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Modelling and Analysis of Controller for Three-Phase Shunt Active Power Filter

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Abstract

Now a days, because of enhancement in high speed computing elements, high voltage controlled semi-conductor devices and emergence of new power circuit topologies, the Voltage Source Converter (VSC) based Active Power Filter (APF) is finding applications for compensating harmonic currents drawn by the various loads. As the active filter consists of semi-conductor devices alone, the response time of this device is very fast and it doesn't suffer from resonance and other stability problems as faced by the normal passive filters.

The Active filters are generally used at harmonic producing loads. Among all APF's the Shunt Active Power Filter (SAPF) is more prominent at medium/high voltage applications, and also it provides higher efficiency. SAPF in the power circuit can be used either by using the voltage-sourced PWM converter equipped with a DC capacitor or a current-sourced PWM converter equipped with a DC inductor.

This paper presents an approach to determine reference compensation currents of the three-phase SAPF under distorted and/or unbalanced source voltages in steady state. It is planned to design a Synchronous Reference Frame (SRF) controller for Voltage Source Converter (VSC) based Shunt active power filter for harmonic compensation. The simulation results have been obtained by using MATLAB/ SIMULINK.

***Keywords**: Shunt Active Power Filter (SAPF), Harmonics, STATCOM, THD, VSC, EPQ*

1. Introduction

The Electric Power Quality [EPQ] has become an important part of the distribution power system. Harmonics need attention in the EPQ of the distribution system because power factor is very important consideration for efficient functioning of system and also economic point of view which is very much effected by the harmonic content.

To overcome the effects of harmonics in the EPQ, the passive filters are viable solution and they are usually designed for custom applications. However, they can mitigate only few harmonics (which can be tuned), and also they can introduce resonance in the power system. Due to the recent advances in power electronic fast commutating switches, APFs appear as a better solution to mitigate harmonics and thus improve power quality [1].

1.1. Three Phase Voltage Source Inverter

Three phase voltage source inverters, as shown in Figure 1, are rapidly gaining popularity for industrial applications. The reasons for this popularity are voltage sharing

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between the series devices and quality of output waveforms as compared to a two level inverter [2].

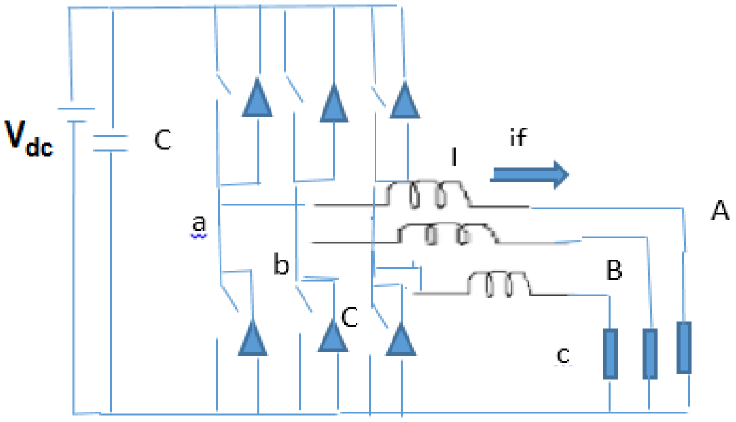

Figure 1. Three Phase Voltage Source Inverter

2. Shunt Active Power Filter (SAPF)

Modern active filters have the multiple functions like harmonic filtering, damping, isolation and termination, reactive power control for power factor correction and voltage regulation, voltage flicker mitigation and load balancing. It is cost effective and thus can be used commercially. The operation of APF depends on the algorithm applied to the controller [4]. The schematic of SAPF is as shown in Figure 2.

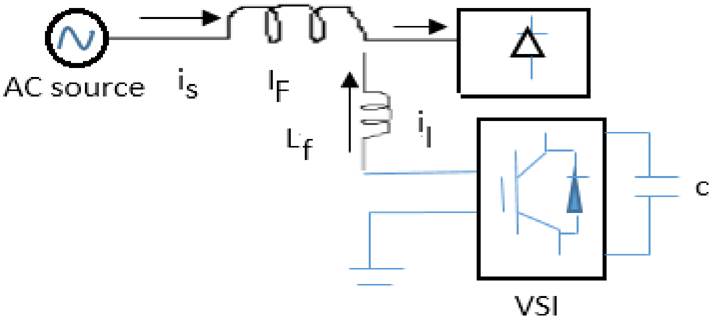

Figure 2. Schematic of Shunt Active Power Filter

The output voltage of Inverter can be controlled both in magnitude and phase, which is coupled to system voltage through a relatively small (0.15 -0.2 pu) tie reactance. For full compensation of load, converter has to supply *reactive power* (Q) of same magnitude, but of opposite sign. So, reactive power drawn from source is zero, thus unity power factor can be achieved.

$$Q_{Source} = Q_{load} + Q_{inverter} \tag{1}$$

Under complete compensation,

$$Q_S = Q_l + Q_i = 0 \tag{2}$$

STATCOM has to draw active power from grid to maintain DC link voltage at desired level.

$$P_S = P_l + P_{stat} \tag{3}$$

The I_q loop in the controller alone controls the reactive power flow in the system [8]. The direction of flow of reactive power whether it is from coupling transformer to the system or from system to the coupling transformer depends upon the difference between the converter output voltage and the ac system bus voltage.

2.1. Harmonic Compensation

Synchronous frame theory (d-q theory) based controller is suggested because it has greater and gives better performance when the supply voltage is distorted. The advantage with SRF method is any harmonic component other than DC present in the element can be filtered out easily because the fundamental components are turned as DC components [6].

3. APF Control Methods

3.1. Instantaneous Active Power Theory (p-q Theory)

The instantaneous active, reactive power method, proposed by Akagi [4], for calculating the reference compensation currents are required to inject into the network at the connected point of the nonlinear load. It remains one of the most popular SAPF control schemes. Since then, the theory has inspired many works dealing with active power filter compensation strategies. One of the peculiar features of a shunt APF is that it can be designed without active energy source units, such as batteries, or in other forms in its compensation mechanism. In other words, an ideal APF does not consume any average power supplied by source [5].

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$P_{\alpha\beta} = V_\alpha i_\alpha + V_\beta i_\beta \tag{6}$$

$$Q_{\alpha\beta} = V_\alpha i_\beta + V_\beta i_\alpha \tag{7}$$

$$\bar{\bar{P}} = \tilde{P} + \vec{\bar{P}}, \bar{\bar{Q}} = \tilde{Q} \tag{8}$$

3.2. Synchronous Reference Frame Method (d-q method or SRF method)

A synchronous reference frame method for obtaining the load currents at the fundamental frequency, which will be the desired source currents. The APF reference compensation currents are then determined by subtracting the fundamental components from the load currents. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The basic structure of SRF controller consists of direct (d-q) and inverse (d-q) park transformations as given below. These can be useful for the evaluation of a specific harmonic component of the input signals.

$$\begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} I_{ld} \\ I_{lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} \quad (10)$$

$$\text{Where, } \theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) \quad (11)$$

$$\overline{\overline{I_{ld}}} = \widetilde{I_{ld}} + \overline{I_{ld}}, \overline{\overline{I_{lq}}} = \widetilde{I_{lq}} + \overline{I_{lq}} \quad (12)$$

One of the main differences of this method from p-q theory is that the d-q method requires the determination of the angular position of the synchronous reference of the source voltages, for which a PLL algorithm is used. After the transformation of load currents into the synchronous reference, a low-pass or high-pass filter is using to separate the fundamental and harmonic components. Finally, the reference currents are transformed to the three phase reference using the inverse synchronous transform.

The voltages V_{abc} are transformed to d-q components such that with an added advantage of d-q theory the voltage axis is aligned in with the d-axis such that the component along the q or quadrature axis will be zero. So,

$$V_d = |V| \,\&\, Vq = 0 \quad (13)$$

The same transformation applied for currents I_{abc} such that the vector I make an angle ψ where ψ refers to phase angle.

From basic definitions of Active power and Reactive power,

$$P = VI \cos\psi \quad (14)$$

$$Q = VI \sin\psi \quad (15)$$

So for a given system voltage, $P \propto I_d$ and $Q \propto I_q$.

From above the active power control means indirectly controlling of $\mathbf{I_d}$ component and reactive power control means indirectly controlling of $\mathbf{I_q}$ component.

4. Compensator Mathematical Modelling

Voltage equation in stationary a-b-c frame is,

$$\begin{bmatrix} V_{ga} \\ V_{gb} \\ V_{gc} \end{bmatrix} = \begin{bmatrix} Ldi_a/dt \\ Ldi_b/dt \\ Ldi_c/dt \end{bmatrix} + \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} \quad (16)$$

The above equation is assumed under the power system is balanced, harmonics are absent and R is small. The a-b-c frame equations can be transformed according to α-β theory.

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} Ldi_{\alpha}/dt \\ Ldi_{\beta}/dt \end{bmatrix} + \begin{bmatrix} V_{i\alpha} \\ V_{i\beta} \end{bmatrix} \tag{17}$$

The α-β components transformed to d-q components,

$$V_{id} = V_{sd} – Ldi_d/ dt + \omega L_{iq} \tag{18}$$

$$V_{iq} = V_{sq} – Ldi_q/ dt + \omega L_{id} \tag{19}$$

In the above equation, Ldi_d/dt and Ldi_q/dt are PI controller outputs of respective current control loops.

4.1. Control Strategy of SAPF

The operation of SAPF mainly depends on algorithm of controller in order tosuppress the harmonics present in the source due to load. From the d-q theory the active and reactive current drawn by the load could be expressed by several components. The equations obtained after transformation consists of "ω" term coupled with current components such as I_d, I_q. Due to this coupling term, the reference current tracking capability of controllers is not rapid enough for coupled systems The main objective of the controller is to improve the performance and to make components as independent one, a decoupled controller is necessary [9, 10].

$$I_d = I_{dfund} + I_{dharm} \tag{20}$$

$$I_q = I_{qfund} + I_{qharm} \tag{21}$$

5. Simulation and Results

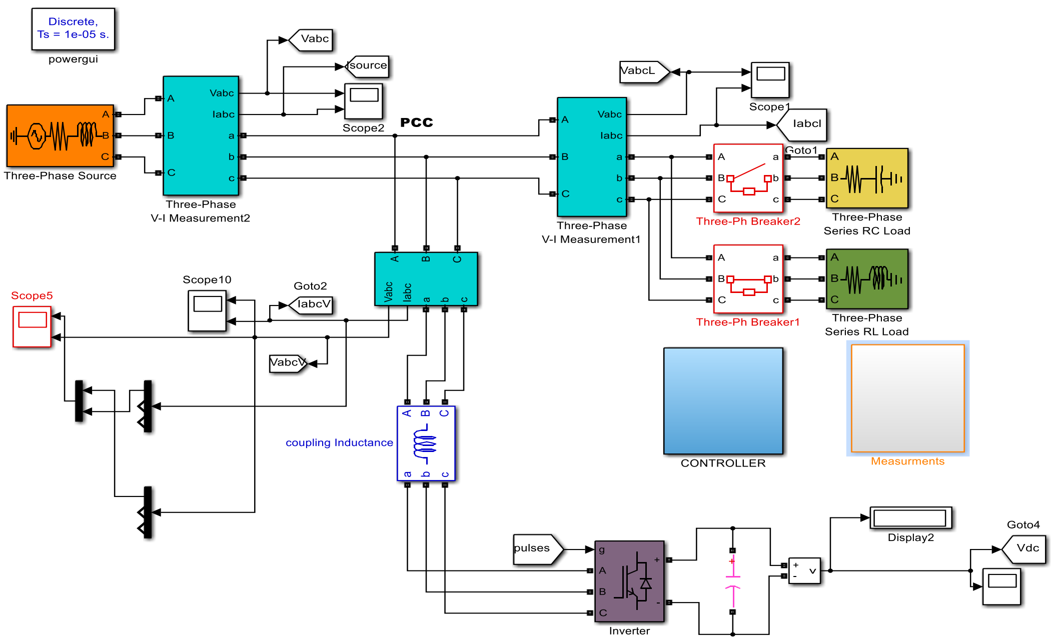

Figure 3. Simulink Model without SAPF

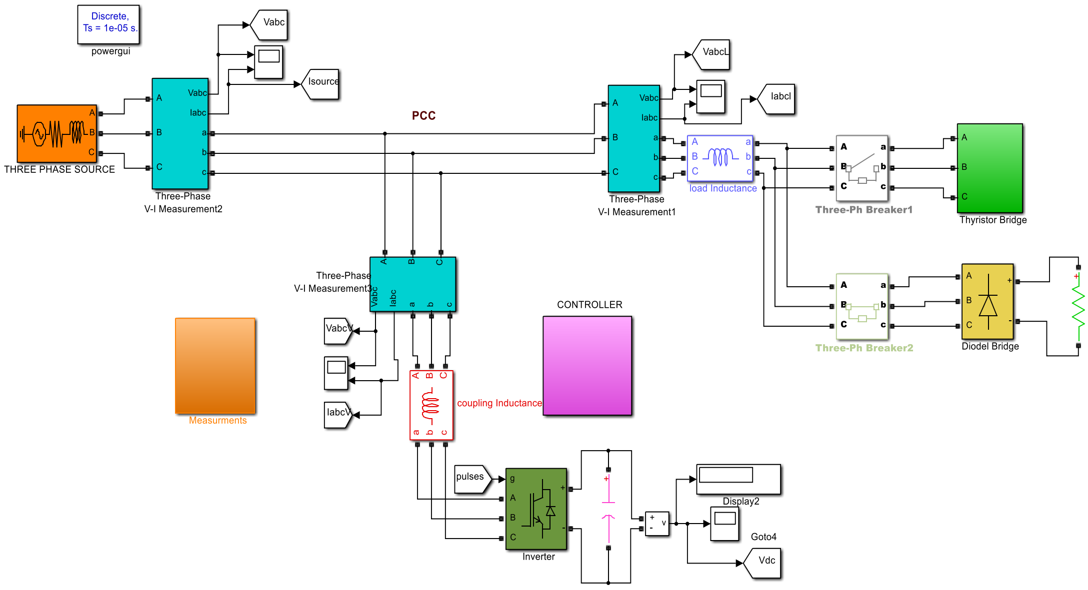

Figure 4. Simulink model with SAPF

The simulink model of STATCOM without and with filter controller is shown in Figure 3 and 4 respectively. The figure 5 shows the subsystem of the SAPF controller developed using MATLAB/ SIMULINK tool. It is developed from the mathematical model of the controller.

The output current waveforms of source load inverter side without APF and with APF are shown in Figures 6 and 7 respectively. The series RC & RL loads are connected to the inverter without APF. Diode Bridge Rectifier and Thyristor Bridge Rectifier are connected as loads to the inverter with APF.

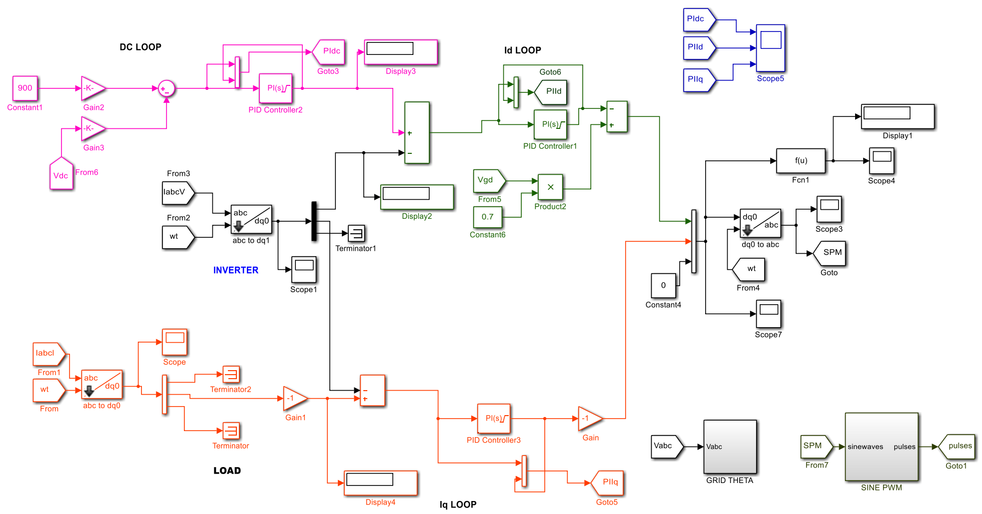

Figure 5. Subsystem of SAPF with Controller

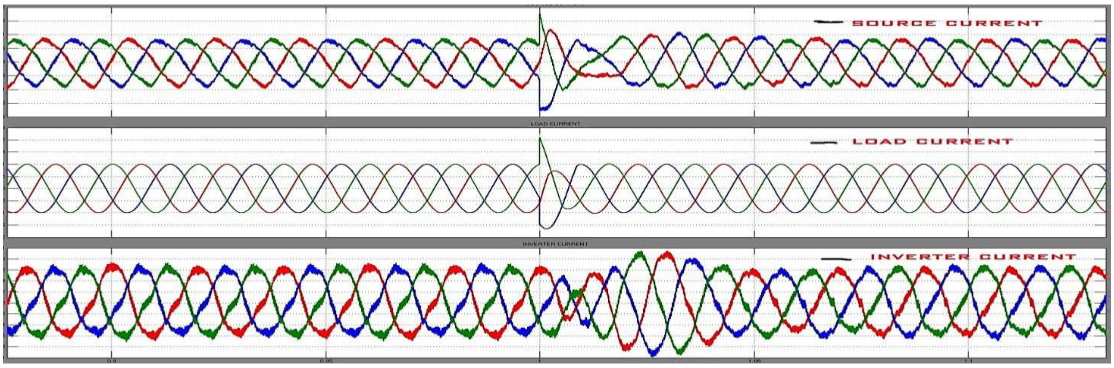

Figure 6. Output Current Waveforms without APF with RC & RL Loads

The Figure 6 shows that STATCOM current follows the source current waveform according to the connected load.

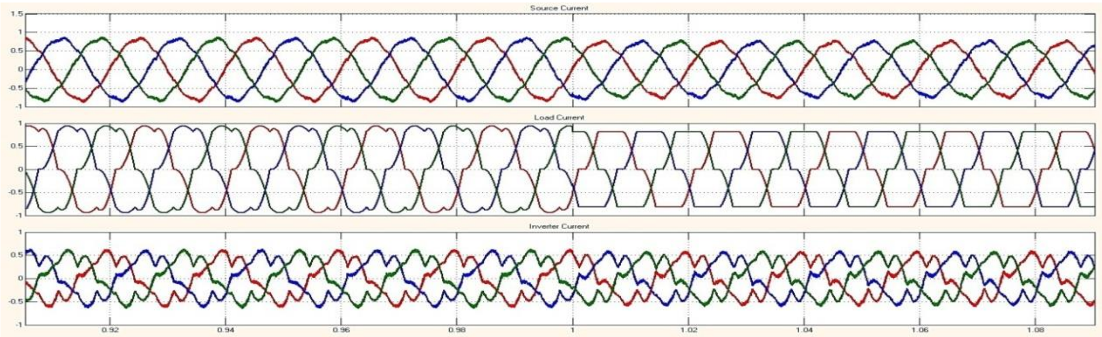

Figure 7. Output current waveforms with APF with DBR & TBR loads

The Figure 7 shows the SAPF gives a smooth output with both compensation of reactive power and harmonic elimination. It provides information that inverter current follows the source current according to the connected loads

The THD of SAPF with DBR and TBR as connected loads can be observed in the table 1. The shunt active power filter gives best performance results.

Table 1. %THD Without & With SAPF

Source Current	Total Harmonic Distortion (THD)%	
	Without SAPF	With SAPF
Diode Bridge Rectifier	11.61	3.32
Thyristor Bridge Rectifier	15.35	4.35

6. Conclusion

The design of SAPF controller is done by using mathematical modeling and analysis. This system is simulated by using MATLAB/SIMULINK upon selecting specified parameters. The Diode Bridge Rectifier and Thyristor Bridge Rectifier are connected as loads. The current waveforms and %THD results with and without SAPF are presented. The SAPF provides better solution to reduce current harmonics.

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