A Comparative Study of Two Control Strategies forThree Phase Shunt Active Power Filter usingAdaptive Hysteresis Band Current Controller

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***Abstract*—A three phase Shunt Active Power Filter (SAPF) is used to compensate the harmonics produced by the nonlinear load and in addition it makes the true power factor unity. In this paper, an Adaptive Hysteresis Band Current Controller (AHCC) is usedtomaintain the switching frequency constant, hence overcoming the drawbacks of hysteresis band current controller (HBC). A Comparative analysis of two reference signal generation technique is presented which shows,indirect control Unit vector PID method is superior in generating the desired reference signal as compared to Synchronous Reference Frame (SRF) method. Various simulation results have been presented under steady-state and transient load condition which demonstrates the effectiveness of using an indirect control Unit vector PID method with AHCC. The proposed three phaseSAPF with AHCC is found to be effective which meets IEEE 519 standard recommended on harmonics levels.**

Keywords-Adaptive Hysteresis Band Current Controller(AHCC), Hysteresis Band Current Controller (HBC), Power Quality, Shunt Active Power Filters(SAPF),Switching Frequency.

I. INTRODUCTION

Various power electronics equipment used in industrial and home application (such as adjustable speed drives (ASD's), furnaces, computer power supplies etc.)act as nonlinear loads, are constantly polluting the power system and creating various power quality problems as mentioned in [1],[2]. In Fig. 1, if we considerL_1 as a nonlinear load, then due to L_1 the source current i_s will get distorted. This distorted source current may interact with the source impedance make the voltage at point of common coupling v_{PCC} distorted, which result in mis-operation of other loads L_2& L_3 . So our main objective is to compensate the harmonic current injected by the nonlinear loads and make source current sinusoidal.

For compensation of harmonic current produced by nonlinear loads, traditionally passive LC filters were used.But for its large size, resonance and fixed compensation, the powerelectronics and power system engineers then developed adynamic and adjustable solution to the power quality problems, known as Active Power Filters (APFs)[3]. Since then APFs were used for multiple purpose such as harmonic mitigation, reactive power compensation, power factor correction, load balancing etc. In this paper a three phase Shunt Active Power filter (SAPF) as shown in Fig. 2, is used, which act as a variable current source, injecting the required compensating current at PCC to make the source current sinusoidal and in phase with the source voltage. To generate the compensating current, SAPF requires a Control strategy. The Control strategy can be divided into two parts. First one is the derivation of the reference current wave. Various reference current calculation techniques have been presented in [4]. In this paper two reference current generation techniques are used namely the Synchronous Reference Frame (SRF) method and indirect control unit vector PID method which based on indirect compensation process as given [5] is used. A brief comparative study of the two techniques is presented.

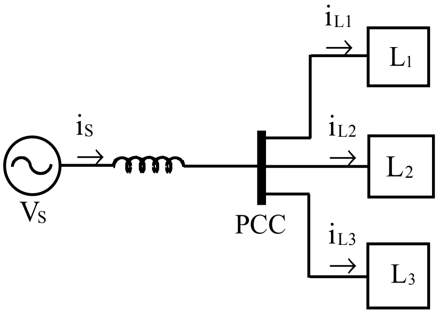

Fig.1. Single line diagram of simple power system

Second, is the generation of the gating signal.Conventionally hysteresis band current control (HBC) method was used for its improved stability, fast transient response, simple implementation &higher accuracy in current tracking [8]. But with the limitation of fixed hysteresis band, it had several undesirable features such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters. In this paper, an Adaptive Hysteresis Band Current Controller (AHCC) has been proposed which maintains the switching frequency nearly constant; by changing the hysteresis bandwidth according to system parameterssuch as modulation frequency, supply voltage, dc capacitor voltage and slope of the reference current signal i_c^*.

Various simulation results are presented which demonstrates the effectiveness of using AHCC. The proposed SAPF is found to be effectively compensating the harmonics injectedby the nonlinear load, both in steady state and

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transient load condition, reducing the THD of source current to meet IEEE 519 standard recommended on harmonics levels.

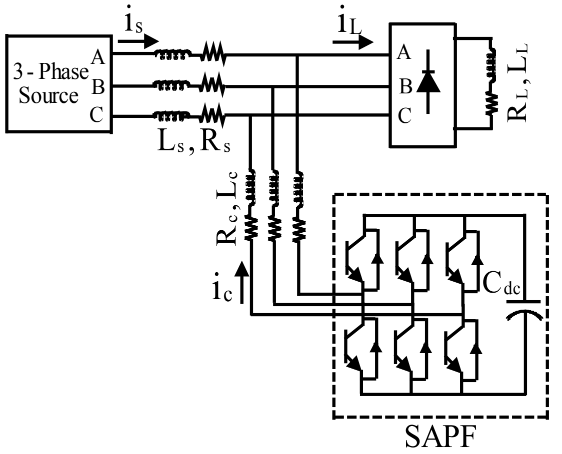


Fig.2. Shunt Active Power Filter.

II. REFERENCE SIGNAL GENERATION

A. SRF method

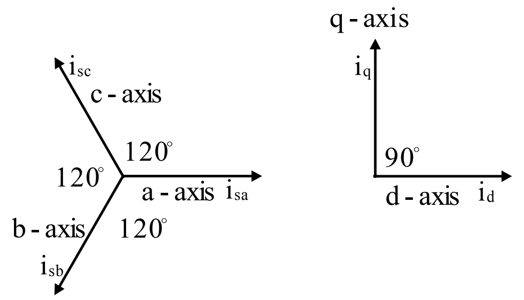


Fig.3. a-b-c to d-q transformation

The synchronous reference frame theory or d-q theory is based on Park transformation is used to generate the reference source current. The three-phase load current is transformed from a–b–c stationary system to the direct axis (d) and quadratic axis (q) rotating coordinate system (Fig.3)to make the analysis simpler. The transformationis done using (1) in [10].Fig.4 shows the control algorithm using SRF method. PLL circuit is used to synchronization the source current with source voltage. After a-b-c to d-q transformation, $i_d$current issent through a lowpass filter (LPF) for filteringthe harmonic components of the load current. The LPF allows only the fundamental frequency components. Here a second order Butterworth LPF is used with a cut off frequency of 50 Hz for eliminating the higher order harmonics. The DC-side capacitor voltage of voltage source inverter (VSI) is sensed and compared with the reference DC bus voltage for calculating the error voltage. This error voltage is passed through a PI controller which accounts for loss in the SAPF, and it is subtracted from the filtered id current. Then inverse transform from d-q axis to a-b-c axis is done to get the required three phase reference supply current.

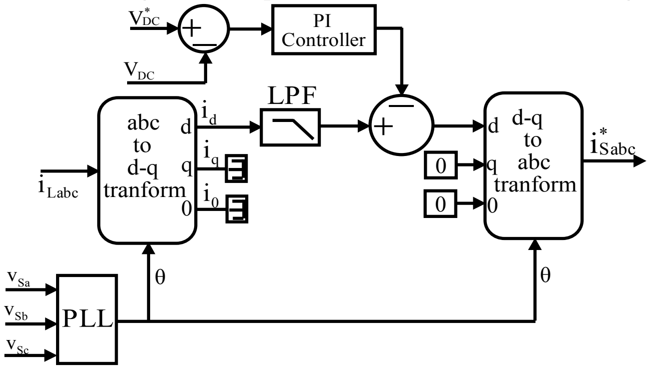


Fig.4. Reference signal generation using SRF method

B. Indirect Control Unit Vector PID Method

In this method, the peak value of the reference current is estimated by controlling the dc side capacitor voltage, while the unit vectors derived from the source voltage are used for synchronisation. Here we do not require any axis transformation which makes this method simpler than SRF method.The schematic diagram for generating the reference source currentusing Indirect Control Unit Vector PID Methodis shown in Fig.5.

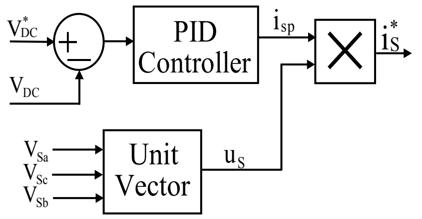


Fig.5.Reference signal generation using Indirect Control Unit Vector PID Method

It is assumed that the source voltage is sinusoidal without any harmonics.

$$v_s(t) = v_m \sin(\omega t) \tag{1}$$

The nonlinear load current $i_L(t)$can be expressed in terms of fundamental component and the harmonic component

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \emptyset_n)$$

$$i_L(t) = I_1 \sin(\omega t + \emptyset_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n) \tag{2}$$

The instantaneous load power(p_L) is then given by

$$p_L(t) = v_s(t) * i_L(t) \tag{3}$$

and this instantaneous power can be divided into real fundamental power(p_f), reactive power(p_r) and harmonic power(p_h) respectively

$$p_L(t) = p_f(t) + p_r(t) + p_h(t) \tag{4}$$

To make the source current sinusoidal, it should only contain the fundamental component. Therefore the source current after compensation should be

$$i_s(t) = p_f(t)/v_s(t) = I_1 * \cos(\emptyset_1) * \sin(\omega t)$$
$$= I_{sm} \sin(\omega t) \tag{5}$$

Where, $I_{sm} = I_1 * \cos(\emptyset_1)$

Compensation by SAPF causes some switching losses in the converter; hence the source should supply a small overhead current I_{sl} for the converter switching losses and capacitor leakage in addition to the real power of the load current I_{sm}. Hence the peak value of the reference source current is.

$$I_{sp} = I_{sm} + I_{sl} \tag{6}$$

This peak value of the reference source current has been estimated by regulating the dc side capacitor voltage [6]. The capacitor voltage is compared with a reference value, and the error is processed through a Proportional-Integral-Derivative(PID) controller and the output of the PID controller has been considered as the amplitude of the reference source current. The Derivative part of the controller is used to reduce the settling time, which brings the system to steady state within two to three cycles.

$$v_e = v_{DC}^* - v_{DC} \tag{7}$$

$$i_{sp} = k_p * v_e + k_i \int v_e dt + k_p \frac{dv_e}{dt} \tag{8}$$

The unit reference current vector (u_{sa}, u_{sb}, u_{sc}) is derived from the source voltage.

$$u_{sa} = \frac{v_{sa}}{v_{ma}}; \quad u_{sb} = \frac{v_{sb}}{v_{mb}}; \quad u_{sc} = \frac{v_{sc}}{v_{mc}} \tag{9}$$

Where $v_{sa,}\ v_{sb}$ and v_{sc} are the source voltages and $\mathrm{v_{ma}}, \mathrm{v_{mb}}$ and $\mathrm{v_{mc}}$ are the corresponding peak value of the source voltages. The peak value of the reference current is multiplied with the unit reference current vector to get the reference source current which is given as in [7].

$$i_{sa}^* = I_{sp} sin(\omega t);$$
$$i_{sb}^* = I_{sp}\, sin(\omega t - 120);$$
$$i_{sc}^* = I_{sp}\, sin(\omega t + 120) \tag{10}$$

III. ADAPTIVE HYSTERESIS BAND CURRENT CONTROLLER

ConventionallyHysteresis band current control method (HBC) was used for its improved stability, fast transient response, simple implementation & higher accuracy in current tracking[8]. Limitation of fixed hysteresis band caused uneven switching frequency as a result acoustic noise is produced and difficulty in designing input filters.

To overcome the drawbacks of HBC with fixed hysteresis band an Adaptive Hysteresis Band Current Controller (AHCC) shown in Fig.6, proposed by B.K Bose [9] is used, which maintains the switching frequency nearly constant, by changing the hysteresis band according to system parameters (reference current, source voltage & dc capacitor voltage).Estimation of the hysteresis band for maintaining the hysteresis band constant is presented in the next section.

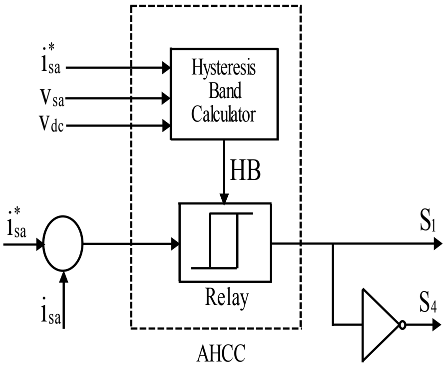


Fig.6. AHCC

IV. ESTIMATION OF HYSTERESIS BAND

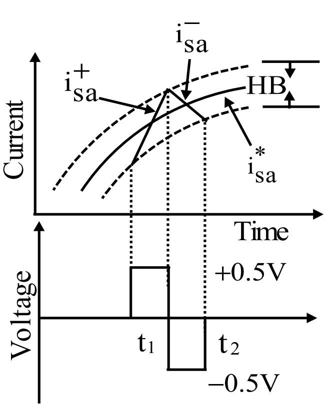


Fig.7. Current & Voltage wave form

The current and voltage waveform for phase 'a' is shown in Fig. 7 where $i_{sa}^*$is the desired reference source current and i_{sa} is the actual source current. When the source current tries to leave the hysteresis band appropriate switch is turned ON or OFF to force the ramping of the current within the hysteresis band. The following equations can be written in the respective switching intervals $t_1$and $t_2$from Fig. 7.

$$\frac{di_{sa}^+}{dt} = \frac{1}{L_c}(0.5V_{dc} + V_s) \tag{11}$$

$$\frac{di_{sa}^-}{dt} = -\frac{1}{L_c}(0.5V_{dc} + V_s) \tag{12}$$

Where, L_c is the filter inductor, i_{sa}^+ and$i_{sa}^-$are the respective rising and falling current segments. From the geometry ofFig.7 we get the following equations:

$$\frac{di_{sa}^+}{dt} t_1 - \frac{di_{sa}^*}{dt} t_1 = 2HB \tag{13}$$

$$\frac{di_{sa}^-}{dt} t_2 - \frac{di_{sa}^*}{dt} t_2 = -2HB \tag{14}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{15}$$

Where,f_c is the switching frequency and i_{sa}^* is the desired reference source current. Adding (13) & (14) and substituting in (15), we will get

$$t_1 \frac{di_a^+}{dt} - t_2 \frac{di_a^-}{dt} - \frac{1}{f_c} \frac{di_{sa}^*}{dt} = 0 \tag{16}$$

Subtracting (13) from (14), we get

$$4HB = t_1 \frac{di_a^+}{dt} - t_2 \frac{di_a^-}{dt} - (t_1 - t_2) \frac{di_{sa}^*}{dt} \tag{17}$$

Substituting (11) & (12) in (16), we get

$$(t_2 - t_1) = -\frac{2L}{v_{dc} f_c} \left(\frac{v_s}{L} + \frac{di_a^+}{dt} \right) \tag{18}$$

Substituting (11) &(12) in (17), we get

$$4HB = \frac{0.5\ v_{DC}}{f_c L} - (t_1 - t_2) \left(\frac{v_s}{L} + \frac{di_{sa}^*}{dt} \right) \tag{19}$$

Substituting (18) in (19) and simplifying, we get

$$HB = \frac{0.125 v_{dc}}{f_c L} \left[1 - \frac{4L^2}{v_{dc}^2} \left(\frac{v_s}{L} + m^2 \right)^2 \right] \tag{20}$$

Where,$m = di_a^*/dt$ is the slope ofdesired reference source current waveform. Hysteresis band (HB) calculated in (20) is modulated at different points of fundamental frequency cycle to maintain the switching frequency of the inverter constant [10]. For Simulink model a 10 kHz switchingfrequencyis taken and the frequency vs. time graph of the gate signal (Fig. 8) shows that switching frequency is maintained almost constant.

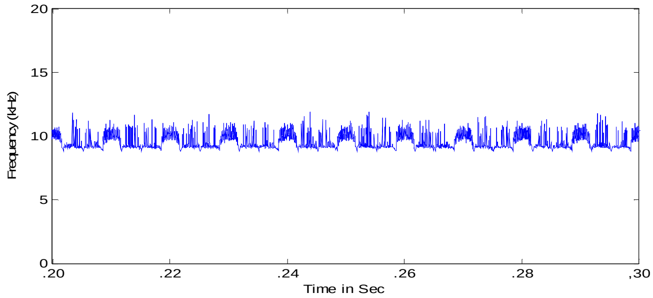


Fig.8. SwitchingFrequency vs. Time Graph

The required gating signal for APF is produced by AHCC, which follow the following switching law to generate the suitable compensating current to be injected at PCC:

- If $i_s > (i_s^* + HB)$The Upper switch of the i$^{\text{th}}$leg is ON and lower switch is OFF,
- If $i_s < (i_s^* + HB)$The Upper switch of the i$^{\text{th}}$leg is OFF and the lower switch is ON,

Here 'HB'is the calculated hysteresis band around the reference current.Complete configuration of the three phase SAPF with unit vector PID control for reference current generation and AHCC for genration gate signal for the the voltage source converter is shown in Fig.9.

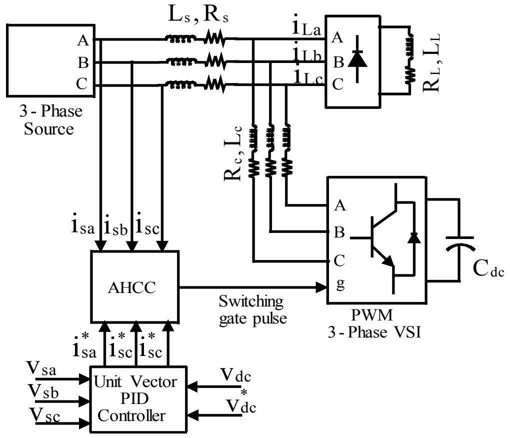


Fig. 9. Schematic diagram of the SAPF model

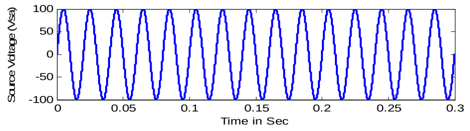
V. SIMULATIONS& RESULTS

For simulation study an ideal three phase voltage source of constant amplitude as shown Fig.10is taken while the non-linear load consists of uncontrolled thyristor based rectifier with a series RL load in the DC side. All the system parameters for simulation study are presented in Table I. For simplification only phase 'a' responses are shown. Load current is non-sinusoidal with a THD of 29.44% shown in Fig.10 (b) & (c).

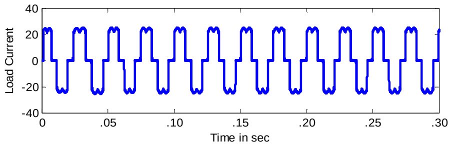
TABLE I

SCHEMATIC DIAGRAM OF THE SAPF MODEL

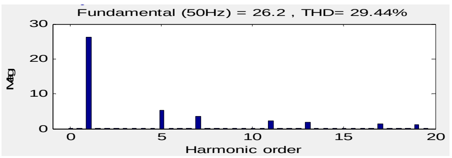
System Parameters	**Values**
Source voltage(v_s)	100V(peak)
System frequency(f)	50Hz
Source impedance(R_s, L_s)	0.1Ω;0.15mH
Filter impedance(R_c, L_c)	0.4Ω;3.35mH
Load impedance(R_L, L_L)	6.7Ω;20mH
DC link capacitance (C_{DC})	2000µF
Reference DC link voltage(V_{DC}^*)	245V
Switching Frequency (f_c)	10kHz



(a)



(b)

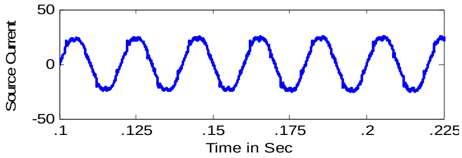


(c)

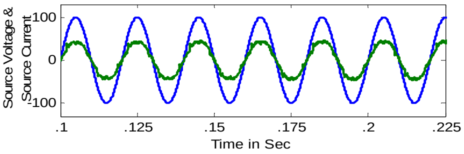
Fig. 10.Results before Compensation,(a) Source Voltage,(b) Load Current,(c) FFT analysis of Load Current

A. Constant load condition

A constant load was taken for simulation study. Compensating results with SRF & AHCC is shown in Fig.11. The source current becomessinusoidal with some ripple content in it, and it is in phase with the source voltage as shown in Fig.11 (a) & (b). The required compensating current &DC capcitor bus voltage is shown in Fig.11 (c) & (d). With the help of the combination of SRF & AHCC the THD of the source current is reduced to 3.64% from 29.44% as shown in Fig. 11 (e).



(a)



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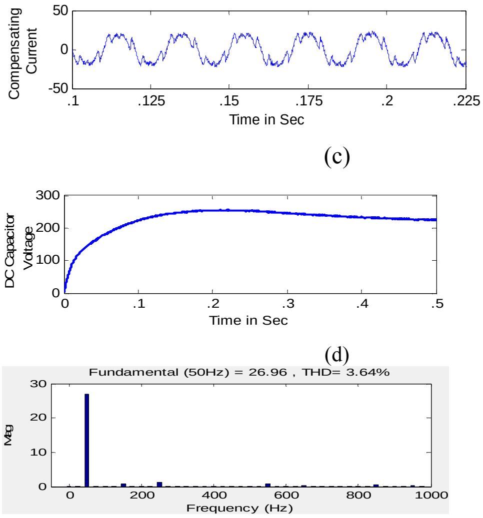


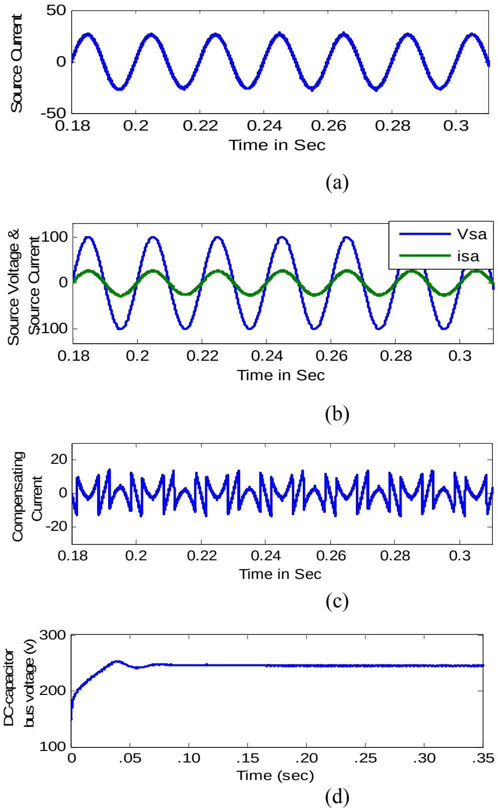
(c)

(d)

(e)

Fig. 11.Compensation with SRF & AHCC (a) Source Current,(b) Source Current in phase with Source Voltage,(c)Compensating Current, (d)DC Capacitor Bus Voltage, (e) FFT analysis of Source current.

But the combination of Indirect control unit vector PID method and AHCC produces better compensating results as shown in Fig.12. The source current is made sinusoidal with minimum harmonic content and it is in phase with the source voltage which is shown in Fig.12 (a) & (b)by injecting the required compensating current shown in Fig.12(c). FFT analysis of the source current shows (Fig. 11(e)) that the THD of the source current is reduced to 1.01% from 29.44%. Fig. 12 (d) shows that the DC capcitor bus voltage comes to steady wthin .1 sec.

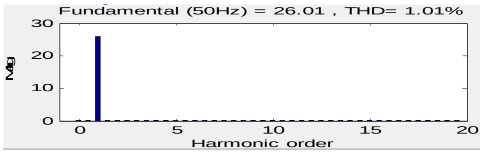


(a)

(b)

(c)

(d)



(e)

Fig. 12. Compensation with Indirect Unit Vector PID Control & AHCC (a) Source Current, (b) Source Current in phase with Source Voltage, (c)Compensating Current, (d)DC Capacitor Bus Voltage, (e) FFT analysis of Source current.

A comparartive study of harmonic contents present in the source current after compensation with the help of the two techniques is presented in Table II.

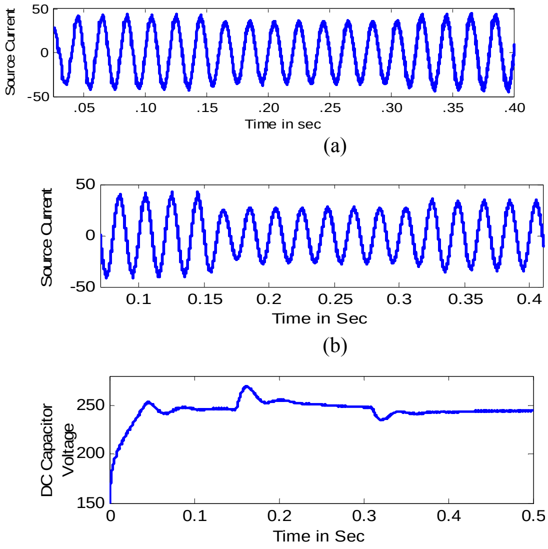
TABLE II

HARMONIC CONTENT BEFORE & AFTER COMPENSATION

Harmonic Order	**Without Compensation**	**SRF & AHCC**	**Unit Vector & AHCC**
05thOrder harmonic	20	1.3	0.2
07thOrder harmonic	15	1.1	0.2
11th Order harmonic	10	0.6	0.15
13th Order harmonic	8	0.6	0.175
17th Order harmonic	6	0.5	0.15
19th Order harmonic	5	0.6	0.20

B. *Transient load condition*

Fortransient load condition a parallel resister is connected in the DC side of the rectifer. The SAPF effectively makes thesource current sinusoidal. Combination of Indirect Unit vector PID control & AHCC gives a better result than the cobination of SRF&AHCC and brings the system into stability within 2 to 3 cycles (as shown in Fig.13 (a) & (b)) during transient condition. Fig.13 (c) shows that the DC capcitor bus voltage have voltage overshoot and voltage under shoot due to swell and sag condition respectively.



(a)

(b)

(c)

Fig. 13.Results under transient load condition (a) Source Current(SRF method), (b) Source Current (Unit vector PID method),(c)DC Capacitor Bus Voltage

CONCLUSIONS

In SRF method it requires load current for compensation while indirect control Unit vector PID methodis an indirect compensation process which requires only the source current for compensation. In this method PLL is not required and for synchronisation unit reference current vector is derived from the source voltages, thus reducing the overall cost. AHCC generates therequired gate signal to compensate the harmonics produced by the nonlinear loads. It effectively maintains the switching frequency nearly constant and hence reducing the losses produced due variable switching frequency. The simulation results show that the combination of Indirect control unit vector PID method and AHCC gives superior performance than the combination of SRF & AHCC reducing the harmonic content in the source current to their minimum values. The three phase SAPF effectively compensates the harmonics even under transient condition and brings the system into steady state within two to three cycles. The source current is made sinusoidal and in-phase with the source voltage thus making the true power factor unity. The THD of the source current is reduced to 1.01% which is below 5%, standard recommended by IEEE-519.

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