A Comparative Study of Standalone Wind Energy Conversion System using Permanent Magnet Synchronous Generator on Linear and Non-Linear Load

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Abstract— This work deals with a new control algorithm for a voltage and frequency controller of permanent magnet synchronous generator (PMSG) based stand-alone wind energy conversion system on linear and non-linear loads. The complete system is simulated in MATLAB-Simulink environment. Simulated results demonstrate the performance of VFC as a load leveler, a load balancer, a neutral current compensator and a harmonic eliminator along with voltage and frequency control.

Key words: Battery, Permanent Magnet Synchronous Generator, Load (Linear and Non-Linear), Wind Energy

I. Introduction

The use of permanent magnet (PM) brushless machines are increasing in industry as motors due to their high efficiency, low maintenance, reduced weight, robust and compact construction and wide speed range operation[1-3]. The permanent magnet synchronous generator (PMSG) has been explored with both variable speed and fixed speed wind turbines [4-5].The variable speed PMSG based stand-alone wind energy conversion systems (SWECS'S) requires two back-back connected voltage source converters (VSC'S) with common dc link to feed power to consumers at regulated voltage and frequency[6-8]. Fixed speed PMSG based SWECS require only one VSC to regulate their voltage and frequency [5-6].

This works deals with a control algorithm based on power balance theory for a new topology of voltage and frequency controller (VFC) of PMSG based SWECS. The VFC is implemented using VSC and a battery energy storage system (BESS). A non-isolated star-delta transformer is used at point of common coupling (PCC). The star terminal of star-delta connected transformer serves the purpose of neutral terminal for feeding three-phase four-wire (3P4W) consumer loads.

II. System configuration and principle of operation

Fig. 1 shows the SWECS of the proposed surface mounted PMSG along with its VFC, a battery energy storage system (BESS) and consumer loads. A three-leg VSC is used with a BESS as a VFC. An RC ripple filter is used at point of common coupling (PCC) to suppress the high frequency switching ripple of the VSC. The VSC supplies the reactive power to PMSG to regulate the terminal voltage during application of different kinds of loads and change in wind speeds. With the battery at its dc bus, an active power balance takes place by exchanging the active power under varying wind speeds and loads.

The battery absorbs the surplus power when the PMSG frequency increases above the rated frequency and delivers the deficit power to the PCC when the PMSG frequency decreases below its rated value. The PMSG frequency depends directly on the instantaneous availability of an input wind power and the connected consumer load demand. The VSC consists of IGBTs (Insulated gate bipolar transistors) based three leg half bridge module and along with a BESS. Each leg comprises of two IGBTs and intermediate point of each leg is connected with an individual phase of the generator bus through an inductor. In practice majority of small loads are single phase loads, therefore to feed 3-phase, 4-wire consumers, a non-isolated star-delta transformer is used to create a load neutral terminal in this SWECS.

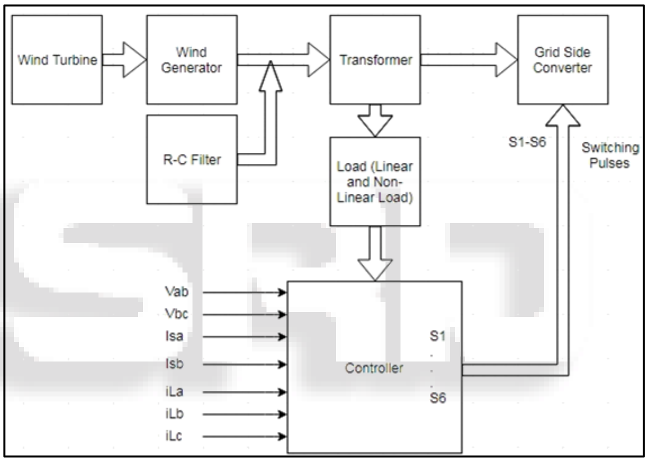


Fig. 1: Block Model

III. Control algorithm

The control algorithm used for the VFC of PMSG based SWECS is the controller is realized using the power balance theory [8]. Using sensed phase voltages va, vb and vc, a set of in-phase (uap, ubp and ucp) and quadrature unit templates (uaq, ubq and ucq) are computed. Three phase load currents (iLa, iLb and iLc) are sensed to compute the active (PL) and reactive power (QL) of the loads and corresponding amplitude of active power component of fundamental load current (ILp) is estimated. The active power component of the fundamental load currents and the output of the PI (Proportional-Integral) frequency controller (Ifp) provide the amplitude of fundamental active power component (I*p) of reference source currents. The amplitude of reactive power component of fundamental load current (ILq) is estimated and using with the output of the PI voltage controller (Iqv) provides an amplitude of the reference fundamental reactive power component (I*q) of the PMSG currents. The product of in-phase unit templates (uap, ubp and ucp) with an amplitude of fundamental active power components (I*p) of the reference source currents provides the three phase reference active power components (i*sap, i*sbp, i*scp) of the PMSG currents. Similarly, the product of quadrature unit templates (uaq, ubq and ucq) with an amplitude of fundamental reference reactive power component (I*q) of the PMSG current gives the three phase reference reactive power components (i*saq, i*sbq, i*scq) of the PMSG currents. The sum of the in-phase (i*sap, i*sbp, i*scp) and the quadrature currents (i*saq,i*sbq, i*scq)

A. In-Phase and Quadrature Unit Templates

1) The in-phase unit templates are derived using amplitude of terminal voltage Vt and instantaneous phase voltages as

$$V_t = \sqrt{2(V_a^2 + V_b^2 + V_c^2)\ /3}$$

$$u_{ap} = \frac{v_a}{v_t},\ u_{bp} = \frac{v_b}{v_b},\ u_{cp} = \frac{v_c}{v_t};$$

Moreover the quadrature unit templates are computed as:

$$u_{aq} = (-u_{bp} + u_{cp}) /\sqrt{3},$$

$$u_{bq} = \{u_{ap}\sqrt{3} + (u_{bp} - u_{cp})\}/2\sqrt{3},$$

$$u_{cq} = \{(-u_{cp}\sqrt{3} + (u_{bp} - u_{cp})\}/(2\sqrt{3})$$

B. Unit templates Quadrature Axis

1) Estimation of Active Power of Loads and Amplitude of Active Power Component of Load Currents

The instantaneous active power of the loads is estimated as,

$$P_L = v_a i_{La} + v_b i_{Lb} + v_c i_{Lc}$$

$$I_{Lp} = (\frac{2}{3})(\frac{\overline{P}_L}{V_t})$$

Active Power of the Load: $P_L = \overline{P}_L + \widetilde{P}_L$

2) Estimation of Fundamental Reactive Power of Loads and Amplitude of Reactive Power Component of Load Currents

The instantaneous reactive power of loads is estimated as,

$$Q_L = \frac{1}{\sqrt{3}}[(v_a - v_b)i_{Lc} + (v_b - v_c)i_{La} + (v_c - v_a)i_{Lb}]$$

$$I_{Lq} = \left(\frac{2}{3}\right)(\frac{\overline{Q}_L}{V_t})$$

Reactive power of the load: $Q_L = \overline{Q}_L + \widetilde{Q}_L$

C. Controller

1) Active Power Component of Reference Source Currents

The output of the frequency PI controller is as:

$$f_e(n) = f_{rf}(n) - f(n) \qquad I_p = I_{fp} - I_{Lp}$$

a) Estimation of Fundamental Three Phase Reference Source Current

$$i_{sap} = u_{ap}\, I_p,\ \ i_{sbp} = u_{bp}\, I_p,\ \ i_{scp} = u_{cp}\, I_p;$$

2) Reactive Power Component of Reference Source Currents

The output of the Voltage PI controller is as,

$$V_e\,(n) = V_{trf}(n) - V_t\,(n)$$

$$I_q = I_{vq} - I_{Lq}$$

a) Estimation of Fundamental Three Phase Reference Source Current

$$i_{saq} = u_{aq}\, I_q,\ i_{sbq} u_{bq}\, I_q,\ i_{scq} = u_{cq}\, I_q$$

3) Generation of Supply Current

The three phase reference source currents are given as,

$$i_{sa}^* = i_{sap} + i_{saq}, i_{sb}^* = i_{sbp} + i_{sbq}, i_{sc}^* = i_{scp} + i_{scq}$$

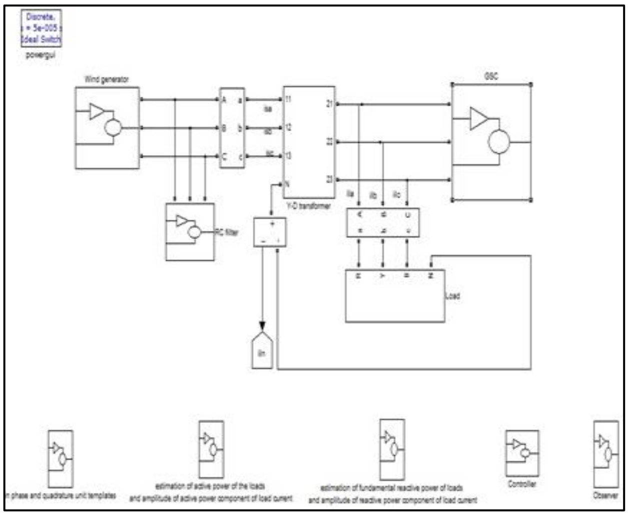


Fig. 2: Matlab based Simulation Model on Linear and Non-Linear Load

IV. MATLAB MODELING OF PMSG BASED SWECS

The MATLAB based model of the PMSG based SWECS consists of a mechanical system, an electrical system, a proposed power balance theory based VFC with consumer loads. The simulation is carried out on the MATLAB version 7.5 using the sim power system (SPS) toolbox and discrete step solver with step time 10µs.

A. Modeling of the Mechanical System

The mechanical power generated by a wind turbine is given as,

$$P_m = 0.5\rho A\ c_p V_w^3$$

Where Vw is the wind speed.

A generic equation is used to model c(λ,β) . The equation based on the modeling turbine characteristics is as:

$$c_p(\lambda, \beta) = c_1(\frac{c2}{\lambda 1} \text{-} c_3 \text{-} c_4)e^{c6/\lambda 1} + c_6\lambda$$

$$\frac{1}{\lambda} = \frac{1}{\lambda + 0.008\beta} - \frac{0.038}{\beta^3 + 1}$$

In the present model β=0.

B. Modeling of the VFC

The VFC consists of a three-leg voltage source converter (VSC) with the battery at its dc link. It consists of three single phase transformers with turn ratio of 1:1:1.

The terminal voltage of the battery is given as follows,

$$V_b = [2\sqrt{2}/\sqrt{3}]\ V_L,$$

Where VL is the line rms voltage of the PMSG. When a capacitor is used to model the battery unit, its capacitance Cb can be determined as follows,

$$C_b = (kwh * 3600 * 10^3)/0.5\ (V_{ocmax}^2 - V_{ocmin}^2),$$

Where vocmax and vocmin are the maximum and minimum open circuit voltage of the battery under fully discharged and fully charged conditions. In the equivalent model, Rin is the equivalent series resistance of the parallel /series combination of a battery, which is usually a small value. The parallel circuit of Cb and Rb is used to describe the stored energy and the resistance responsible for self-discharging.

C. *Modeling of the RC Ripple Filter*

A high pass RC filter tuned at half the switching frequency (5 kHz) is used to filter high frequency switching ripple of VFC at PCC as shown in Fig.1.

V. RESULTS AND DISCUSSION

The proposed control algorithm based on power balanced theory of VFC for fixed pitched wind turbine driven PMSG is used under linear/non-linear three- phase four wire loads. The waveforms of the generated voltage (vs), generator current (Ig), load currents for three phases (iLa), (iLb) and (iLc), frequency f, terminal voltage (Vt), the wind speed (Vw) and Active power of the load (PLreal).

A. *Performance of VFC under Balanced/Unbalanced linear Consumer Loads at Fixed Wind Speed*

In Fig. 3. Three single-phase7.5kW, 0.92 lagging power factor linear consumer loads are connected between each phase and neutral terminal. The wind speed is considered at 12m/s and PMSG is developing its rated power 27 kW. Till 4.1s, the loads are balanced and the battery is charging with surplus power (difference of Pg and PL i.e. 4.5kW). At 4.1s, the load on phase 'b' is removed and the load becomes unbalanced. There is a reduction in consumer load power and BESS is charged with 12 kW. It is observed that even the load currents are unbalanced; the generator currents are balanced and sinusoidal in nature. The consumer loads become balanced again at 4.3s.

B. *Performance of VFC at Non-linear Consumer Loads under at Fixed Wind Speed*

In Fig. 4, three phase diode bridge rectifier with R-L load are used to as non-linear loads. The wind speed is considered as 12m/s. and PMSG is developing its rated power 27 kW. Till 6.9s, the loads are balanced and changed at 7.0s to 8.0s where we observe nonlinear load effects on SWECS and where the battery is charging with surplus power. There is a reduction in consumer load power and BESS is charged. Frequency is a constant and load current are increased on non-linear condition. It is observed that the load currents are unbalanced and the consumer loads become constant again at 8.1s.

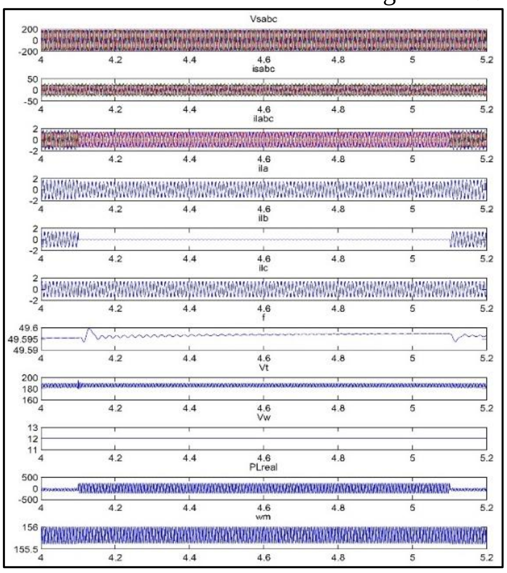


Fig. 3: Result of Standalone Wind Energy Conversion System using Permanent Magnet Synchronous Generator on Linear Load

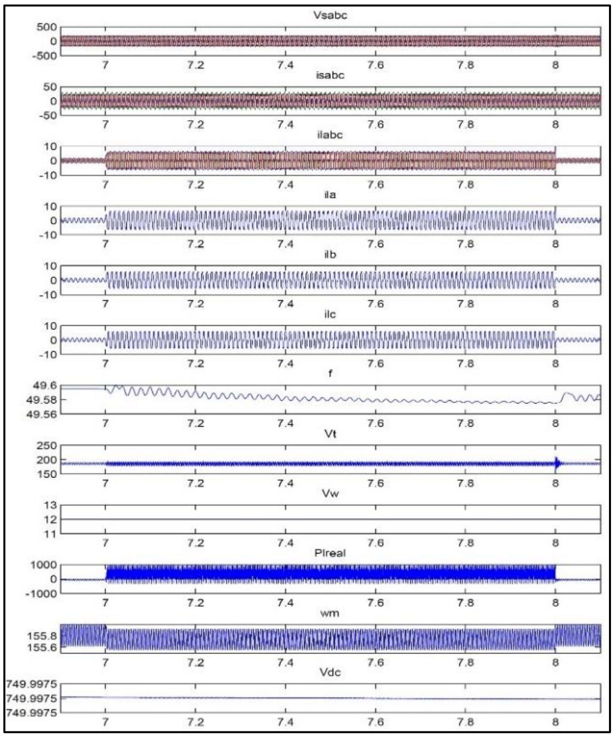
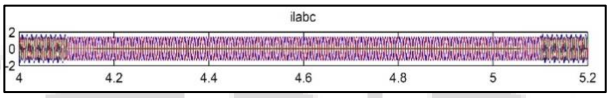
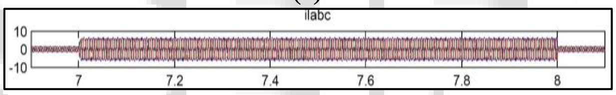


Fig. 4: Result of Standalone Wind Energy Conversion System using Permanent Magnet Synchronous Generator on Non-Linear Load



(a)



(b)

Fig. 5: Result (A) for Three-Phase Load Current on Linear Load And Result (B) For Three-Phase Load Current on Non-Linear Load

VI. CONCLUSION

The performance of VFC for PMSG based SWECS has been demonstrated successfully as a load leveler, a load balancer, a neutral current compensator and a harmonic eliminator along with voltage and frequency controller under LINEAR & NON-LINEAR loads and at fixed wind speeds.

APPENDICES

A. *Permanent Magnet Synchronous Generator*

- 30 kVA,
- 415V,
- 50Hz,
- 4-pole,
- 0.9 pf,
- R=0.03Ω,
- X=0.596Ω,
- Rated flux=1.1T

B. *Wind Turbine*

- 30KW
- J=1.5Kg/m^2
- Cut in speed =8 m/sec

- Rated speed=12m/s,
- Cpmax=0.48
- λm =8.1,

C. VFC Parameters

- L=2.5mH
- Battery voltage vdc=750V
- Cb=25000F
- Rb=10kΩ
- Rin=0.1Ω.

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