Goertzel Algorithm Based Shunt Active Power Filter Using Sliding Mode Controller

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Abstract—**In this paper control of Goertzel Algorithm based shunt active power filter with sliding mode controller is considered. Shunt active power filter involves harmonics mitigation due to three phase non linear loads under balanced and unbalanced load conditions. The sliding mode controller is used to regulate voltage of the capacitor used in inverter. The sliding mode controller improves the dynamic response of the system and provides faster convergence. The performance of the sliding mode controller is compared with the conventional PI controller. The above system is investigated for balanced and unbalanced load conditions using MATLAB/Simulink. From the analysis it can be observed that the Goertzel algorithm based shunt active power filter with sliding mode controller gives a better response than the conventional PI controller. The simulation results prove the effectiveness of the proposed system.**

Keywords—Shunt active power filter, total harmonic distortion,Goertzel Algorithm, sliding mode controller.

I.   INTRODUCTION

The increased use of nonlinear loads, such as switch mode power supply in computers, rectifier devices in TVs, ovens and telecommunication power supplies and commercial lighting systems cause excessive neutral currents, harmonic injection and reactive power burden in the power system. They result in poor power factor, lower efficiency and interference to adjacent communication systems. In the past L-C filters were employed to reduce harmonics and power capacitors were used to improve the power factor of the AC mains, however, they have the demerits of fixed compensation level, large size and resonance. In the last two decades, a device generally named as active power filter (APF) has been investigated to provide an appropriate solution to most of these problems. Elimination of current harmonics, reactive power compensation and voltage regulation are the main functions of active power filters for the improvement of power quality. T. C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp).

There exist several active power filter topologies in the literature in accordance with their circuit configurations and connection types [1]. There are different control methods that are introduced by different authors. In [2] simplified method using instantaneous power theory based shunt

active power filter using PI controller is discussed. They have used hysteresis current control technique for pulse generation. In [3] active power filter with sliding mode control is discussed which is capable of controlling dc bus voltage of capacitor as well. The ANN based shunt active power filter is discussed in [4].

Shunt active power filter (SAPF) is made up of inverter and a control circuitry, which decides operation of inverter. SAPF provides harmonic compensation as well as reactive power compensation. In this paper we discuss only about harmonics compensation using hysteresis control technique. The PI controller is used to control the voltage across the capacitor. This paper uses Synchronous Reference Frame method for reference current calculation.[5-8]

Shunt Active Power Filters are mainly operated as harmonic isolator between nonlinear load and utility system. The SAPF connected in parallel to supply system protects utility from harmonics generated by non-linear load. It can be used to provide reactive power to the load as well. Fig. 1 shows basic schematic of Shunt Active Power Filter constituting of following steps:[9-11]
- •   Measurement of Current and Voltage signals
- •   Reference Current generation
- •   Pulses generation for operation Inverter

The use of Goertzel algorithm constitutes an alternative method for DFT which reduces the number of operations. Goertzel algorithm evaluates the DFT and saves computation time as well as storage memory, as there are only two real coefficients to store if compared with the 2N coefficients required by DFT. Regarding to the number of operations, Goertzel algorithm employs only $N + 1$ multiplications and $2N + 2$ sums

II.   SLIDING MODE CONTROLLER

Better operation of Shunt APF is guaranteed if the voltage across DC link capacitor is maintained at prescribed reference DC voltage. Sliding Mode Controller is used to regulate voltage across capacitor by comparing it with reference DC voltage. The controller sets a reference DC current required to maintain the voltage across capacitor constant. This is done as shown in figure 1 below.
The error $e(n)$ is calculated as difference between reference and measured DC voltage.[10-11]
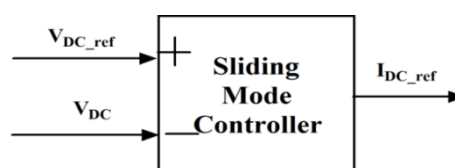
$$x_1 = V_{DC}^* - V_{DC} = e(n) \qquad (1)$$

Figure 1. Basic schematic of Sliding Mode Controller

The derivative of error,

$$x_2 = \frac{1}{T} e(n) - e(n-1) \qquad (2)$$

Where, T is sampling interval and x_1, x_2 are state variables. The state equation is given by equation (3) below.

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -k \end{bmatrix} u \qquad (3)$$

The sliding mode plane is represented by equation (4) below.

$$s = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = Cx_1 + x_2 \qquad (4)$$

And $\dot{s}$ is given by,

$$\dot{s} = \begin{bmatrix} C & 1 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = C\dot{x}_1 + \dot{x}_2 \qquad (5)$$

In this paper Constant Rate Reaching Law is used which is given as,

$$\dot{s} = -Q * sgn(s) \qquad (6)$$
$$\text{Where,}$$
$$sgn(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \end{cases} \qquad (7)$$

Putting equation (3) in (5) and after that equating it with equation (6), we can get the required control law (u), as shown below.

$$u = \frac{1}{K}[cx_2 + Q * sgn(s)] \qquad (8)$$

The output of sliding mode controller is taken as I_{DC_ref}, which is then multiplied by V_{DC} to generate capacitor power loss component P_{loss}.
If we directly implement this law for Shunt APF system, the voltage across capacitor never approaches the reference DC voltage. There exists steady state error of magnitude nearly equal to 3 volts as shown in figure 9.
This steady-state error can be eliminated by placing a constraint on control law (u)specified in equation (8). The constraint placed is stated in equation (9) below.

$$\frac{1}{2} * \frac{d}{dt}(s^2) \leq -\eta * |s| \qquad (9)$$

Where, η :- Positive Constant.
The value of η determines the degree to which the system state is attracted to the switching surface.
Equation (9) states that, the squared distance to the sliding surface (s^2) decreases along all system trajectories. Thus it constraints the trajectories to point towards the surface "s".

A. Augmenting the equivalent control:
Here, the VSC control takes the form,

$$u = u_e + \Delta u$$

Where, u_e, is the equivalent sliding mode control, whereas Δu is added to satisfy the reaching condition. A commonly used form for Au is a relay control.

B. Relay control:
Here, the VSC for each element of the control vector Δu takes the form of a relay. The relay gain may be either fixed or state dependent.

$$\Delta u_i(x) = k_i^+, whens_i(x) > 0$$

$$\Delta u_i(x) = k_i^-, whens_i(x) < 0$$

Where, $i = 1,2,....m$
The values of k_i^+ and k_i^- are chosen to satisfy the desired reaching condition.
The output of sliding mode control u is taken as I_{DC_ref}, which is required to charge the capacitor.

C. Chattering Problem Elimination:

Due to use of signum function for designing SMC law introduces chattering effect which is undesirable in any dynamic system due to its infinite switching frequency. Chattering problem can be overcome by smoothing out the signal with continuous function like Saturation, which closely approximate the signum function especially around the neighborhood of the sliding surface. The saturation function allows the introduction of a small boundary layer near the surface. So we can substitute sgn(s) by sat (s/µ) as follows:

$$sat\left(\frac{s}{\mu}\right) = \frac{s}{\mu} \qquad ; if|s| < \mu$$
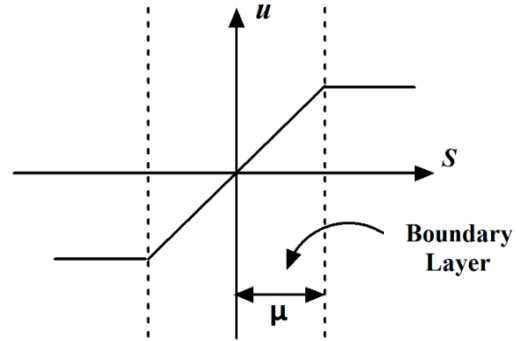$$= sgn(s); \text{Otherwise}$$

Figure.2. Boundary Layer for Sliding Mode

Fig. 4 shows boundary layer control by using saturation function, where "u" is magnitude of control action.

III. CONTROL STRATEGY BASED ON GOERTZEL ALGORITHM

The Goertzel algorithm is used to compute Discrete Fourier Transform spectra. It is a special case of DFT where the algorithm provides amplitude spectra and phase spectra only for a specified number of frequencies. The algorithm is implemented in the form of second order infinite impulse response filter. The block diagram for Goertzel algorithm is as shown in Figure 2. The values of coefficients are as follows: $k1 = 2\cos\left(\frac{2\pi k}{N}\right)$ and $k2 = -e^{\frac{2\pi K}{N}}$.
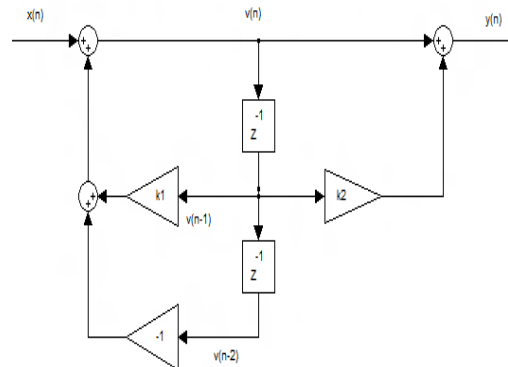

Figure 3 Goertzel Algorithm block diagram

The amplitude and phase of 50 Hz component can be obtained using above algorithm as

$$|y_k(N)|^2 = v_k^2(N-1) + v_k^2(N-2)$$
$$-v_k(N-1)v_k(N-2) \times 2\cos\left(\frac{2\pi k}{N}\right)$$

(1)

$$\theta = \arg\{y_k(N)\}$$
$$= \arctan\frac{\sin\left(\frac{2\pi k}{N}\right)V_k(N-2)}{V_k(N-1) - \cos\left(\frac{2\pi k}{N}\right)V_k(N-2)}$$

(2)

This paper introduces use of Goertzel algorithm for the extraction of fundamental component of current and voltage and its use in Shunt Active Power filter. The method can detect the amplitude and phase accurately under noisy environment. Thus the reference current generation for the shunt active power filter is done using this method. The advantages of the method are that the accuracy and speed of response can be controlled, the structure is robust with respect to setting of internal parameters and the performance is immune to noise and external distortions. Hysteresis Current Controller is an instantaneous feedback system which detects the current error and produces directly the drive commands for the switches when the error exceeds an assigned band. The hysteresis controller is used to control the current and determine the switching signals for inverter gates. When $I_{ca} > I_{ca}^* + (HB/2)$ then hysteresis controller gives output 0. When $I_{ca} < I_{ca}^* - (HB/2)$ then it gives output equal to one. In this way, Hysteresis PWM is used as pulse generator for inverter, so that current tracks the reference.[12-13]
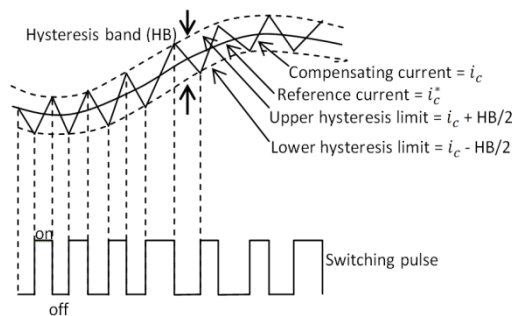

Figure 4. Hysteresis Current Controller

DC voltage controller is used to regulate dc voltage across the capacitor .The regulation loop consists of the comparison of the measured voltage with the reference voltage and the error is given to PI controller which sets i_{dc}^* reference current as shown in figure 4. This reference current is added to output of the Low Pass Filter.
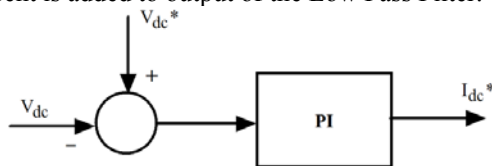

Figure 5. DC voltage controller

IV.   PROPOSED WORK

The basic aim of this paper is to simulate the implementation of SAPF for power quality improvement using Goertzel algorithm with DC voltage control using PI controller and Sliding Mode Controller and performance comparison. To simulate the two methods under discussion, MATLAB/ Simulink is used with diode bridge rectifier as the non-linear load. This load makes the load current non-sinusoidal and to keep the source current as clean as possible, Shunt Active Power Filter (SAPF) is used. For the reference current generation for this SAPF, the above mentioned two methods are separately implemented and compared for performance specifications like source current THD and amplitude, voltage balancing, source power factor, dynamic response and response speed.

In the simulation diagram as shown in figure 6,the load current is sensed using Goertzel algorithm. The algorithm extracts the 50 Hz component of the load current. Thus, the fundamental components of three phase load currents are measured. The output of algorithm consists of magnitude and phase of the fundamental component of current. The power supplied to the inverter used in SAPF through the DC link capacitor and the current required to charge this capacitor is taken from the source itself. This current is termed as loss current which is then added to the fundamental current computed by Goertzel algorithm to find the total current to be compensated. The three phase template currents are generated with their amplitudes equal to the addition of fundamental current and the loss current. These template currents are subtracted from the load current and the resultant is then compared with the compensating current using Hysteresis current controller.

Thus the reference current signals are generated for the switching of PWM inverter.

To study the performance of Goertzel algorithm under balanced load conditions, THD of load current is 23.09% with the magnitude of fundamental current being 18.75ampere for both, PI controller and SMC whereas THD of source current is 2.55%with the magnitude of fundamental current being 18.04amperefor PI controller as against THD of source current is 1.55%with the magnitude of fundamental current being 18.04amperefor SMC. The waveforms of load and source currents for balanced load condition are shown in Fig.7 and 8 respectively. Figures 9 and 10 respectively show Voltage balancing of DC link capacitor of SAPF using PI Controller and using SMC under balanced load conditions.

For unbalanced load, an additional single phase rectifier is connected to phase A of 3 phase 4 wire system as shown in Fig.10. The DC link capacitor of SAPF is split into two equal parts with the center point grounded and is then connected to neutral. In this case, neutral current also comes into picture and is to be compensated. The waveforms of load and source currents for unbalanced load condition are shown in Fig.11 and 12 respectively. Figures 13 and 14 respectively show Voltage balancing of DC link capacitor of SAPF using PI Controller and using SMC under unbalanced load conditions.
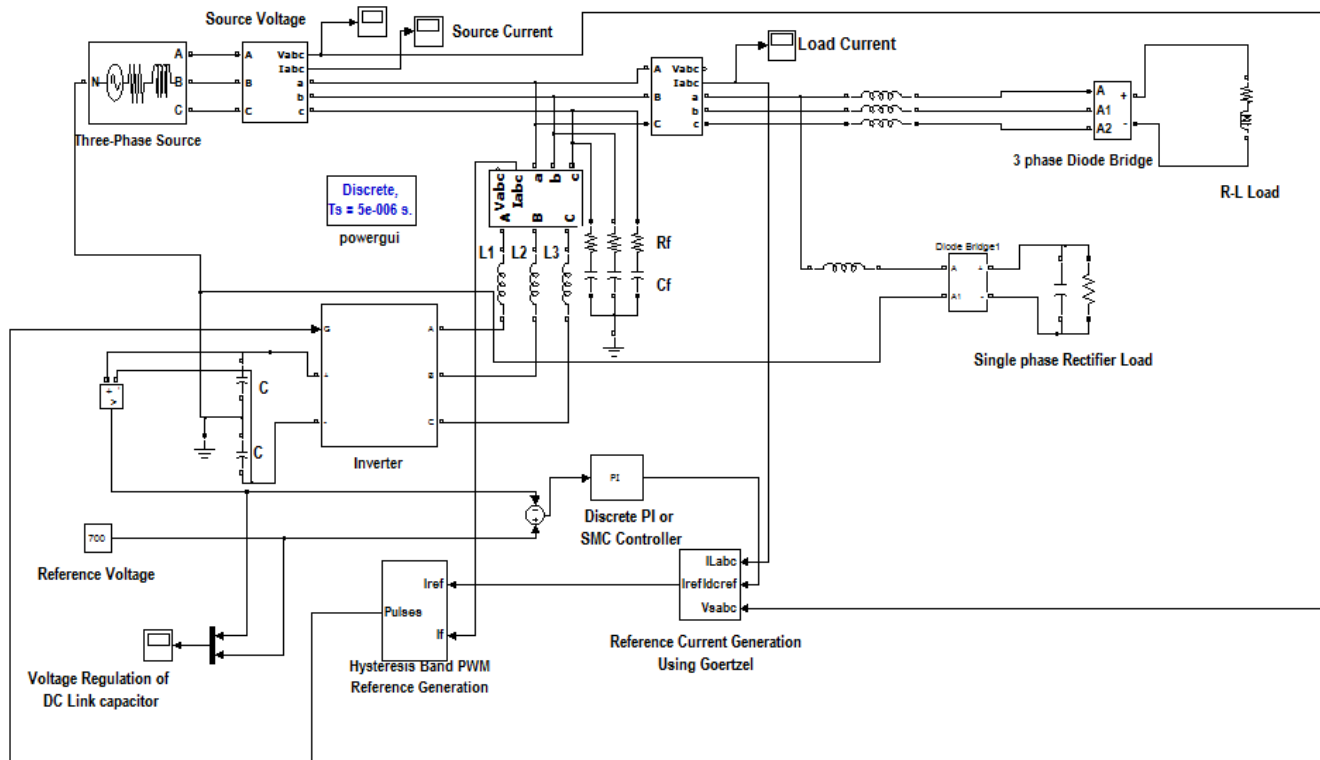
Figure 6. Goertzel algorithm for reference current generation under unbalanced load conditions with DC voltage balancing using PI controller or SMC
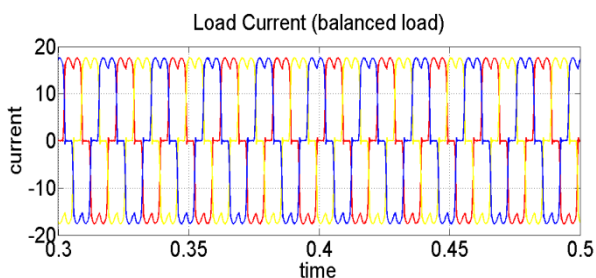

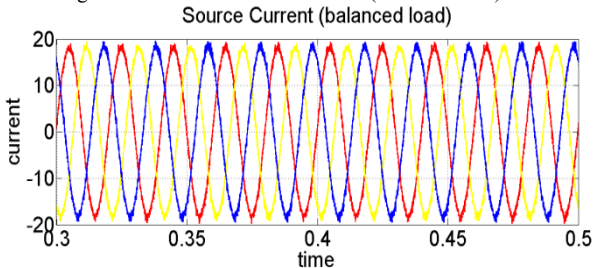Figure 7. Waveform of load current (balanced load)

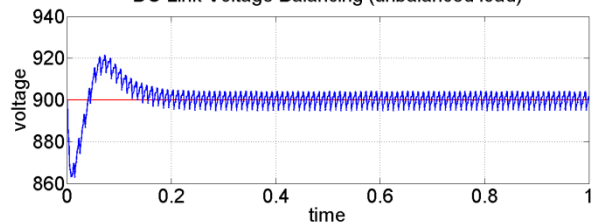Figure 8. Waveform of source current (balanced load)

Figure 9. Voltage balancing of DC link capacitor of SAPF using PI Controller (balanced load)
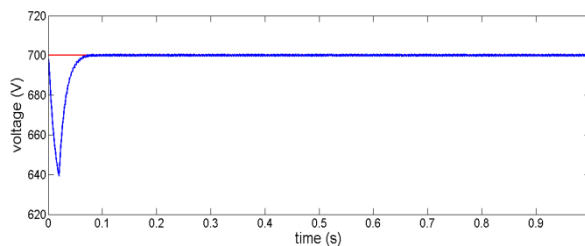

Figure 10. Voltage balancing of DC link capacitor of SAPF using Sliding Mode Controller (balanced load)
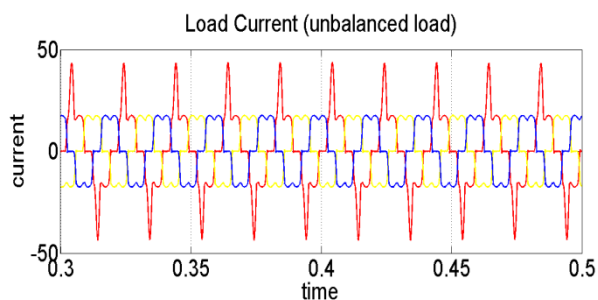

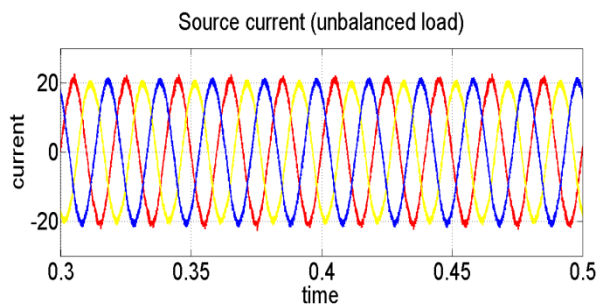Figure 11. Waveform of load current with dynamic change in load (unbalanced)

.Figure 12. Waveform of source current with dynamic change in load (unbalanced)
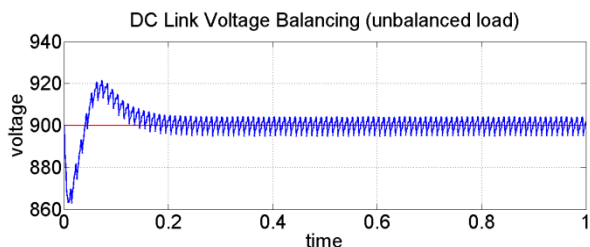
Figure 13. Voltage balancing of DC link capacitor of SAPF using PI Controller (unbalanced load)
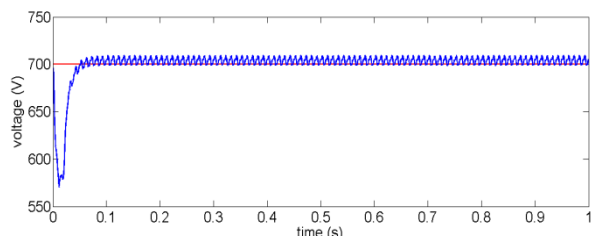

Figure 14. Voltage balancing of DC link capacitor of SAPF using Sliding Mode Controller (unbalanced load)

THD of load current is 27.34% with the magnitude of fundamental current being 35.54ampere for both, PI controller and SMC whereas THD of source current is 2.90%with the magnitude of fundamental current being 30.43amperefor PI controller as against THD of source current is 1.45%with the magnitude of fundamental current being 30.43ampere for SMC.

Table 1 Performance Analysis of PI and SMC Controllers

Controller	Performance Analysis			
	Settling Time (sec)	Rise Time	Peak Time	% Overshoot
PI	0.2	0.02	0.03	14.38
SMC	0.03	0.03	0.00	0.00

V.   CONCLUSION

The simulation results show the performance of Shunt Active Filter using Goertzel Algorithm and Enhanced Phase Locked Loop. The Goertzel Algorithm provides faster response as compared to EPLL based system. The system reaches steady state within 1 to 2 cycles in Goertzel Algorithm and so a faster convergence is possible with this method. The calculations required for implementing the Goertzel algorithm are less as compared to EPLL. So, the implementation of Goertzel Algorithm for reference current generation is easier as compared to EPLL. Both the methods perform good under unbalanced conditions and are insensitive to voltage perturbations.

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