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ORIGINAL CONTRIBUTION

Isolated Power Generation System Using Permanent Magnet Synchronous Generator with Improved Power Quality

Sabha Raj Arya[1] · Ashish Patel[1] · Ashutosh Giri[1]

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Abstract This paper deals wind energy based power generation system using Permanent Magnet Synchronous Generator (PMSG). It is controlled using advanced enhanced phase-lock loop for power quality features using distribution static compensator to eliminate the harmonics and to provide KVAR compensation as well as load balancing. It also manages rated potential at the point of common interface under linear and non-linear loads. In order to have better efficiency and reliable operation of PMSG driven by wind turbine, it is necessary to analyze the governing equation of wind based turbine and PMSG under fixed and variable wind speed. For handling power quality problems, power electronics based shunt connected custom power device is used in three wire system. The simulations in MATLAB/Simulink environment have been carried out in order to demonstrate this model and control approach used for the power quality enhancement. The performance results show the adequate performance of PMSG based power generation system and control algorithm.

Keywords Wind turbine · Distribution static compensator (DSTATCOM) · Voltage source converter (VSI) · Battery · Variable speed · Voltage regulation (VR)

✉ Sabha Raj Arya
sabharaj1@gmail.com

[1] Department of Electrical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat 395007, Gujarat, India

Introduction

The wind energy is a renewable source of energy for the generation of electrical power [1, 2]. It is a natural event due to different causes such as heat variation, air stress and the earth rotation stress [3]. It is approved that wind is a type of energy. In a short while, significant debate is being applied to better usage of wind energy because of it being a sufficient, neat, environmentally friendly and costless energy [4]. Topologies like, multi speed wind turbine consists of countless generator converter structure, positioned on price tag, effectiveness, and annual power captures and overall model complication. Multi speed wind turbines based on permanent magnet synchronous generator are examined an appropriate and appropriate mechanics in wind energy system. It is a fact that Permanent Magnet Synchronous Generator (PMSG) is self excited, possible to operate at high power factor and has great effectiveness [5, 6]. Furthermore, the gearbox can be neglected because of its very slow rotational speed. The kinetic energy of the wind is to be converted into the mechanical energy using wind turbine converters for transformation into electricity [7]. One of the major advantages of multi speed wind generators is that it allows the wind turbine to operate at its best tip speed ratio and due to that maximum power efficiency for broad range of wind velocity can be achieved. Out of these various generators, synchronous generators are considered as a best chose. In permanent magnet synchronous generator the necessity of slip rings and contact brushes are also vanished. In comparison to their fixed-speed rotational parts, the multi speed generators allow the wind turbine to operate at the maximum power coefficient for a huge wind velocity range [8, 9]. In this article, a constant and variable wind velocity is considered with introducing the frequency control loop in the proposed control algorithm, so the generated output voltage and frequency remain constant.

Ideally, power distribution company should provide their customers with an undisturbed flow of power with flat sinusoidal voltage at the demanded amplitude level and frequency. Moreover, the distribution networks have lots of loads that are non-linear in nature, which extremely disturb the condition of power supplies [10]. Due to non-linear properties of loads, the clarity of supply current spectra is vanished. This ends up creating huge issues related to quality of power. Power quality interruption can be characterized as the divergence of voltage and the current from its classical waveform [10–12]. The occurring interruptions at the distribution side may cause sag or swell in voltage magnitude either in the full system or a big part of it. Also, due to heavy loading conditions, there may be the possibilities of voltage drop in the network [11, 12]. To solve these problems, the voltage source inverter based compensators have been generally used for harmonics mitigation, to compensate voltage sags and swells, managing the voltage at the load point. Out of many devices, Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Restorer (DVR) are most useful and effective [13]. In comparison with DVR, DSTATCOM is more popular due to nature of distribution system loads [10–13].

Many control techniques have been introduced by many researchers in the literature for shunt compensation. Some of the researchers have discussed the implementation of Phase Lock Loop (PLL) with the help of p-q theory based control algorithm [14]. It is well known that, no one can predict the behaviour of the power system like frequency response, current analysis, voltage magnitude at the bus [15]. So in order to track the frequency response of the waveform and the angle at which all the phases are operated, one need to implement the algorithm based on PLL technique [16]. Many researchers have discussed 1-phase robust PLL in order to capture the network amplitude, phase, and frequency. The main feature of PLL is easily provide error free solution and useful for better synchronization. Higher order PLL allows the fast tracking of signal and at the same time it provides the stable operation of the power system under abnormal condition. In order to extract the reference fundamental positive sequence currents, different types of PLL techniques are used such as modified synchronous reference frame (SRF) based PLL, advanced PLL and phase lock loop technique based on Adaptive Linear Optimal Filter (ALOF) PLL etc. [14–17]. Some researchers have discussed different techniques for the extraction of positive sequence component of grid voltage under abnormal conditions in power system. Same techniques are used for synchronisation of various grid connected distributed power generation system such as Q-PLL, DSOGI-FLL and EPLL etc. [17–19]. The DSOGI-FLL and DEPLL based algorithm have been used in order to eliminate the phase error due to the unbalance and harmonics in the distribution system [20]. The fundamental frequency component extraction is implemented by Singh and Arya [21]. It is based on single phase enhanced PLL for three phase three wire AC distribution system. However, these control algorithms are capable to contribute accuracy in case of weak AC power system. Moreover, it will take more computational time due to three single phase operation in three-phase circuits.

In this paper, in order to overcome the problem of loss due to phase and computational error of the control technique, an advanced version of three phase Advanced Enhanced Phase-Locked Loop (AEPLL) based controller have been proposed. AEPLL technique is used for getting an error free calculation of fundamental frequency of symmetrical component signals attributes. Moreover, feature of the proposed three phase AEPLL algorithm is that, it provides error free calculation, high accuracy and stable operation of the power system under abnormal condition. The other key factor of this control algorithm is as follows [19].

(1) In order to have desired damping and speed, one need to incorporate Zero Sequence Selectors (ZSS).
(2) Zero sequence selectors do not cause error in the system performance.
(3) The degree of performance for the controlled algorithm is decided by the internal parameters.

System Configuration and DSTATCOM

The PMSG based power generation system is developed with wind energy conversion system. The design data for the modelling of wind turbine, Drive Train and PMSG is given in Appendix. A DSTATCOM is used in this DPGS (distributed power generation system) for power quality improvement. The major component of the DSTATCOM is converter based on voltage source (VSC), a capacitor or a battery at the input of the voltage source converter to provide energy. It is connected at the load point, which is generally known as Point of Common Interface (PCI). The feature of DSTATCOM is to provide reactive power compensation at load end, elimination of harmonics which are generated due to the non-linearity in load. It is also used to regulate terminal voltage at the PCI through PI regulator. Figure 1 shows the schematic diagram of distribution static compensator, it is connected to system network at PCI through interfacing inductor. The three phase thyristorised rectifier and reactive load with lagging power factor is modelled as nonlinear and linear load respectively.

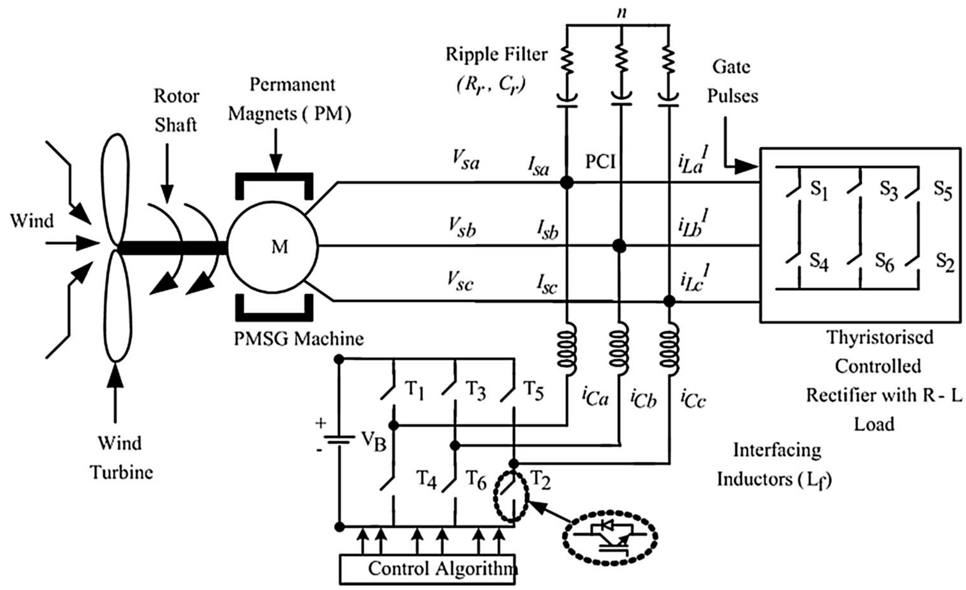


Fig. 1 Schematic diagram of DSTATCOM with PMSG configuration

The firing angle α chosen for the switching of the semiconductor switch in nonlinear load is 20°. The main purpose of using interfacing inductor (L_f) at AC side of the Voltage Source Converter (VSC) is to minimize the ripple content of the compensating current for better performance of DSTATCOM. A three phase series RC filter is used at PCI to eliminate high switching frequency noise. This is connected in shunt with the loads and the DSTATCOM. The profile of the compensating currents (i_{Ca}, i_{Cb}, i_{Cc}) injected by the distribution static compensator is such that it will cancel the harmonics and also to manage the voltage at its rated value. It injects required amount of reactive power at PCI.

Control Algorithm of DSTATCOM

Figure 2 shows the block diagram of proposed control algorithm which is based on AEPLL technique for estimating the reference source currents. Basic mathematical for calculation of various control signals of this algorithm are given as follows.

Computation of In-Phase and Quadrature Unit Voltage Templates [20, 21]

Three phase sensed PCI voltages are V_{sa}, V_{sb} and V_{sc}. In-phase unit templates calculation of PCI voltages as follows,

$$u^1_{sap} = \frac{V_{sa}}{V_t}, \quad u^1_{sbp} = \frac{V_{sb}}{V_t}, \quad u^1_{scp} = \frac{V_{sc}}{V_t} \tag{1}$$

The quadrature unit templates calculation of PCI voltages as follows,

$$u^1_{saq} = \left(\frac{-u^1_{sbp} + u^1_{scp}}{\sqrt{3}}\right), \quad u^1_{sbq} = \left(\frac{3u^1_{sap} + u^1_{sbp} - u^1_{scp}}{2\sqrt{3}}\right)$$
$$u^1_{scq} = \left(\frac{-3u^1_{sap} + u^1_{sbp} - u^1_{scp}}{2\sqrt{3}}\right) \tag{2}$$

So, now the amplitude of PCI voltages (V_t) is computed as follows,

$$V_t = \sqrt{\frac{2\left(V^2_{sa} + V^2_{sb} + V^2_{sc}\right)}{3}} \tag{3}$$

The amplitude of (V_t) contains average value and oscillation component due to the presence of negative sequence component in PCI voltages. For remove of oscillating component from the PCI voltages, it is processed through the low pass filter.

Computation of Fundamental Active and Reactive Power Components of Load Currents [19]

AEPLL controlled algorithm is used to extract the fundamental components of three phase load currents. Used AEPLL accept the input signal as the phase ˋaˊ load current component i^1_{La}, phase ˋbˊ load current component i^1_{Lb}, and phase ˋcˊ load current component i^1_{Lc}. After applying the AEPLL controlled algorithm, one can able to extract the positive sequence (o_1), negative sequence (o_2), and zero sequence (o_o) components of the three phase load currents. Extracted the positive, negative and zero sequence components of load currents are added together and subtracted from the total actual value of load current. After comparing error is generated and it can be defined as an ˋe^1ˊ. It is

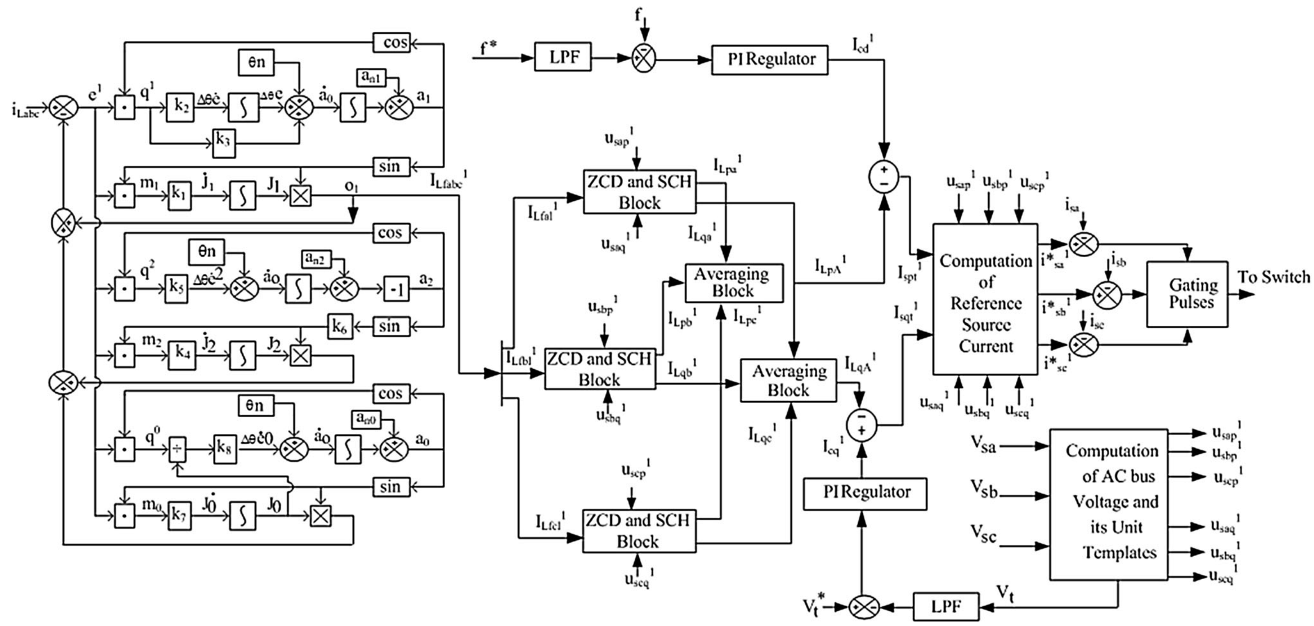


Fig. 2 Control technique based on AEPLL control algorithm

considered as a feed back signal. The accuracy of announced controlled algorithm mainly depends upon the internal parameters of the controlled algorithm. The internal parameter of control algorithm is considered as k_1, k_2, k_3, k_4, k_5, k_6, k_7, and k_8. This all parameters k_1 to k_8 control the steady state and transient behaviour of advanced enhanced phase-lock loop technique. In this application, the selected values of k_1, k_2, k_3, k_4, k_5, k_6, k_7, and k_8 are used as 25, 25, 1, 25, 1, − 1, 25, and 1 respectively. So, after applying AEPLL algorithm, it is possible to consider only positive sequence fundamental component (I^1_{Lfabc}) from the three phase load current. These generated positive sequence fundamental component (I^1_{Lfabc}) of load currents are separated as I^1_{Lfa1}, I^1_{Lfb1} and I^1_{Lfc1} in respective three phases using de-mux block. The generated fundamental component of load current (i^1_{Lfa1}) is in phase with the input signal of phase 'a' load current (i^1_{La}). This is true for other phases. The generated fundamental component of phase 'a' load current (i^1_{Lfa1}), it is running with certain phase difference with the reference in-phase template (u^1_{sap}). Similar process can be observed in other two phases. In order to have the required amplitude of real power component of load currents which is having fundamental value, in phase with the PCI voltage, one needs to track the zero crossing point of the input PCI voltages for improving the degree of proposed controlled algorithm. For that quadrature component of phase 'a' (u^1_{saq}) is processed through the zero crossing detectors. The captured sample signal (i^1_{Lfa1}) can be considered as a reference of sample and hold circuit and the output of the zero crossing detectors (ZCD) are going to be used as triggering pulses for the sample and hold circuits. The derived output signal after the sample and hold circuit is going to be considered as a required magnitude of 'a' phase real power component. This contains only fundamental component value and that it is represented as a (I^1_{Lpa}). Similar process can be done for phase 'b' and phase 'c', which is required for getting fundamental real power components of load current (I^1_{Lpb}) and (I^1_{Lpc}).

Similar, process has to be carried out in order to get the reactive power component of load current of phase 'a' (i^1_{La}), it is considered as reference input of sample and hold circuit and in phase unit template (u^1_{sap}) is considered as input of another zero crossing detector. The extracted output signal from the ZCD is going to used in Sample and Hold Circuit (SCH) as a triggering signal. The generated output signal from the sample and hold circuit will be is considered as a magnitude of 'a' phase reactive power component (I^1_{Lqa}). It is considered as fundamental component. Similar process can be done for phase 'b' and phase 'c' for extraction of reactive power current components as I^1_{Lqb} and I^1_{Lqc} respectively.

Computation of Required Magnitude of Real and Reactive Power Components of Load Currents

In order to compute the required average magnitude of real and imaginary power current components, one can need to add the fundamental components of real and imaginary power of three individual three phases. So, by adding the fundamental real power component (I^1_{Lpa}), (I^1_{Lpb}), and (I^1_{Lpc}) for respective phases as follows,

$$I^1_{LpA} = \left(\frac{I^1_{Lpa} + I^1_{Lpb} + I^1_{Lpc}}{3}\right) \quad (4)$$

Now, by adding the fundamental reactive power component (I^1_{Lqa}), (I^1_{Lqb}), and (I^1_{Lqc}) for respective phases as follows,

$$I^1_{LqA} = \left(\frac{I^1_{Lqa} + I^1_{Lqb} + I^1_{Lqc}}{3}\right) \quad (5)$$

This generated magnitude of real and imaginary powers components, which is having fundamental value, is going to be used for balancing the load.

Computation of Magnitude of Real Power Components of Reference Source Currents

In order to get the total required magnitude of real power component of reference source currents, it is required to take the reference frequency of supply network. Then it is going to be compared with the sensed frequency of the network. The frequency of the supply network is processed through Proportional Integral (PI) controller which is helpful in order to regulate the frequency of the supply network during load unbalancing and some disturbances. It is represented as a (I^1_{cd}). The required magnitude of real power component of the reference source current (I^1_{spt}) is estimated after the subtraction of average amplitude of real power components of load currents (I^1_{LpA}) from the (I^1_{cd}) as follows,

$$I^1_{spt} = I^1_{cd} - I^1_{LpA} \quad (6)$$

Computation of Magnitude of Reactive Power Components of Reference Source Currents

In order to get the total required magnitude of reactive power component of reference source currents, it is required to take the reference terminal voltage (V_t^*) at the Point of Common Interfacing (PCI) is going to be compared with the sensed voltage (V_t) at PCI. The generated error is processed through proportional integral (PI) controller in order to maintain the terminal voltage at its rated value. It is represented as (I^1_{cq}). The magnitude of the reactive power component of the reference source current (I^1_{sqt}) is computed after subtracting (I^1_{LqA}) component from the (I^1_{cq}) as follows,

$$I^1_{sqt} = I^1_{cq} - I^1_{LqA} \quad (7)$$

This generated component (I^1_{sqt}) is used for generation of reference reactive power components of source currents. This generated (I^1_{sqt}) component is also called as a leading reactive component, which will be used to manage the terminal voltage at the load point or at the point of common interfacing.

Computation of Reference Source Currents and Gate Pulse Generation Schemes

In order to generate the reference source currents, it is required to consider four quantities like magnitude of real power components of current (I^1_{spt}), magnitude of reactive power components of current (I^1_{sqt}), in phase unit templates of voltage (u^1_{sap}), (u^1_{sbp}), and (u^1_{scp}) and quadrature unit templates of voltage (u^1_{saq}), (u^1_{sbq}), and (u^1_{scq}) of three phases. By using these four quantities, one can generate the reference source currents as follows,

$$I^1_{sap} = I^1_{spt} u^1_{sap}, \quad I^1_{sbp} = I^1_{spt} u^1_{sbp}, \quad I^1_{scp} = I^1_{spt} u^1_{scp} \quad (8)$$

$$I^1_{saq} = I^1_{sqt} u^1_{saq}, \quad I^1_{sbq} = I^1_{sqt} u^1_{sbq}, \quad I^1_{scq} = I^1_{sqt} u^1_{scq} \quad (9)$$

In order to have total reference source currents, its required to add reference real and reference reactive power components of source currents as follows,

$$i^{*1}_{sa} = I^1_{sap} + I^1_{saq}, \quad i^{*1}_{sb} = I^1_{sbp} + I^1_{sbq}, \quad i^{*1}_{sc} = I^1_{scp} + I^1_{scq} \quad (10)$$

These generated 3-phase reference source currents (i^{*1}_{sa}, i^{*1}_{sb}, i^{*1}_{sc}) are compared with the actual source currents (i^1_{sa}, i^1_{sb}, i^1_{sc}) to find out the errors due to difference. These generated errors are processed through PI controller in order to amplify those errors. These amplified errors are compared with carrier signal for generation PWM pulses of VSC.

Results and Discussion

The objective of this article is to improve the power quality in PMSG based power generation system. A distribution static compensator with AEPLL technique is used in order to remove the issues related power quality in isolated distributed power generation system. This model is tested with 7 KW wind turbine generator system. Data used in software implementation is given in Appendix. In simulated model, it is assumed that the velocity of wind is fixed at 15 m/s and it remains constant through out the time period. One can observe that at the fixed wind velocity of 15 m/s the rotor speed is settled around 300 r.p.m. after some dynamics. The generated output voltage by the PMSG is 415 V (L–L) at constant velocity of wind. As the velocity of wind is constant the frequency of the generated output voltage is also constant. Figure 3 shows the waveform of wind velocity, mechanical torque, electromagnetic torque, generated voltage and rotor speed respectively.

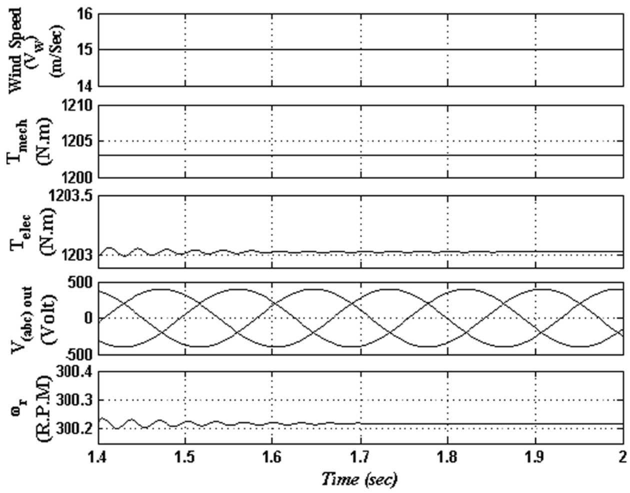
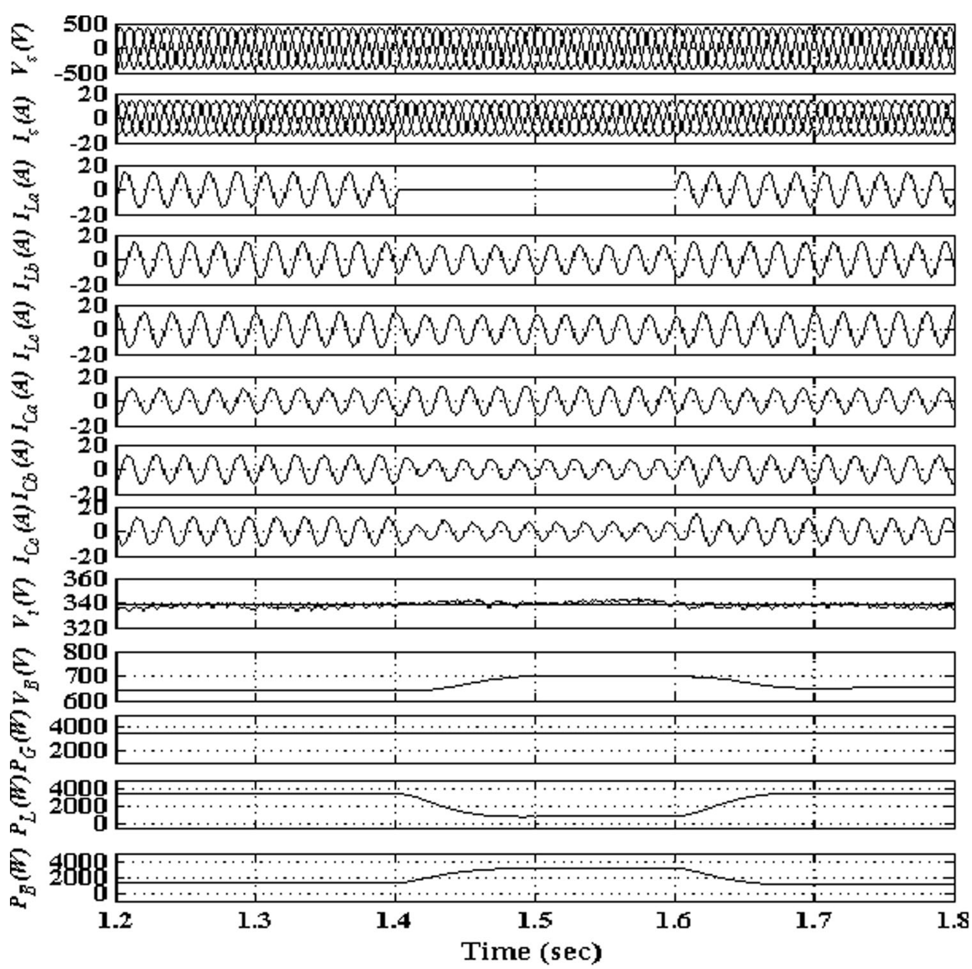


Fig. 3 Performance analysis of wind affected factor

Performance of DSTATCOM Under Linear Load Condition with Fixed Wind Velocity

It is a fact that linear loads are not going generate any harmonics into the network. However, when there is a sudden change in loading condition like injection and removal of very heavy inductive load, removal and injection of capacitive load, and opening of any one of the phase of load circuit. In this case opening of phase 'a' is done by using breaker. So, when such types of condition occur, it is required to take care of the terminal voltage to the point at which load is connected. Because such type of events always allows the voltage sags and swells at the load point due to the injection and removal of reactive demand by the load. After observing Fig. 4 on can see that, at a time period (t = 1.4 s to t = 1.6 s) disturbance is going to be applied by opening the phase 'a', which is connecting to the load. At that time, load current of phase 'a' (I_{La}) becomes zero and other phases are also disturbed due to the dynamic condition of load. So, during the time period (t = 1.4 s to t = 1.6 s), the voltage at the load terminal is increased by some value. In order to manage that terminal voltage (V_t) at the load point, the DSTATCOM must inject the required amount of reactive power as a function of compensating currents (I_{Ca}, I_{Cb}, I_{Cc}) such that it will manage the terminal voltage (V_t) to its rated value. In the voltage managing modes of operation, the value of PCI

Fig. 4 Dynamic performance of DSTATCOM under time varying linear loads in VR mode of operation



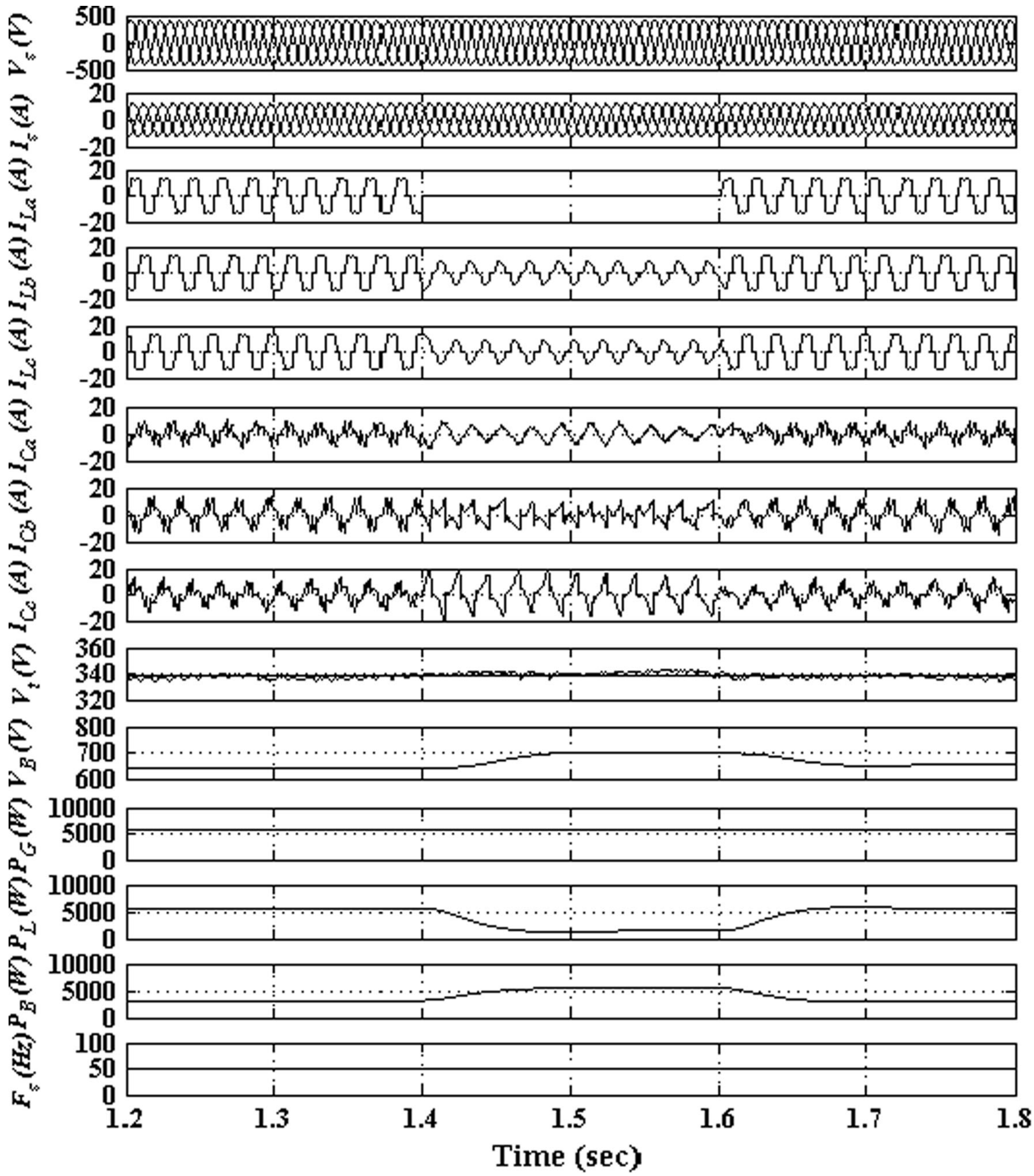


Fig. 5 Dynamic performance of DSTATCOM under time varying non-linear loads in VR mode of operation

phase voltage, source current and load current are 337.7 V, 13.08 A, 13.50 A respectively. Total Harmonic Distortions (THDs) of the phase 'a' at PCI voltage, source current and load current are 1.87, 4.10 and 1.3% respectively.

For the proper functioning of the custom power device like DSTATCOM, battery is connected at the input of the voltage source converter. So, when the battery is providing active power to the voltage source converter, the voltage of battery (V_B) is going to be reduced as shown in same figure. Moreover, during the time period (t = 1.4 s to t = 1.6 s), unbalance is applied in loading condition by opening the phase 'a' of load, at that time load power (P_L) requirement will be reduced and the remaining power from the source is being diverted to the voltage source converter side in order to charge the battery voltage to its required rated value (V_B). The battery power (P_B) is going to be increased to its required value and generated power (P_G) remains at its fixed value. So, by examine Fig. 4 one can say that, the machine is operated at constant power mode.

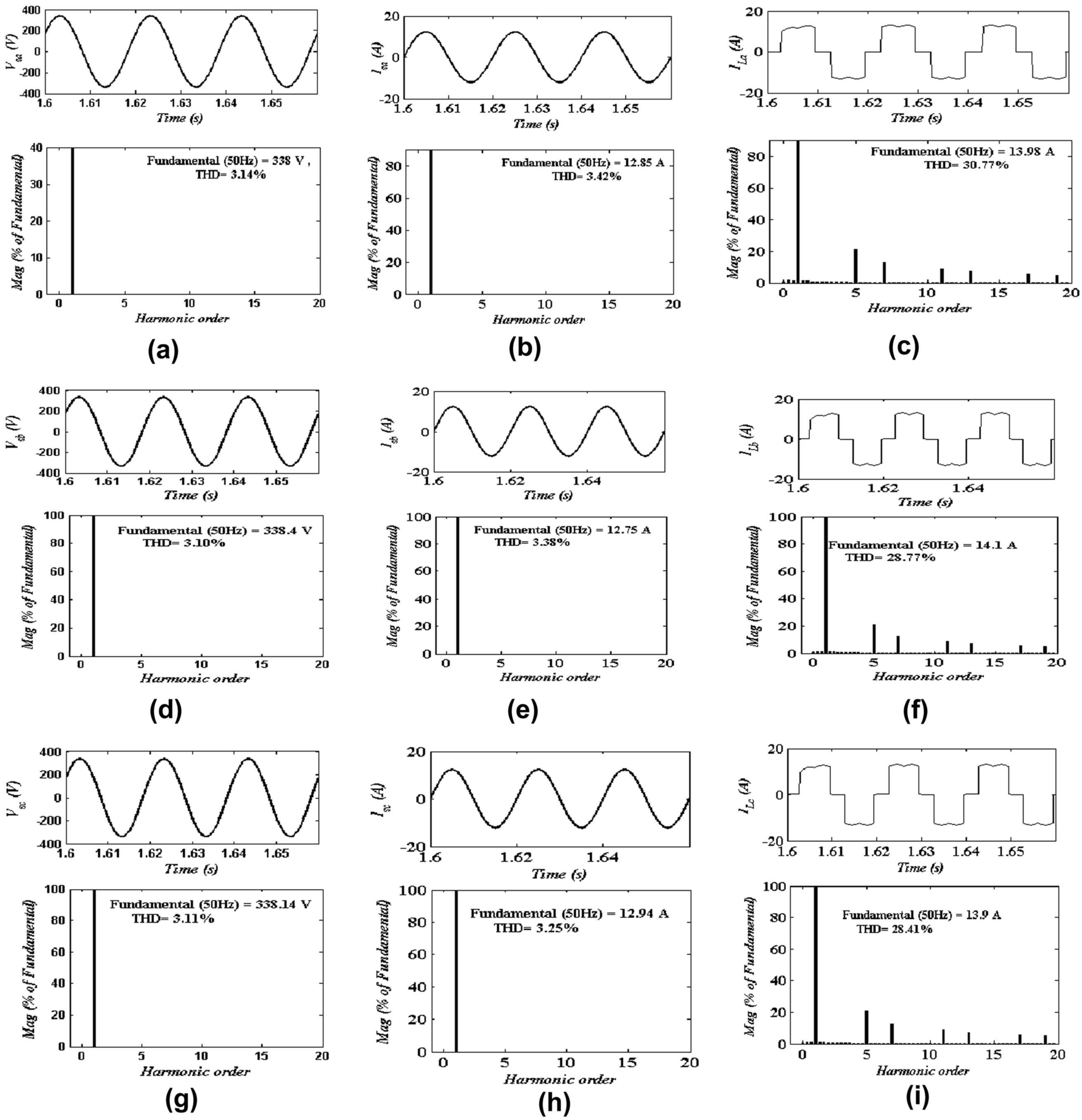


Fig. 6 Waveforms and harmonic spectra of **a** PCI voltage of phase "a", **b** source current of phase "a", **c** load current of phase "a", **d** PCI voltage of phase "b", **e** source current of phase "b", **f** load current of phase "b", **g** PCI voltage of phase "c", **h** source current of phase "c" and **i** load current of phase "c" in VR mode

Performance of DSTATCOM Under Non-linear Load Condition with Fixed Wind Velocity

The waveform spectra of load current (I_{La}, I_{Lb}, I_{Lc}) and waveform spectra of source current (I_{Sa}, I_{Sb}, I_{Sc}) is same before compensation due to non-linearity in load. It contains significant amount of harmonic distortion. After examining Fig. 5, it can be observed in order to reduced the harmonics content of the source currents waveform, DSTATCOM will inject the required spectra of compensating current (I_{Ca}, I_{Cb}, I_{Cc}) such that only fundamental frequency component appeared in the supply waveform. Shunt connected DSTATCOM injects exactly anti-phase component of harmonics spectra. The addition of source current waveform (I_S) and compensating currents (I_{Ca}, I_{Cb}, I_{Cc}) injected by the DSTATCOM, all the higher order

Table 1 Performance of DSTATCOM with distributed power generation system under fixed speed

Performance indices	Linear load	Nonlinear load
Phase 'a' PCI voltage (V), %THD	337.7 V (1.87%)	338 V (3.14%)
Phase 'a' source current (A), %THD	13.08 A (4.10%)	12.85 A (3.42%)
Phase 'a' compensator current (A)	10.24 A	10.50 A
Phase 'a' load current (A), %THD	13.50 A (1.30%)	13.98 A (30.77%)
Phase 'b' PCI voltage (V), %THD	338.4 V	338 V (3.10%)
Phase 'b' source current (A), %THD	13.08 A	12.75 A (3.38%)
Phase 'b' compensator current (A)	9.24 A	9.98 A
Phase 'b' load current (A), %THD	13.50 A	14.18 A (28.77%)
Phase 'c' PCI voltage (V), %THD	337.7 V	338.1 V (3.11%)
Phase 'c' source current (A), %THD	13.08 A	12.94 A (3.25%)
Phase 'c' compensator current (A)	10.75 A	10.25 A
Phase 'c' load current (A), %THD	13.50 A	13.9 A (28.4%)
DC bus voltage (V)	700 V	700 V

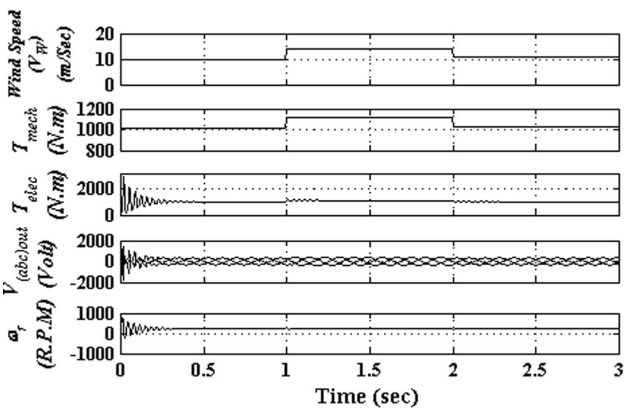


Fig. 7 Parameters variation of PMSG under varying wind velocity

harmonics generated due to the non-linear property of load will be vanished from source current. At a time period (t = 1.2 s to t = 1.4 s), in order to fulfil the load power demand (P_L), source power (P_G) is delivered to the load. Thus, during that period of time, the battery voltage (V_B) or battery power (P_B) is reduced because it is the device that can provide real energy to the voltage source converter for the proper functioning of DSTATCOM. At a time period of (t = 1.4 s to t = 1.6 s), phase 'a' of the load will be removed, so during that time of duration, load current spectra (I_{La}, I_{Lb}, I_{Lc}) will also change and at the same time compensating current spectra (I_{Ca}, I_{Cb}, I_{Cc}) can also follow the load profile i.e. injected profile of the compensating current will also be changed due to the change of load spectra (I_{La}, I_{Lb}, I_{Lc}) due to opening of phase 'a' of the load, load power (P_L) requirement will be reduced and during that time source power is being diverted to the converter side in order to charge the battery voltage (V_B) to its required value. At the same time, frequency control regulation is also needed for the better power quality. In the voltage managing modes of operation, the value of PCI phase voltage, source current and load current are 338 V, 12.85 A, 13.98 A respectively. As shown in Fig. 6a–i THDs in PCI voltage, source current and load current for phase 'a' are 3.14, 3.42 and 30.77% respectively. Similarly THDs in PCI voltage, source current and load current for phase 'b' and 'c' are 3.10, 3.38, 28.77 and 3.11, 3.25, 28.41% respectively The performance of DSTATCOM with linear and nonlinear load is shown in Table 1.

Performance of DSTATCOM Under Non-Linear Load Condition with Variable Wind Velocity

When the wind velocity is fixed then the generated output voltage by the PMSG and frequency of the source voltage will be also be constant. As wind velocity is always changing naturally from time to time. The study of generated voltage and frequency of the PMSG is required. The Simulation results of various performance parameters with variable wind velocity are shown in Fig. 7. During the time period (t = 0 s to t = 1 s), the wind velocity is set at 10 m/s. For transient analysis at time (t) = 1 s to 2 s wind velocity is set at 15 m/sec and from t = 2 s onwards wind velocity is set at 12 m/sec. Now from the graphs, it is clear that generated voltage envelope is more at time (t = 1 s to t = 2 s) as compared to lower wind speed. With the changing wind speed condition, the generated electromagnetic torque (T_{elec}), generated mechanical torque (T_{mech}) and the rotor speed (ω_r) are also changing as shown in Fig. 7.

It is also observed from Fig. 8 that, due to the non-liner properties of the load, harmonic content in the source current would be very high. In order to compensate it, the

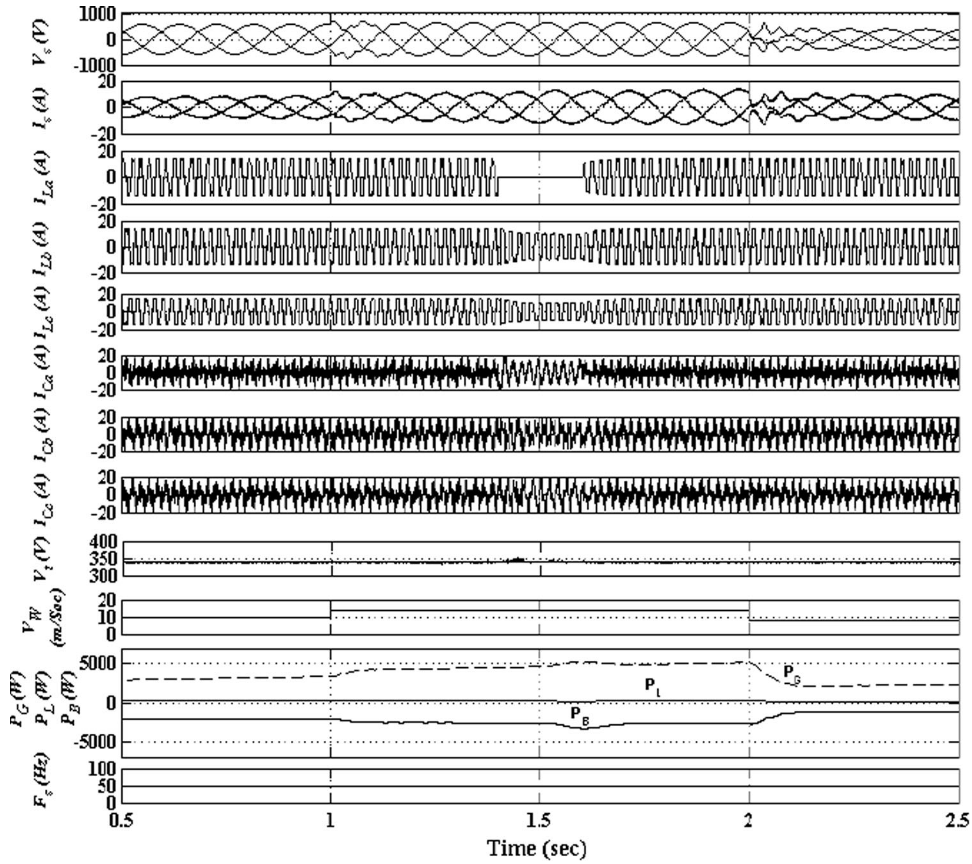


Fig. 8 Dynamic performance of DSTATCOM under time varying non-linear loads in VR mode of operation with varying wind speed

DSTATCOM has injected the required compensating current (I_{Ca}, I_{Cb}, I_{Cc}) such that harmonics in the supply current are reduced below the allowable limits during single phasing (Phase 'a' open) created at the time (t) = 1.4 s to (t) = 1.6 s. The terminal voltage at the load point is maintained at its rated value (V_t). Now, as the wind velocity vary, power generated by the PMSG (P_G) will also vary and at the same time battery power (P_B) has also changed. When wind velocity is increased during the time (t) = 1 s to (t) = 2 s, the generated power (P_G) is more than the power consumed by the load then excess power is stored in the battery via DSTATCOM. When single phasing occurs between the duration of (t) = 1.4 s to (t) = 1.6 s, the excess generated power (P_G) is taken by the battery connected through DSTATCOM to maintain the supply frequency and terminal voltage (V_t).

Conclusion

A control technique based on AEPLL has been developed for the power quality improvement in wind based power generation system. It is used in DSTATCOM for compensation of non-linear loads under fixed and variable wind speed. After observing the performance, it is concluded that a DSTATCOM is able to perform its duty like harmonics elimination, frequency control, and maintenance of the terminal voltage at the PCI. This is carried out by injecting required amount of KVAR. The simulated graphs demonstrate the rapid response and capturing of fundamental frequency components of load currents under dynamic condition. THD of source currents has been observed and found to be acceptable limit of 5%. The response of DSTATCOM and proposed control technique has been found satisfactory during varying load conditions.

Appendix

KW Wind Turbine Parameters

Rotor diameter: 10 m, rotor rated speed: 300 r.p.m, cut-in wind speed: 3 m/s, rated wind speed: 15 m/s, inertia: 18 kg m^2.

The $f_p(\lambda)$ curve of the wind turbine can be expressed approximately using the following polynomial equation [1]:

$$f_p(\lambda,\beta) = f_1\left[\frac{f_2}{\lambda_i} - f_3\beta - f_4\right] e^{\frac{f_5}{\lambda_i}} + f_6\lambda \qquad (11)$$

where, $f_1 = 0.5176$, $f_2 = 116$, $f_3 = 0.4$, $f_4 = 5$, $f_5 = 21$, $f_6 = 0.0068$, tip speed ratio (λ) = 0.54, pitch angle (β), internal coefficient (λ_i) and optimum value of power coefficient (f_{pmax}) = 0.495.

KW PMSG Parameters

Rated phase voltage: 240 V, line current (rated): 16.86 A, rated frequency: 50 Hz, rated speed: 300 r.p.m, $L_d^1 = L_q^1 = 15$ mH, magnetic flux: 0.80 Wb, $R_s = 1.8$ O, pole pairs: 10, inertia: 0.140 kg m^2.

DSTATCOM Parameters

Supply: 3-phase, 415 V (L–L), 50 Hz; load: (1) linear: series connected resistive and inductive load operated at 7.5 kVA with p.f. 0.8 (lagging); (2) non-linear: Three phase thyristorised rectifier load with firing angle ($\alpha = 20°$) connected to RL load with value R = 29 Ω, L = 70 mH; battery voltage (V_B): 700 V; interfacing inductor (L_f) = 3 mH, sampling time (t_s) = 100 µs, cut off frequency of low pass filter used in frequency loop = 2nd order, 14 Hz, ripple filter: $R_f = 4.5\Omega$, $C_f = 10$ µF, cut off frequency of low filter used in amplitude of terminal voltage: 2nd order, 11 Hz, gains of PI controller for frequency controlled loop: $k_{pd} = 1.968$, $k_{id} = 2.85$; gains of ac voltage PI controller: $k_{pq} = 4.5$, $k_{iq} = 0.5$.

The Relation between Wind Speed, Power and Mechanical Torque

The wind power acting on the swept area, A, of the blade is a function of the air density ρ and the wind speed V_w. The transmitted power P_m is generally deduced from the wind power using the power coefficient F_p, as:

$$P_m = (1/2)F_p(\lambda)A\rho V_w^3 \quad (12)$$

The power coefficient is a non-linear function of the tip speed ratio λ which depends on the wind velocity and the rotation speed of the shaft ω.

$$\lambda = (R\omega/V_w) \quad (13)$$

where, R represents the blade radius. As the wind turbine and generator shafts are directly coupled, there is only one state variable. So, that relation between wind speed, electromagnetic torque, and mechanical torques are related as:

$$(d\omega/dt) = (1/j)(T_m - T_e - f\omega_m) \quad (14)$$

where, T_m is the mechanical torque, T_e is the electromagnetic torque, ω is the mechanical speed of the rotor, j is the moment of inertia and f is the coefficient of viscous friction.

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