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CURRENT HARMONICS MITIGATION FROM GRID CONNECTED VARIABLE SPEED WIND TURBINE DUE TO NONLINEAR LOADS USING SHUNT ACTIVE POWER FILTER

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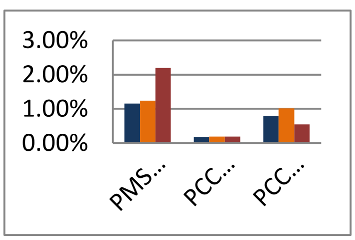
Graphical abstract



Abstract

The quality of power nowadays is of great concern due to increasing demand of supply and energy resources are limited, another cause is increasing penetration of nonlinear loads in the power system. In order to overcome energy supply challenges, the focus of technologists is shifting to the renewable energy side such as the wind and solar energy and so on. As such, mitigating effect of nonlinear loads have become ever important as well. In this context, various techniques have been used by researchers in past decades. Shunt active power filter (APF) have long been used to mitigate current harmonics from fixed wind turbine generator (WTG). In this study shunt APF has been applied with variable speed WTG using synchronous reference frame (SRF) for the extraction of compensation signal for APF. Gate driver signals are generated from Bang-Bang Controller (Hysteresis Band Current Controller HBCC). A MATLAB/SIMULINK based Model have been developed. The Simulation results show decreased THD levels of the system and clearly suggest the effectiveness of Shunt APF in meeting the IEEE-519 standard recommendation for harmonic levels in WTG.

Keywords: Wind Turbine Generator, Shunt Active Power Filter, Synchronous Reference Frame, THD

Abstrak

Kualiti kuasa mendapat perhatian yang tinggi kerana permintaan yang semakin meningkat sumber bekalan dan tenaga adalah terhad, punca lain dikuatkan penembusan beban tak linear dalam sistem kuasa. Untuk mengatasi mandat tenaga, teknologi beralih ke bahagian tenaga boleh diperbaharui; angin atau solar, dan sebagainya. Untuk mengurangkan kesan beban linear pelbagai teknik telah digunakan oleh penyelidik dalam beberapa dekad yang lalu. Ulama pirau digunakan kuasa aktif penapis (APF) untuk mengurangkan harmonik semasa daripada penjana turbin angin tetap (WTG), dalam Shunt kertas ini APF telah digunakan dengan kelajuan boleh ubah WTG menggunakan bingkai rujukan segerak (SRF) untuk pengekstrakan isyarat pampasan bagi APF. Isyarat pemandu Gate dihasilkan dari Bang-Bang Pengawal (Histerisis Band Pengawal semasa HBCC). Model telah dibangunkan dengan menggunakan MATLAB / SIMULINK, keputusan simulasi menggambarkan menurun tahap THD sistem dan jelas menunjukkan keberkesanan Shunt APF dalam memenuhi standard IEEE-519 disyorkan untuk tahap harmonik.

Kata kunci: Angin Generator Turbin, Shunt Power Active Filter, Frame Rujukan Segerak, THD

1.0 INTRODUCTION

The ever increasing electricity demand have resulted in huge investments in renewable energy sources and subsequently added utilisation of power electronics controlled devices. This has resulted, in particular with nonlinear loads, power system characteristics with increased distortion level in current and voltage waveforms in shape of 'Harmonics' [1].

Various problems caused by harmonics in the power system, which also cause an effect on consumer products, such as distorted voltage waveforms result in equipment overheating, blown capacitor fuses, transformer overheating, excessive neutral currents, low power factor, etc. [2-5]. Different techniques have been employed by the researchers in the last decades to mitigate the issue of harmonics and to ensure consistent power supply, close to sinusoidal waveform, to the consumers to avert damage or loss of their equipment. Furthermore, the current harmonics also induces more losses in the generator and thereby producing more heat which in turn reduce efficiency and life of the generator[6]. Similarly, the grid-tied wind turbine generators are also affected by these current harmonics and supply distorted waveform at the Point of Common Coupling (PCC).

Passive and Active filters have been enforced to reduce harmonic distortion. Passive filters have the drawback that they only provide over or under compensation for harmonics whenever a change in load occurs. They are also bulky in size, have resonance problems, provide only fixed compensation performance which also reduces component aging [7, 8]. Active filters which are generally known as Active Power Filters (APF) are preferred over the passive filters. Active Power Filters offers a benevolent solution to the problems of power quality which not only allow the compensation of current harmonics but altogether provide reactive power compensation [9].

The Shunt APF operates through injecting the reactive, unbalanced, and harmonic load current components into the utility system with the same magnitude as the non-active load currents demanded by a given non-linear load but with opposite phases [10-13]. The method for extraction of harmonic compensation signal and determination of reference current play a central role as these are related to accuracy and speed of Shunt APF response. As such, the careful design of Shunt APF for the desired application of the same matter greatly. [14]. The reference current extraction methods are categorised into two groups, i.e. Time domain and frequency-domain methods [15, 16]. Time-domain methods include d–q transformation (or SRF), p–q transformation (or instantaneous reactive power), symmetrical component transformation and etc., which are based on the measurements and transformation of three-phase quantities [9]. Time domain method compared with the frequency domain has the fast response whereas frequency domain, based on Fourier's transformation has an accurate response [14]. The compensation method used in this study is synchronous reference frame (SRF) technique based on time domain control in which all harmonic load current components are targeted and compensated. The control strategy and the current injection depend on reference signal extraction method. The performance of Shunt APF with the grid-connected variable-speed wind turbine is then analysed by calculating total harmonic distortion of compensated quantities using MATLAB/SIMULINK model.

2.0 METHODOLOGY

2.1 Topology and Operational Principle of Shunt Active Power Filter

Shunt Active Power Filters are widely used compared to all other types of the filters [17-24]. Shunt APF induces the compensation current in the system which is equal in magnitude but in anti-phase to the measured harmonic load current. This mitigates the effect of harmonics from the supply side and delivers almost sinusoidal power to consumers. Figure 1, depicts the shunt APF with the grid-connected wind turbine generator. Shunt APF comprises two main parts, namely reference current extraction and gate driver signal for the inverter. Reference current is extracted from the load current measured at PCC and accordingly APF will supply/draw current at PCC. The effectiveness of SAPF depends on gate driver signal control [25]. The application of APF involves various PWM current control techniques proposed by many researchers. But in terms of quick current controllability and easy implementation, HCC has the highest rating among other methods such as sinusoidal- PWM and triangular current controller [26, 27]. Line inductance is used here in order to remove ripples generated by the filter. For maintaining and regulation of DC voltage, dc link capacitor is used with a conventional PI controller. A full bridge diode rectifier is also connected at the PCC. The combination of R, L, and C loads are connected across the bridge rectifier (source of harmonics generation). Principal operation of SAPF is based on the current controlled compensation to draw/supply current from/to the power system (PCC). This compensation of current enables the active power filter to cancel and compensate reactive power drawn by nonlinear loads.

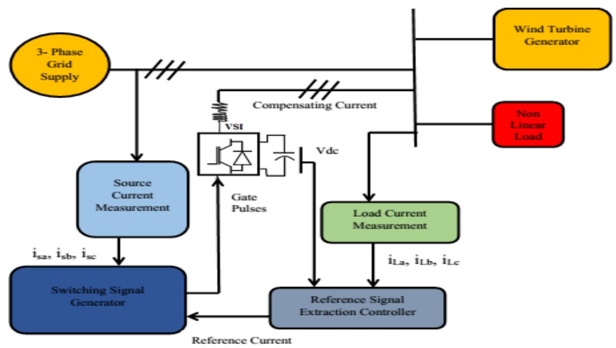


Figure 1 Configuration of Shunt APF

2.2 Harmonic Current Extraction Technique

Synchronous Reference Frame (SRF) method for the extraction of harmonic current was developed in MATLAB/SIMULINK for SAPF under the unbalanced condition due to variable speed wind. Under SRF distorted 3-phase load current is transferred from its a-b-c stationary reference frame to d-q reference frame [28] using equation (1).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

The components of current Id and Iq extracted from load current represent active and reactive power components of current and can be decomposed using equation (2 and 3).

$$i_d = \bar{i_d} + \tilde{i_d} \tag{2}$$
$$i_q = \bar{i_q} + \tilde{i_q} \tag{3}$$

For filtering harmonic contents extracted id-iq current is passed through Low Pass Filter (LPF) which allows only the fundamental frequency components in the circuit. Further, the function of PI controller is to regulate capacitor dc link voltage. The dc capacitor voltage is sensed and compared with some sets of reference voltage to calculate error voltage. This voltage error is involved with PI gain (KP=0.1 and KI-1) to regulate capacitance in dynamic conditions. In addition, the output of PI controller is subtracted from d-axis current to eradicate steady state error [29]. The procedure is then developed to extract reference signal in the d-q rotating frame which is converted back to a-b-c stationery frame using inverse Park's transformation utilising equation (4, 5 and 6). Figure 2 illustrates the Simulink model for SRF method.

$$i_{so}^* = i_d \sin(\omega t) + \cos(\omega t) \tag{4}$$
$$i_{sb}^* = i_d \sin\left(\omega t - \frac{2\pi}{3}\right) + \cos\left(\omega t - \frac{2\pi}{3}\right) \tag{5}$$
$$i_{sc}^* = i_d \sin\left(\omega t + \frac{2\pi}{3}\right) + \cos\left(\omega t + \frac{2\pi}{3}\right) \tag{6}$$

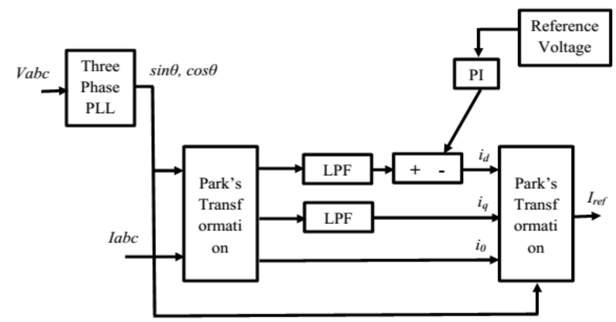


Figure 2 Simulink Model for SRF Method

2.3 Gating Signal Generator for APF

As comprehended in the previous section, the objective of gate driver controller is to generate suitable gating signals for the switching APF based on the extracted reference signals. Therefore, the performance of an APF is merely dependet on appropriate selection of gate driver controller technique. This suggest that optimal choice and strategic implementation of the gate driver technique is very important for the achievement of a satisfactory APF performance.

Further, the Hysteresis Band Current Controller (HBCC) has been selected for driving gate pulses for APF in this study. It imposes a bang-bang type instantaneous control that forces the APF compensation current (i_f) signal to come with its estimated reference signal ($i_{f,ref}$) within a certain tolerance band. A block diagram for such control system is shown in Figure 3 [30]. Following this control system, a signal deviation (H) is designed and imposed on $i_{f,ref}$ to form the upper and lower edges of a hysteresis band. The i_f is then measured and compared with $i_{f,ref}$; the resulting error is subjected to a hysteresis controller to determine the gating signals which exceeds the upper or lower limits set by estimated reference signal + H/2 or – H/2.Provided that, when an error is within the hysteresis band, no switching action will be taken. Switching occurs whenever the error hits the upper or lower limit hysteresis band. The APF is therefore switched in such a way that the peak-to-peak compensation current/voltage signal is limited to a specified band determined by H.

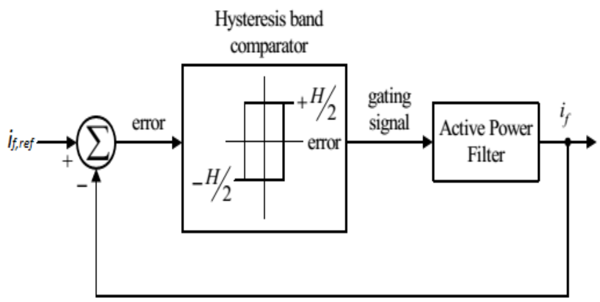


Figure 3 Hysteresis Current Control Method

2.4 System Parameters and Working

This study also focuses on power grid i.e. the consequences of connecting wind turbine generator with the grid and share of harmonics at PCC due to nonlinear loads. The ratings of the power grid for the study are given in Table 1.

Table 1 Ratings of Power Grid

Element	Parameter
Power Grid	120 kV
Transformer (T1)	120 kV/25 kV, 47 MVA
Transformer (T2)	25 kV/575 V, 2.5 MVA
Transmission Line (TL)	R_1= 0.1153 Ω R_0= 0.413 Ω L_1= 1.05 mH L_0= 3.32 mH C_1= 11.33e^{-009} F C_0= 5.01e^{-009} F Length= 30 km

The 120 kV grid systems connected with PMSG wind turbine system through 30 km transmission line, having a non-linear load connected at PCC. The effect of nonlinear load and wind turbine system on grid voltage and current will be analysed at PCC. In order to examine the aforementioned effects on the grid; initially, WTG will be operated without SAPF and then in the presence of SAPF. The level of total harmonic distortion will be checked under both circumstances for the validation purpose.

3.0 RESULTS AND DISCUSSION

Simulations of the system without compensation (APF) are shown in Figure 4, THD level of PMSG current for Phase A, Phase B, and Phase C is 5.76%, 4.62% and 4.83% respectively and PCC current THD levels are 7.42%, 6.75% and 5.70% for Phase A, B and C respectively. Further, PCC voltage THD level for its corresponding Phase A, B and C are 8.05%, 7.30%, and 6.76% respectively.

After simulating the system with Shunt APF, the obtained results are shown in Figure 5 which suggest reduced THD levels. THD level of PMSG current are reduced to 1.15%, 1.24% and 2.19% from 5.76%, 4.62% and 4.83% for their respective phaseA, B and C respectively. It is important to note that PCC current THD levels decreased from 7.42%, 6.75% and 5.70% to 0.18%, 019% and 0.19% for their corresponding Phase A, B and C. Voltage THD at PCC decreased to 0.80%, 1.01% and 0.55% from 8.05%, 7.30% and 6.76% of their Phase A, B and C respectively. The compensated current injected by Shunt APF to mitigate the effect of harmonics is depicted in Figure 6.

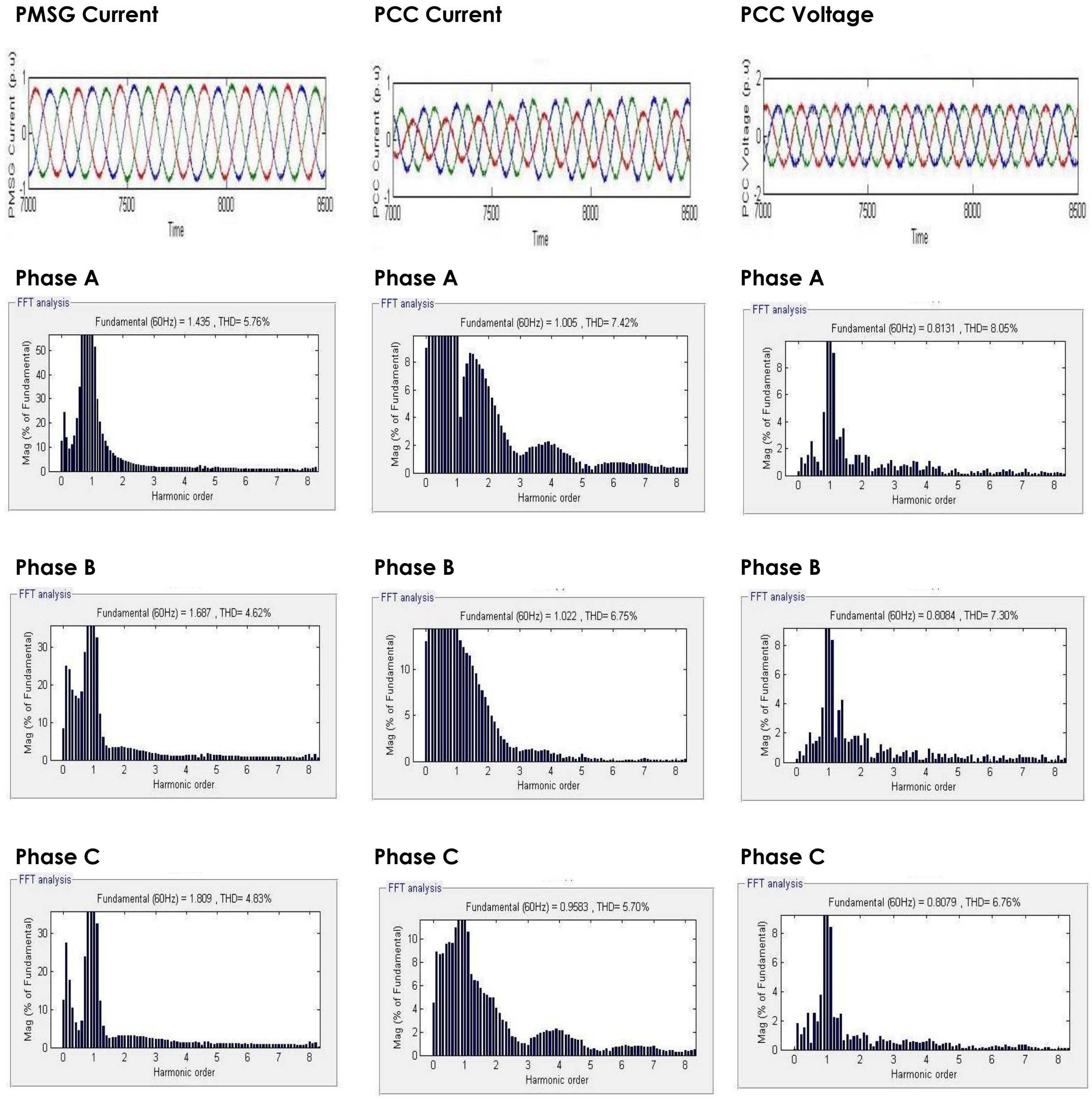


Figure 4 PMSG Current, PCC Current and PCC Voltage with their THD Levels without SAPF

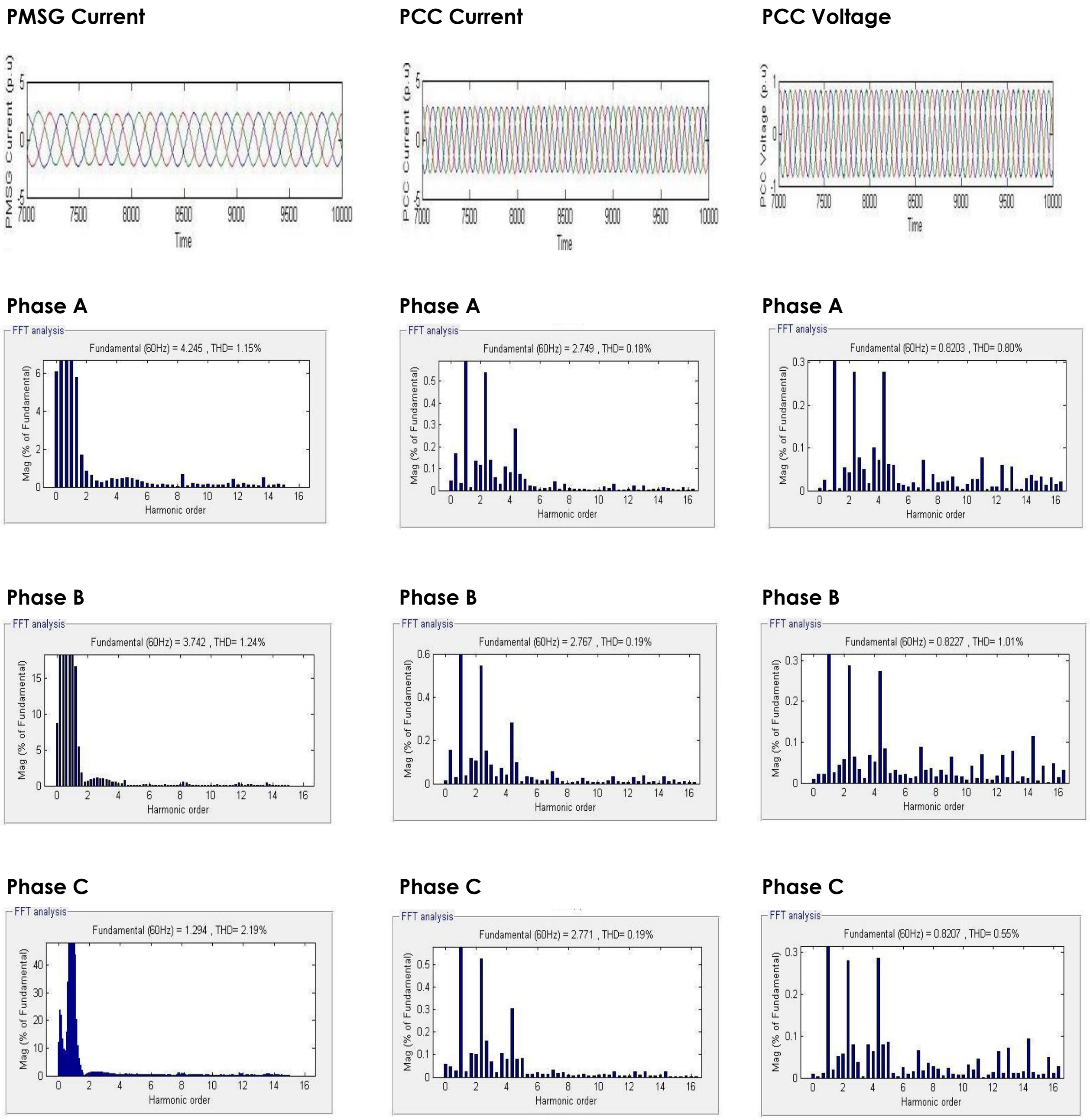


Figure 5 PMSG Current, PCC Current and PCC Voltage with their THD Levels with SAPF

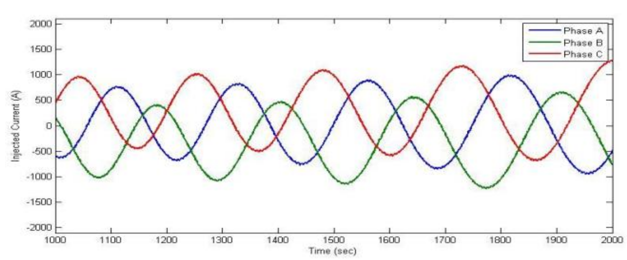


Figure 6 Compensation Current injected by SAPF

3.1 Summary of Simulation Results

Figure 7 below elaborates the percentage magnitude of Total Harmonic Distortion (THD) in each phase of PMSG current, PCC current and PCC voltage without compensation. This suggests that system is not running under the harmonic standard IEEE-519 specified by IEEE [31]. However, following the application of Shunt APF along with Synchronous Reference Frame (SRF) method for the extraction of harmonic components under the variable speed of the wind, the system shows decreased level of THD magnitude as specified in Figure 8. Table 2 below summarises the results shown in Figure 7 and 8. As such, phase to phase comparison of the system without compensation and with SAPF is evident now. These results that using SAPF system, the THD level has reduced within the limits specified in IEEE-519.

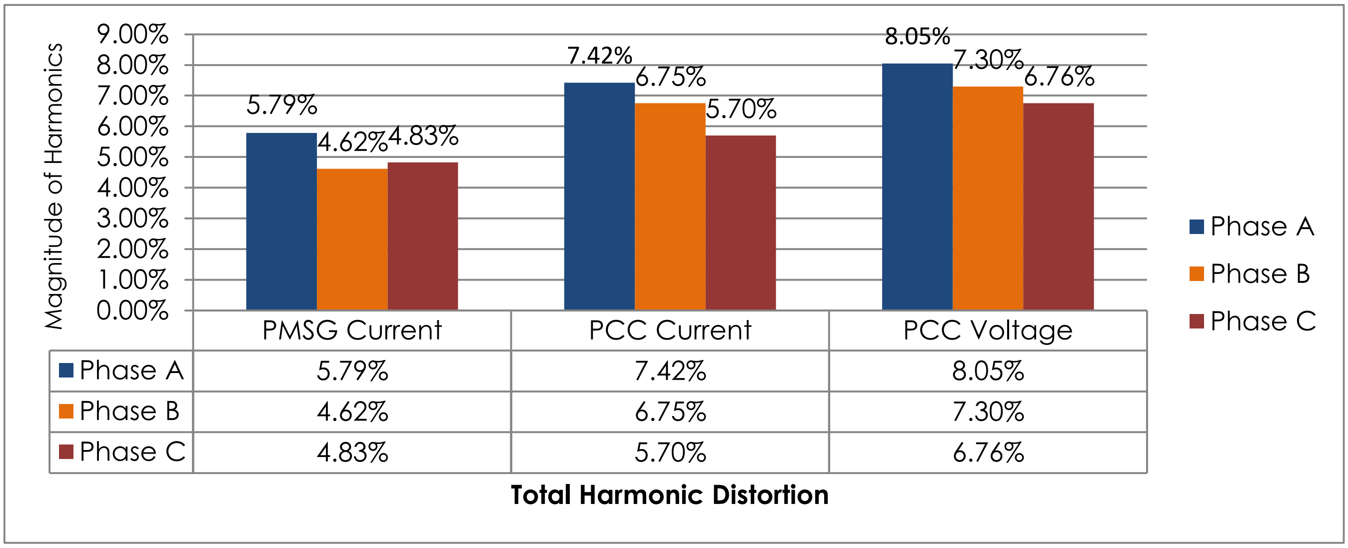


Figure 7 THD Magnitude without SAPF

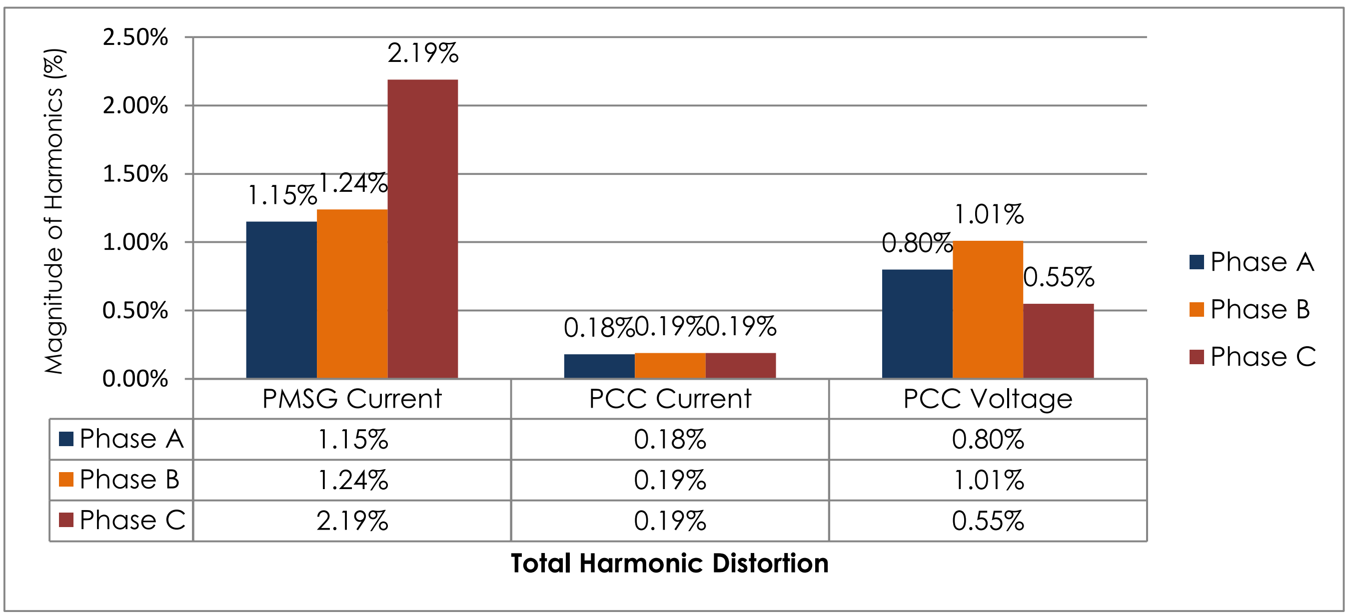


Figure 8 THD Magnitude with SAPF

Table 2 Summary of THD Levels

Compensation Method	**PMSG Current**			**PCC Current**			**PCC Voltage**		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Without any Compensation	5.79%	4.62%	4.83%	7.42%	6.75%	5.70%	8.05%	7.30%	6.76%
With SAPF	1.15%	1.24%	2.19%	0.18%	0.19%	0.19%	0.80%	1.01%	0.55%

4.0 CONCLUSION

Application of Shunt Active Power Filter with grid connected variable speed PMSG in a wind turbine generator system was studied in this study to analyse mitigation of harmonics owing to non-linear loads. Simulation results show reduction of current and voltage harmonics levels of the system. Therefore, establishing that application of this technique is to ensure reduced harmonics to the benefit of system as well as same will not affect life span of generator. Further, the SAPF voltage supplied to consumers also ensure supply with a sinusoidal waveform which in turn will not damage their appliances and utilities.

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