Stand-Alone Wind Energy Conversion Systems
Feeding Single-Phase Loads

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Abstract—This paper deals with a stand-alone wind energy conversion system (SWECs) employing an isolated asynchronous generator (IAG) and feeding single-phase loads. To achieve maximum power point tracking (MPPT) under change in wind speed, a three-leg voltage source converter (VSC) is used at IAG terminals to facilitate variable voltage variable frequency power generation through an IAG. A battery system is used at intermediate DC bus of VSC and a single-phase voltage source inverter (VSI) to enable load leveling under change in consumer loads. A single-phase VSI provides regulated load voltage at constant frequency. The MATLAB R2007b is used to simulate the proposed SWECs using a discrete step solver. The performance of developed voltage and frequency controller is demonstrated as a load leveler, a harmonic eliminator, a maximum power point tracker and a voltage and frequency controller.

Keywords—Isolated Asynchronous Generator, Battery, Voltage Source Converter, Voltage Source Inverter, Wind Energy

I. INTRODUCTION

An isolated asynchronous generator (IAG) is quite promising up to few kW rating in wind energy conversion system (WECS) due to its simplicity, ruggedness, brushless construction, inherent short circuit protection, high torque/weight ratio and almost maintenance free operation [1]. Moreover, variable speed wind turbines are currently used in WECS technology [2]. The variable speed operation is possible due to the power converters which provide complete decoupling from the grid [3]. Watson et al [4] have proposed first time, the IAG based variable speed WECS for controllable DC power supply. A three-phase controlled rectifier has been used at the generator side to convert variable voltage-variable frequency AC supply to constant voltage DC supply. Raina and Malik [5] have reported the excitation control of an IAG which has been achieved by single value capacitor and thyristor controlled reactor. Simoes et al [7] have described the control strategy, design and performance evaluation of a fuzzy logic based variable speed wind energy conversion using an IAG. The efficiency and performance of the WECS have been optimized using fuzzy logic control. Poddar et al [8] have reported a variable speed controller for a 225 kW IAG based grid integrated wind energy conversion system. Goel et al [9] have reported a voltage and frequency controller for a wind-hydro hybrid system employing IAG’s for stand-alone power generation. However most of work has been reported for grid integration or supplying three-phase consumer loads. Due to the aforementioned advantages, IAG based stand-alone wind energy conversion system (SWECs) is always a prominent choice up to medium rating installations. Moreover, to electrify a remote village, single phase distribution system is preferable to reduce capital investments [10].

This paper deals with a three-phase IAG based SWECs feeding single-phase consumers. A three-phase voltage source converter (VSC) is used at IAG terminals and a single-phase voltage source inverter (VSI) is used to feed single-phase loads.

II. SYSTEM CONFIGURATION

Fig. 1 shows the system configuration of an IAG based SWECs feeding single-phase loads. The mid-point of each leg of a VSC is connected at IAG terminals to convert a variable voltage variable frequency generation in to DC. A single-phase VSI is used to provide regulated voltage and frequency supply to consumer loads. The DC bus of a VSI and a VSC is interfaced and supported with a battery system. The battery system at intermediate DC bus provides the function of load leveling under change in wind speed or consumer load demand. A LC filter is used at the output of VSI to absorb switching ripples. Three-phase VSC also provides reactive power to an IAG to build its reference voltage under change in an IAG speed to achieve maximum power point tracking (MPPT).

![Isolated Asynchronous Generator](image_url)

Fig. 1 System configuration of IAG based SWECs feeding single-phase loads

III. CONTROL SCHEME

Fig. 2 shows the block diagram of control scheme used for a voltage and frequency controller (VFC) of an IAG based SWECs feeding single-phase consumer loads. The control scheme is segregated in two parts defined as control of grid-side converter (GSC) and control of load-side inverter (LSI) as follows.
A. Control of GSC

The GSC is controlled in stator-flux reference frame. The rotor electrical speed \( \omega_r \) is sensed and integrated to obtain rotor position \( \theta_0 \). The wind speed is measured and using a 2-D look table with embedded wind turbine characteristics, the reference rotor speed \( \omega_r^* \) is estimated. These reference and sensed rotor speeds are compared as,

\[
\omega_r(n) = \omega_r^*(n) - \omega_r(n) \tag{1}
\]

The rotor speed error \( \omega_r \) is processed in a proportional-integral (PI) regulator to obtain reference active power component of IAG currents \( I_{q^*}^* \) as follows,

\[
I_{q^*}^*(n) = I_{q^*}^*(n-1) + K_p (\omega_r(n) - \omega_r(n-1)) + K_i \omega_r(n) \tag{2}
\]

The reference d-axis component \( I_{d^*}^* \) of an IAG currents is obtained from rotor flux set point \( (\Psi_{d^*}) \) at and at the \( n^\text{th} \) sampling instant, it is given as,

\[
I_{d^*}^* = \frac{R}{L_{s^*}} / I_{d^*} \tag{3}
\]

or \( I_{d^*}^* = \frac{R}{L_{s^*}} (\omega_0/\omega_0) \) if \( \omega_0 \geq \omega_0 \)

where \( L_{s^*} \) is the magnetizing inductance of an IAG.

For the generation of three-phase reference IAG current \( (i_{d^*}, i_{q^*}, i_{e^*}) \), the transformation angle \( (\theta_0) \) is obtained. For this, the slip speed \( (\omega_s) \) is given as follows [10],

\[
\omega_s = \int \omega_s \, dt
\]

where \( \omega_s \) is the rotor-side resistance, self inductance, reference q-axis component of an IAG currents and reference d-axis component of an IAG currents.

The slip angle \( (\theta_s) \) is obtained after integrating the slip speed \( (\omega_s) \) as follows,

\[
\theta_s = \int \omega_s \, dt
\]

The transformation angle \( (\theta_0) \) is obtained as follows,

\[
\theta_0 = \theta_s + \theta_s
\]

The reference d-q component of an IAG currents are converted to \( (i_{d^*}, i_{q^*}, i_{e^*}) \) using transformation angle as,

\[
i_{d^*} = I_{d^*} \sin(\theta_0) + I_{q^*} \cos(\theta_0)
\]

\[
i_{q^*} = I_{d^*} \sin(\theta_0 - 2\pi/3) + I_{q^*} \cos(\theta_0 - 2\pi/3)
\]

\[
i_{e^*} = I_{d^*} \sin(\theta_0 + 2\pi/3) + I_{q^*} \cos(\theta_0 + 2\pi/3)
\]

These estimated three phase reference IAG currents \( (i_{d^*}, i_{q^*} \text{ and } i_{e^*}) \) are compared with sensed IAG currents \( (i_{d}, i_{q}, \text{ and } i_{e}) \) to compute the current errors \( (i_{d}, i_{q}, \text{ and } i_{e}) \). These computed current errors are processed through a set of PI controllers to generate modulating signals. These modulating signals are compared with fixed frequency (10 kHz) triangular carrier wave to generate gating pulses for six IGBTs of a GSC.

B. Control of Single-Phase LSI

The objectives of controlling single phase LSI are to regulate the output voltage and its frequency. The reference load voltage is given as,

\[
v_{oL}^*(n) = V_{os} \sin(2\pi ft)
\]

where \( V_{os} \) is the maximum value of the reference AC voltage (i.e. 325 V in this case) and \( f \) is the frequency reference of the load voltage (i.e. 50 Hz in this case).

The reference and sensed voltages are compared individually at \( n^\text{th} \) sampling instant as follows,

\[
v_{ocel}(n) = v_{oL}^*(n) - v_{os}(n)
\]

The error voltage \( (v_{ocel}) \) is fed to a PI controller to obtain the reference LSI currents \( (i_{LSI}) \) at \( n^\text{th} \) sampling instant is as follows,

\[
i_{LSI}(n) = i_{LSI}(n-1) + K_p (v_{ocel}(n) - v_{ocel}(n-1)) + K_i v_{ocel}(n)
\]

This reference LSI current \( (i_{LSI}) \) and sensed LSI current \( (i_{LSI}) \) are compared and the current error \( (i_{LSI}) \) is fed to a PI controller to obtain control signals. This control signal is compared with a fixed frequency triangular carrier wave (10 kHz) of unit amplitude to generate the uni-polar switching signals for IGBTs of a single phase LSI.

IV. MATLAB MODEL

The model of the VFC is developed in MATLAB R2007b using discrete step solver with step time 10 µs. The detailed modeling of each part is given as follows,

A. Modeling of Wind Turbine

A generic equation used to model wind turbine is given as,

\[
C_p (\lambda, \beta) = C_1 \left[ (C_2 / \lambda - C_3) \right] e^{C_4 / \lambda} + C_5 \lambda (1/ \lambda) = 1 \left( (\lambda - C_7 \beta) \right) - \left[ C_8 / (\lambda + 1) \right]
\]

where \( C_p \) is the performance coefficient of a wind turbine which is a function of tip speed ratio \( (\lambda) \) and blade pitch angle \( (\beta) \). The \( C_1-C_8 \) are wind turbine constants whose values are given in Appendix.

The mechanical output power \( (P_m) \) of a wind turbine is defined as,

\[
P_m = 0.5 \rho AC_p v_{wind}^3
\]

where \( \rho \) is the specific density of air and \( A \) is the swept area of blades in SI units. \( v_{wind} \) is defined as the wind speed.

B. Modeling of GSC

For a 3.7 kW three-phase IAG, the required reactive power to supply rated active power at unity power factor is nearly 4 kVAR [11]. The apparent rating of a VSC used for a GSC is given as,

\[
S_g = \sqrt{P_g^2 + Q_g^2}
\]
It is obtained as 5.44 kVA. The maximum current through switching devices is $1.25\left(\frac{I_{pp}}{2L_{GSC}}\right)$ [11]. Considering 5% $I_{pp}$ and $I_{GSC}$ is 14.5 A, a three-leg VSC with 25 A, 600 V IGBTs is selected.

### E. Design of LC Filter

The PWM frequency of a single-phase LSI is selected 10 kHz and fundamental load voltage frequency is 50 Hz. For the considered resonant frequency of 1000 Hz, the selected value of LC filter are as $L_d = 3$ mH and $C_f = 10 \mu F$.

### V. Results and Discussion

The performance of an IAG in SWECS under fall in wind speed is shown in Fig. 3. A single-phase LSI is feeding a linear load of 3.7 kW at unity power factor. The wind speed is changed from 12 m/s to 8 m/s at 2 s. Due to reduction in wind speed, there is a fall in an IAG speed to achieve the MPPT. Till rated wind speed, generated power $P_g$ and load power $P_L$ are equal and as wind speed falls, there is a reduction in $P_g$. The BESS is supplying the deficit load power to keep load voltage and its frequency constant.

#### A. Performance of SWECS under fall in wind speed

The performance of an IAG in SWECS under fall in wind speed is shown in Fig. 3. A single-phase LSI is feeding a linear load of 3.7 kW at unity power factor. The wind speed is changed from 12 m/s to 8 m/s at 2 s. Due to reduction in wind speed, there is a fall in an IAG speed to achieve the MPPT. Till rated wind speed, generated power $P_g$ and load power $P_L$ are equal and as wind speed falls, there is a reduction in $P_g$. The BESS is supplying the deficit load power to keep load voltage and its frequency constant.

#### B. Performance of SWECS under Linear Loads

Fig. 4 depicts the performance of a SWECS under linear loads and wind speed is 12 m/s. Due to fixed wind speed, the IAG speed $(\omega_i)$, IAG currents $(i_{abc})$ and its generated power...
(P_L) are constant. Till 1.5 s, a 3.7 kW unity power factor load is supplied through a LSI and the load and generated powers are equal. At 1.5 s, due to complete removal of loads, the load power demand is almost zero. It is observed that even under sharp transition from rated loads to no load, the rms load voltage (V_L) and its frequency (f) are fairly constant. It is observed that the VFC performs as a load leveler.

C. Performance of SWECS under Non-Linear Loads

Fig. 5 shows the performance of a SWECS under non-linear loads at a constant wind speed. A single-phase diode rectifier feeding constant voltage load (R=20 Ω and C=150 μF) is used as a non-linear load. Till 1.5 s, rated load is present at load bus and there is a rated power generation due to which the battery is in floating state. It is observed that even with non-linear load current, the load voltage is sinusoidal. At 1.5 s and 1.6 s
the load is removed and it is connected back to the load bus respectively. It is observed that even with such large load perturbations, load voltage and frequency are fairly constant. Figs. 6 (a-b) show the harmonic spectra of load voltage and current. The THD of load voltage is 2.96% even the load current \( i_o \) THD is 35.83%.

**APPENDIX**

A. **Isolated Asynchronous Generator**

3.7 kW, 230 V, 14.5 A, 50 Hz, Y- Connected, 4-Pole, \( R_s=0.3939 \) Ω, \( R_r=0.4791 \) Ω, \( L_{ls}=2.01 \) mH, \( L_{lr}=2.5 \) mH, \( L_m=76.6 \) mH, \( J=1 \) kg/m\(^2\).

B. **Wind Turbine Data**

\( C_{pmax}=0.48, \lambda_m =8.1, C_1 =0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068, C_7=0.008, C_8=0.035 \). Radius \( r=1.63 \) m, Gear box ratio=3, \( kW=4 \)

C. **VFC Data**

\( L_f =3 \) mH, \( C_f =10 \) μF, \( f_c = 10 \) kHz, \( K_{pw}=1, K_{iw}=4, K_{pv}=0.8, K_{iv}=10 \)

D. **Battery Data**

\( V_{nom}=444 \) V, \( V_{max}= 507 \) V, \( V_{min}=381 \) V, \( C_b=965 \) F, \( R_{in}=0.001 \) Ω, \( R_{b}=10 \) kΩ, 33 units of 12 V, 17 Ah are connected in series and two such strings are connected in parallel. Rated capacity= 15 kWh.

**REFERENCES**


