)} = \phi \cdot drw/L_{mnw} \tag{12}
\]

where \( L_{mnw} \) is the magnetizing inductance of SCIG.

3) Generation of PWM Signal for Machine-Side Converter:

For generation of three-phase reference SCIG\textsubscript{W} stator coil currents, the transformation angle \( \theta \) rotorfluxw is generated where \( \theta_{rotorflux} = \theta_{slipw} + (pw/2) \theta_{rw} \) is the slip angle, that is, generated by integrating slip frequency \( (\omega_{slip}) \). \( \omega_{slipw} \) at the nth sampling instant is generated as

\[
\omega_{slipw(n)} = Rw I^*_{qsw(n)}/Lrw I^*_{dsw(n)} \tag{13}
\]

where \( Lrw \) is the rotor self-inductance and \( Rw \) is the rotor resistance of SCIG\textsubscript{W}. The references for d-q components of SCIG\textsubscript{W} stator currents are converted to three-phase reference SCIG\textsubscript{W} stator currents \((i_{sda}, i_{swb} \text{ and } i_{sce})\) by d-q to abc transformation using angle \( \theta \) rotorfluxw. The three-phase reference SCIG\textsubscript{W} stator coil currents \((i_{sda}, i_{swb} \text{ and } i_{sce})\) are then compared with the sensed SCIG\textsubscript{W} stator currents \((iswa, iswb \text{ and } iswc)\) to compute the SCIG\textsubscript{W} stator current errors, and these current errors are amplified with gain \((K = 5)\) and the amplified signals are compared with a set frequency \((10 \text{ kHz})\) triangular carrier wave of unity amplitude to produce gating signals for the IGBTs of the machine-side VSC. The sampling time of the controller is taken as 50µs, as this time is sufficient for completion of calculations in a typical DSP controller.

The reference three-phase SCIG\textsubscript{H} currents are then compared with the sensed SCIG\textsubscript{H} currents \((isha, ishb, \text{ and } ishc)\) to compute the SCIG\textsubscript{H} current errors. These current errors are amplified with gain \((K=5)\), and the amplified signals are compared with fixed-frequency \((10\text{kHz})\) triangular carrier wave of unity amplitude to produce gating signals for IGBTs of the load-side converter. The sampling time of the controller is taken as 50µs, as this time is sufficient for completion of computations in a standard DSP controller.

### III. DESIGN

A. Turbine

The wind hydro hybrid system being thought of has a wind turbine of 50kW and a hydro turbine of 50 kW respectively. The rating of the SCIG\textsubscript{H} is equal to the rating of the wind turbine, i.e. 50 kW.

B. Selection of voltage of dc link and battery design

The dc-bus voltage \((V_{dc})\) must be more than the peak of the line voltage for satisfactory PWM control as

\[
V_{dc} > 2\sqrt{3}/3 V_{ac} m_a \tag{14}
\]

where \( m_a \) is the modulation index normally with a maximum value of one and \( V_{ac} \) is the rms value of the line voltage on the ac side of the PWM converter. The maximum rms value of the line voltage at the load terminals is 415 V. Substituting this value in \((10)\), \( V_{dc} \) should be more than 677.7 V. The voltage of the dc link and the battery bank is selected as 700 V. The maximum rms value of the line voltage at the load terminals is 415 V. Substituting this value in \( V_{dc} \) should be more than 677 V. The voltage of the dc link and the battery bank is selected as 700 V.

Considering the ability of the proposed system to supply electricity to a load of 60 kW for 10 h, 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 A·h, and the total ampere hour needed is:

\[
(600 \text{ kW} \cdot 10\text{ h}/700 \text{ V}) = 857 \text{ A} \cdot \text{h.}
\]

The number of such sets required to be connected in parallel would be \((857 \text{A} \cdot \text{h} /150 \text{Ah}) = 5.71\) or 6 (selected). Thus, the battery bank comprises of six parallel-connected sets of fifty nine series connected battery cells. Thevenin’s model is used to explain the energy storage of the battery in which the parallel combination of capacitance \((C_b)\) and resistance \((R_b)\) in series with internal resistance \((R_m)\) and an ideal voltage source of voltage 700 V are meant for modelling the battery.

\[
C_b = (Kw.h*3600+1000)/0.5(V_{ocmax}−V_{ocmin}) \tag{15}
\]

Taking the values of \( V_{ocmax} = 750 \text{ V}, \ V_{ocmin} = 680 \text{ V}, \) and \( Kw.h = 600, \) the value of \( C_b \) obtained is 43156 F.

C. Selection of rating of ac inductor and rc filter on ac side of load-side converter
An inductor is used on the ac side of the load-side con-verter for boost function. Inductance (Lf) of the inductive filter can be calculated as

\[ Lf = \left( \frac{\sqrt{3}}{2} \right) n_\omega Vdc / (6a fIr_p Vsc) \]  \hspace{1cm} (16)

where \( f_s \) is the switching frequency and is equal to 10 kHz and \( Ir_p Vsc \) is the peak-to-peak ripple current in the load-side 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 \( ma \) is taken as one. Thus, the value of inductance of the filter is 0.76mH

A high-pass first-order filter tuned at half the switching frequency is used to filter out the noise from the voltage at the load terminals. The time constant of the filter ought to be very less compared with the fundamental time period (T), or

\[ RC < < \frac{T}{10} \]  \hspace{1cm} (17)

When \( T = 20 \) ms, considering, \( C = 5\mu F \), \( R \) is chosen as 5 \( \Omega \). This combination provides a low impedance of 8.1 \( \Omega \) for the harmonic voltage at a frequency of 5 kHz (half of the switching frequency).

D. Selection of specifications of wind turbine and gear ratio

The wind turbine is designed for 50 kW at 11.2 m/s, which is considered as rated wind velocity. For wind speeds below rated wind speed, the mechanical power \( Pm \) captured by the turbine is a function of wind speed \( Vw \), radius of turbine \( rw \), density of air \( \rho \), and coefficient of performance \( Cp \), and is given as:

\[ Pm = 0.5Cp \rho Vw^3 \]  \hspace{1cm} (18)

The maximum coefficient of performance (\( Cp_{max} \)) is achieved optimum tip ratio \( (\lambda_{s_{\omega}}) \). The values of \( Cp_{max} \) and \( \lambda_{s_{\omega}} \) obtained from the Figure. 3.1 are 0.4411 and 5.66, respectively. Substituting, \( Pm = 50 \) kW, \( Cp = 0.4411 \), wind speed \( Vw = 11.2 \) m/s, and density of air \( \rho = 1.1544 \) kg/m3 in 4.1, the radius of the wind turbine \( rw \) is obtained as 7.5m. At 11.2 m/s wind speed, the generator rotor speed is taken into account as 100 rad/s. Substituting the value of tip speed ratio = 5.66, radius of the wind turbine = 7.5 m, wind speed = 11.2 m/s, and generator speed = 100 rad/s, the gear ratio is obtained as

\[ \eta_{\omega} = \omega_{\omega} \omega_{g} / \lambda_{g} \omega_{Vw} \]

= 100 \times 7.5 / 5.66 \times 11.2

= 11.8 \approx \sim = 12 \) (selected).

Above equations are used to simulate wind turbine. In the real turbines above the rated wind speed, the blade-pitch control comes into operation, and the turbine blades are pitched slightly out of the wind to limit power. Conversely, the blades are turned back into the wind whenever the wind drops again. The ratings and therefore specifications of the selected elements of the hybrid system based on the aforementioned design procedure are used for simulation purpose.

E. PV Model

The model consists of a current source, a diode (D), and a series resistance (Rs). In the MATLAB function model for the PV system, relevant equations are encoded as a program. The open circuit voltage per cell is 2000/NS where \( Ns=\) no of series cells= 1000 and the short circuit current per cell is 170A. The open circuit voltage per cell is 2V. The reference temperature of the cell is taken as 298K. The short circuit current is proportional to the intensity of irradiance.

![Figure 3: Equivalent circuit of PV cell](image)

**IV. SIMULATION RESULTS AND DISCUSSION**

Simulation models are developed in MATLAB using Simulink and Sim Power System set toolboxes. The simulation is carried out on MATLAB version 7 with ode3 solver. The electrical system is simulated using Sim Power System. The different loads are modeled using resistive and inductive elements. The unbalanced load is modeled using breakers in individual phases. A balanced linear load at wind speed of 15m/s is connected to the above networks.

In each of three modes, the output waveforms of load voltage, load current and load frequency are studied. The model is working satisfactorily for the above mentioned loads. The waveforms are purely sinusoidal as expected for the above three conditions. Also, under the above conditions both the magnitude and frequency of the load voltage are maintained constant. The obtained waveforms are shown in figures.

![Figure 5: Load voltage waveform for Mode 1](image)
CONCLUSION

Among the renewable energy sources, small hydro, solar and the wind energy have the ability to complement each other. Further, there are many isolated locations which can't be connected to the grid and where the wind, solar and hydro potential exist simultaneously. For such locations, a new three-phase four wire autonomous wind-solar and wind hydro hybrid system using cage generators and PV system along with BESS, has been modeled and simulated in MAT-LAB with Simulink and Sim Power System tool boxes. The design procedure for selection of various components has been demonstrated for the planned hybrid system. The performance of the planned hybrid system has been demonstrated for three modes of operation for linear loads.

REFERENCES


Hybrid Systems: Wind Solar and Wind Hydro Hybrid Systems with Battery storage


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