A New Control Approach to Three-Phase Active Filter for Harmonics and Reactive Power Compensation

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ABSTRACT — This paper deals with a new control scheme for a parallel 3-phase active filter to eliminate harmonics and to compensate the reactive power of the non-linear loads. A 3-phase voltage source inverter bridge with a dc bus capacitor is used as an active filter (AF). A hysteresis based carrierless PWM current control is employed to derive the switching signals to the AF. Source reference currents are derived using load currents, dc bus voltage and source voltage. The command currents of the AF are derived using source reference and load currents. A 3-phase diode rectifier with capacitive loading is employed as the non-linear load. The AF is found effective to meet IEEE-519 standard recommendations on harmonics level.

I. INTRODUCTION

Solid state power converters are widely used in applications such as adjustable speed drives (ASD), static power supplies and asynchronous ac-dc links in wind and wave generating systems. These power converters behave as non-linear loads to ac mains and inject harmonics and result in lower power-factor and efficiency of the power system. Conventionally, passive filters were the choice for the elimination of harmonics and to improve power-factor. These passive filters have the disadvantages of large size, resonance, and fixed compensation. In the last couple of decades, the concept of active filters (AF) has been introduced and many publications have appeared on this subject [1-16]. Several approaches, such as, hybrid filters and multistep inverters are reported to reduce the size of active filters [16]. Many control concepts, such as instantaneous power theory [5, 10, 11, 16], notch filters [14], and flux based controllers [15] have also been introduced. Most of these control schemes require various transformations and are difficult to implement. This paper presents a simple algorithm to achieve the control for AF. In AF, the main objective is to maintain sinusoidal unity power-factor supply currents (by shunt AF) to feed active power to the load and to meet the losses in the AF. These two components of active power can be computed from load currents, dc bus voltage and supply voltages.

From the measured active power required by the system, reference unity power-factor supply currents are derived. By subtracting load currents from these reference supply currents, compensating currents of the AF phases are obtained.

The results of simulation study of the new AF control strategy are presented in this paper. The study is based on a 3-wire 3-phase system. The familiar 3-phase uncontrolled rectifier with capacitive loading is taken as a non-linear load. The steady state and transient performance of the proposed control scheme is found quite satisfactory to eliminate the harmonics and reactive power components from utility currents.

II. SYSTEM CONFIGURATION AND CONTROL SCHEME

The basic building blocks of the conventional parallel AF are shown in Fig. 1. The AF is composed of a standard 3-phase voltage source inverter bridge with a dc bus capacitor to provide an effective current control. A hysteresis based carrierless PWM current control is employed to give fast response of the AF. The non-linear load is a dc resistive load supplied by 3-phase uncontrolled bridge rectifier with an input impedance and dc capacitor on the output. Due to capacitive loading the uncontrolled bridge rectifier draws non sinusoidal pulsating currents from ac source. Depending upon the load magnitude and its parameters it also draws reactive power from the mains. The basic function of the proposed parallel AF is to eliminate harmonics and meet the reactive power requirements of the load locally so that the ac supply feeds only the sinusoidal balanced unity power factor currents. The desired AF currents are estimated by sensing the load current, dc bus voltage, and source voltage. The hysteresis current controller generates the switching signals to AF devices to force the desired currents into the AF phases. With this control feature, the AF meets harmonic and reactive current requirements of the load. The AF connected in shunt with the load, also enhances the system efficiency as the source does not process harmonic and reactive power.

![Fig. 1 Basic Building Block of the Active Filter](image-url)
Fig. 2 shows the proposed control scheme of the shunt AF. The ac source feeds fundamental active power component of load currents and another fundamental component of current to maintain the average capacitor voltage to a desired value. This later component of source current is to feed the losses in the converter such as switching loss, ohmic loss, capacitor leakage loss, etc. in the steady state and to maintain the stored energy on the dc bus during transients conditions such as sudden fluctuations of load etc.

This component of source current ($I_{smd}$) is computed using dc bus capacitor value ($C_d$), average voltage on dc bus ($V(jc)$) and a chosen reference voltage of the dc bus ($V(jc)$). The fundamental active power component of the load currents ($I_{smp}$) is computed using sensed load currents and voltages.

The total reference source peak current ($I_{sm}$) is computed using components $I_{smc}$ and $I_{smp}$. The reference instantaneous source currents ($i_{sa}$, $i_{sb}$ and $i_{sc}$) are computed using their peak value ($I_{sm}$) and unit current templates ($u_{sa}$, $u_{sb}$ and $u_{sc}$) derived from sensed source voltages. The command currents of the AF ($i_{ca}$, $i_{cb}$ and $i_{cc}$) are computed by taking the difference between instantaneous source reference currents ($i_{sa}$, $i_{sb}$ and $i_{sc}$) and sensed load currents ($i_{La}$, $i_{Lb}$ and $i_{Lc}$). The hysteresis rule based carrierless PWM current controller is employed over the reference AF currents ($i_{ca}$, $i_{cb}$ and $i_{cc}$) and sensed AF currents ($i_{ca}$, $i_{cb}$ and $i_{cc}$) to obtain the gating signals to the devices of the AF.

The devices of the AF are considered ideal. The value of AF inductance ($L_c$) is selected on the basis of proper shaping of compensating currents. With higher value of $L_c$, compensating currents do not track reference currents and if a lower value of $L_c$ is chosen, there are large ripple in compensating currents. The AF meets the requirements of harmonic and reactive components of load currents locally, resulting in sinusoidal unity power factor source currents under varying operating conditions of the system.

in. ANALYSIS AND MODELING

The system comprises of ac source, non-linear load, the AF and the new control scheme. The components of the system are analyzed separately and integrated to develop the complete model for the simulation.

A. Control Scheme

The operation of the control scheme has been explained in the previous section. The governing equations for the different blocks are deduced in sequence.

Peak Source Current Estimation

The peak source current ($I_{sm}$) has two components estimated as follows. The source active component corresponding to the load ($I_{smp}$) is computed from the average load power ($p_s$). The instantaneous power $p_L$ is,
\[ PL = \dot{v}_{sa}^* L_a + \dot{v}_{sb}^* L_b + \dot{v}_{sc}^* L_c \]  

Here, \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) are three-phase sensed load currents and \( v_{sa}, v_{sb} \) and \( v_{sc} \) are the sensed 3-phase source voltages and under ideal conditions these can be expressed as:

\[ \begin{align*}
  v_{sa} &= V_{sm} \sin \alpha t \quad (2) \\
  v_{sb} &= V_{sm} \sin (\alpha t - 2\pi/3) \\
  v_{sc} &= V_{sm} \sin (\alpha t + 2\pi/3)
\end{align*} \]

In Eq. (2), \( V_{sm} \) is the peak of source voltage and \( \omega \) is the frequency of the ac mains in rad/sec.

If \( PL \) is averaged over one sixth the period of supply frequency it results in \( p_s \) which may be expressed as:

\[ p_s = (3/2) V_{sm} i_{sm}^* \]  

The peak fundamental unity power-factor source current component \( i_{sm}^* \) can be estimated using \( p_s \) and \( V_{sm} \) from Eq. (3).

The second component of source current \( i_{smd}^* \) is to maintain the average voltage on the dc bus at a constant value, overcoming the switching, ohmic and capacitor losses in the AF. The computation of \( i_{smd}^* \) is based on the following logic. A reference dc bus average voltage \( (v_{dc}^*) \) is assumed. By sampling the actual dc bus voltage the average \( (\bar{v}_{dc}) \) is computed over the one sixth period of supply frequency \( (T_x) \). The energy difference corresponding to \( v_{dc}^* \) and \( \bar{v}_{dc} \) over the \( T_x \) is:

\[ \Delta E_{dc} = \bar{v}_{dc}^* - \bar{v}_{dc} = \frac{C_{dc}}{2} \left[ v_{dc}^2 - v_{dc}^2 \right] \]  

The AF attempts to draw this energy difference \( \Delta E_{dc} \) from ac mains through unity power-factor current with a peak value of \( i_{smd}^* \), over the same interval \( T_x \). This energy relationship can be expressed as:

\[ \Delta E_{dc} = \left( \frac{3}{2} V_{sm} i_{smd}^* \right) T_x \]  

From Eq. (5), \( i_{smd}^* \) is obtained. When \( V_{dc} \) well chosen, under steady state operation \( v_{dc}^* \) will never become equal to \( \bar{v}_{dc} \) but \( i_{smd}^* \) will be established to a fixed value as demanded by the losses in the AF. Under transient condition, \( i_{smd}^* \) will take either positive or negative value as demanded by the energy exchange between the AF and the load.

The total peak source current from equations (3) and (5) is:

\[ i_{sm}^* = i_{sm}^* + i_{smd}^* \]  

\[ p_{ic} = -(R_c/L_c) i_{ca} + (v_{sa} - V_{ca}^c) \]  

\[ p_{ic} = -(R_c/L_c) i_{cb} + (v_{sb} - v_{b})/T_c \]  

Harmonic free unity power-factor, 3-phase source currents may be estimated using unit current templates in phase with source voltages and the computed peak values.

\[ v_{sa} = V_{sa}/V_{sm}; \quad v_{sb} = V_{sb}/V_{sm}; \quad v_{sc} = V_{sc}/V_{sm} \]

The reference 3-phase source currents are estimated as:

\[ i_{sa}^* = i_{sm}^* v_{sa}/v_{sm}; \quad i_{sb}^* = i_{sm}^* v_{sb}/v_{sm}; \quad i_{sc}^* = i_{sm}^* v_{sc}/v_{sm} \]

The 3-phase AF reference currents are estimated using the reference source currents in Eq. (8) and the sensed load currents as:

\[ i_{ca} = -i_{ca} - i_{La}; \quad i_{cb} = i_{sm}^* v_{sb}/v_{sm}; \quad i_{cc} = i_{sm}^* v_{sc}/v_{sm} \]

\[ v_{sa} = v_{sa} + \frac{v_{sb}}{V_{sm}}; \quad v_{sb} = V_{sm} v_{sb}/v_{sm}; \quad v_{sc} = V_{sm} v_{sc}/v_{sm} \]

**Reference AF Currents Generation**

The current controller decides the switching pattern of the AF devices. The switching logic is formulated as follows:

If \( i_{ca} < (i_{ca} - h_b) \) upper switch is OFF and lower switch is ON for leg ‘a’ (SA = 1).

If \( i_{ca} > (i_{ca} + h_b) \) upper switch is ON and lower switch is OFF for leg ‘a’ (SA = 0).

\[ i_{ca} = i_{ca} - i_{La}; \quad i_{cb} = i_{sm}^* v_{sb}/v_{sm}; \quad i_{cc} = i_{sm}^* v_{sc}/v_{sm} \]

\[ v_{sa} = v_{sa} + \frac{v_{sb}}{V_{sm}}; \quad v_{sb} = V_{sm} v_{sb}/v_{sm}; \quad v_{sc} = V_{sm} v_{sc}/v_{sm} \]

**Reference AF Currents Generation**

The 3-phase AF reference currents are estimated using the reference source currents in Eq. (8) and the sensed load currents as:

The AF currents \( i_{ca}, i_{cb} \) and \( i_{cc} \) are regulated to be in good agreement with the reference values \( i_{ca}^*, i_{cb}^* \) and \( i_{cc}^* \).

**B. Active Filter (AF)**

Three-phase ac source through the source inductances is the input to the AF (3-phase VSI bridge) and dc bus with a capacitor \( (C_{dc}) \) is its output. The AF operating in the current controlled mode is modeled by the following differential equations:

\[ p_{ic} = -(R_c/L_c) i_{ca} + (v_{sa} - V_{ca}^c) \]  

\[ p_{ic} = -(R_c/L_c) i_{cb} + (v_{sb} - v_{b})/T_c \]
impedance and capacitive-resistive loading is taken as a non-

$\frac{d}{dt}$ and switching functions

$V(j_{reflected \ on \ ac \ input \ side \ of \ the \ AF \ expressed \ in \ terms \ of \ the \ instantaneous \ dc \ bus \ voltage \ (V_{dc}) \ and \ switching \ functions}$

as:

$v_{ca} = (v_{dc}/3)(2SA - SB - SC)$

$v_{cb} = (v_{dc}/3)(-SA + 2SB - SC)$

$v_{cc} = (v_{dc}/3)(-SA - SB + 2SC)$

C. Nonlinear Load

A 3-phase uncontrolled diode bridge rectifier with input

impedance and capacitive-resistive loading is taken as a non-

linear load (Fig. 1). It has two operating modes based on the
diode conduction state.

When the diodes are conducting, the ac source (line-line

voltage) is connected to the load and the basic equations are :

$2 R_s i_{d} + 2 L_s i_{p} + v_L = v_a$

which may be modified as :

$p i_d = (v_s - v_L - 2 R_s i_d)/(2 L_s)$

The capacitor charging/discharging equation is :

$p v_L = (i_d - i_{R_L})/C_L$

where $R_s$ and $L_s$ are the resistance and inductance of the ac

source. $C_L$ is the load capacitance on the dc side and $V_L$ is

the instantaneous voltage across it. "id" is the current flowing

from ac source through a diode pair to charge the capacitor

$C_L$ and $fr$ is the resistive load current ($V_L/R_s$).

"v_a" is the ac source line voltage segment ($v_{a_b}, v_{a_c},$

$v_{b_c} > v_{c_b} > v_{c_a} > v_{a_c}$) depending on which diode pair is

conducting. Similarly the load currents in all the 3-phases of

the ac source ($iLa, iLb, iLc$) are obtained using the

magnitude of id and sign corresponding to conducting pairs of
diodes. When none of the pairs of diodes is conducting, id and

its derivative will be zero. However, charged capacitor

$C_L$ will be discharged through load resistor $R_L$ and equation

(16) will be modified accordingly.

The set of first order differential equations (10), (11),

(12), (13), (15), and (16) along with other expressions define

the dynamic model of the AF system. These equations are

solved using fourth order Runge-Kutta method in FORTRAN

to analyze the dynamic and steady state performance of

the AF system. A standard FFT package is used to compute the

harmonic spectrum and THD of the ac load and source currents.

IV. PERFORMANCE OF AF SYSTEM

Performance characteristics of the AF system with

proposed control scheme are given in Figs. 3-5 illustrating the

steady state and transient behavior at different loads. The

parameters of the system studied are given in the Appendix.

Fig. 3 shows the source voltage, 3-phase currents, load

current, AF current and dc bus voltage when an extra load of

10 kW is added after two cycles. The source currents respond

very quickly and settle to steady state value within a cycle.

the AF current increases almost instantaneously to feed the

increased load current demand by taking the energy

instantaneously from dc bus capacitor. DC bus capacitor

voltage recovers within a cycle. Source currents always

remain sinusoidal and lower than the load currents. Load

current changes from discontinuous to continuous with

increased load. The active power supplied from source

changes from 8 kW to 18 kW. The sixth harmonic voltage

ripple is observed in dc bus voltage and its magnitude varies

well within 2 % of the reference value. Fig. 4 shows similar

results as in Fig. 3 for sudden decrease of load. The active

power supplied from source is decreased from 18 kW to 8

kW. Source currents settle to steady state value within a cycle

demonstrating the excellent transient response of the

AF. DC bus voltage rises only to 481 V but reaches the

steady state value within a cycle. Load current changes from

continuous to discontinuous form. Source currents remain

always less than the load currents under all operating

conditions. The AF meets the requirements of harmonic and

reactive components of load current and maintains the source

currents sinusoidal in transient and steady state conditions.

Fig. 4 shows the harmonic spectra of the load and the

source currents at light (8 kW) and heavy (18 kW) load

conditions. It may be observed from the harmonic spectra of

Figs. 5(a) and 5(c) that the dominant harmonics in load

currents are of order below 30th and the AF is found effective

to eliminate them. The THD of source current is reduced

from 105 % to 2.07 % under light load (8 kW) and from 53 %
to 1.07 % during heavy load (18 kW). The AF is quite

effective to reduce the THD well below the specified 5 %

limit of standard IEEE-519.

The performance of the proposed control algorithm of the

AF is found to be excellent and the source current is

practically sinusoidal and in phase with the source voltage.

The fast response of the AF ensures that the AF is not

overburdened during transient conditions. The voltage ripple

is quite small in dc bus capacitor voltage and may be reduced

further by increasing the capacitor value. Surge in dc bus

voltage is observed to be +8 % during transients which may be

controlled by the design to a lower value but at the expense of

increased value of source currents during transients. However, this surge in dc bus voltage reduces with increased value of bus capacitor.

V. CONCLUSIONS

This paper demonstrates the validation of a simpler

control approach for the parallel active power filter. The AF
is observed to eliminate the harmonic and reactive components of load current resulting in sinusoidal and unity power-factor source currents. It is observed that the source current remains below the load current even during transient conditions. The AF enhances the system efficiency because the source need not process the harmonic and reactive power demanded by the load. Experimental verification of the scheme based on the new concept is being performed and test results will be reported in the future.

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VII. REFERENCES


VIII. APPENDIX

\[ V_{\text{rms/phase}} = 127 \text{ V, } F = 60 \text{ Hz, } R_c = 0.1 \text{ ohm, } \]
\[ L_c = 0.3 \text{ mH, } C_L = 330 \mu \text{F, } R_s = 0.01 \text{ ohm, } L_s = 0.25 \text{ mH, } \]
\[ C_{dc} = 1500 \text{ fiF.} \]

IX. BIOGRAPHIES

Bhim Singh was born at Rahamapur, U.P. (India) in 1956. He received his B.E. degree from University of Roorkee, and M. Tech. and Ph.D. degrees from Indian Institute of Technology, New-Delhi in 1977, 1979 and 1983, respectively. In 1983 he joined as a Lecturer and subsequently became Reader in 1988 in Department of Electrical Engineering, University of Roorkee. In December, 1990 he joined as an Assistant Professor in the Department of Electrical Engineering at IIT, New-Delhi. Since February 1994 he is an Associate Professor at Indian Institute of Technology, New-Delhi. His field of interest includes CAD, power electronics, active filters, static VAR compensation, analysis and digital control of electrical machines. He is a member of IE(I) and life member of ISTE, SSI and NIQR.

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