Harmonic elimination, reactive power compensation and load balancing in three-phase, four-wire electric distribution systems supplying non-linear loads

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Abstract

In this paper, a new control scheme of a three-phase active power filter (APF) is proposed to eliminate harmonics, to compensate reactive power and neutral currents and to remedy system unbalance, in a three-phase four-wire electric power distribution system, with unbalanced non-linear loads. The APF is realized using three single phase IGBT based PWM-VSI bridges with a common dc bus capacitor. A hysteresis rule based carrierless PWM current controller is used to derive gating signals for the IGBTs. Three-phase balanced reference supply currents are estimated using load currents, dc bus voltage and supply voltages. The reference currents of the APF are derived by taking the difference of corresponding reference supply current and load current. The APF forces the compensating currents to conform to the desired reference currents. The APF is found effective to compensate reactive power and neutral current while eliminating harmonics with load balancing.

Keywords: Harmonic elimination; Reactive power compensation; Active power filter; Load balancing

1. Introduction

In modern electric power supply distribution systems, there is a sharp rise in the use of single phase and three-phase non-linear loads such as computer power supplies [1], commercial lighting [2], rectifier equipment in telecommunication networks, domestic equipments like TVS, ovens, adjustable speed drivers (ASD) and asynchronous ac–dc links as in wind, and wave electric power generation systems. These non-linear loads generally have solid state control of electric power and draw non-sinusoidal unbalanced currents from ac mains resulting in harmonic injection, reactive power burden, excessive neutral currents and unbalanced loading of ac mains. Further, they cause poor power-factor, low efficiency, neutral conductor bursting and interference with nearby communication networks. Conventionally loss-less L-C filters are used to reduce harmonics and power capacitors are employed to improve the power factor of the ac supply but they have drawbacks of fixed compensation characteristics, resonance and large size. Because of increased pollution of the supply system, this field has attracted the attention of power electronics experts in the last two decades and a number of attempts [3–26] have been made on the analysis, design and development of equipment generally named as active power filter (APF) to provide a dynamic and adjustable solution to eliminate harmonics and reactive power burden on the ac mains.

Initially APFs were developed using BJTs [3] but nowadays other devices such as GTO, MOSFET, SIT and IGBT are being employed in a number of APF configurations. Large number of APF circuit concepts are reported with shunt [8–11], series or hybrid configurations [14,15] generally named as unified power quality conditioners [16]. Many approaches such as notch filter [20,21], instantaneous reactive power theory [11], syn-
chronous detection method [19], synchronous d–q frame method [14], flux based control [15] and closed loop P–I [14,15] and sliding mode control [13,17] are used to improve the performance of the APFs. These approaches have become feasible because of the advent of new microelectronic devices such as DSPs and micro-controllers, and availability of fast and accurate hall effect sensors.

The problem of unbalanced load is well known to power engineers for a long time and thyristor based compensators [5,6] were developed but they introduced harmonics in the ac mains. In the literature, numerous attempts are reported on individual aspects of three-phase, three-wire APFs [8–15] and single phase APFs [23–26] to cancel neutral currents [21,22] and harmonic elimination of unbalanced non-linear loads [18–20]. It is worthwhile to investigate a new control method of an APF which can compensate harmonics, reactive power burden, load unbalance and neutral currents. This paper presents studies on the new control scheme of such an APF.

2. System configuration and control scheme

Fig. 1 shows the basic APF scheme including a set of non-linear loads on a three-phase, four-wire electric supply system. The load may be either single phase, two-phase or three-phase and non-linear in nature. In the present case, three single phase uncontrolled diode bridge rectifiers with resistive-capacitive loading are considered as non-linear unbalanced loads on fourwire, three-phase ac mains. This load draws a non-sinusoidal currents from ac mains.

An IGBT based voltage source inverter [11] having an energy storage capacitor on dc bus is employed as an APF. It has three single phase VSI bridges with a common dc bus to facilitate the independent control of all the three phases of the APF and return path through neutral conductor [11]. A hysteresis rule based carrierless PWM current control technique [10,14,15] is used to realize desired currents in the three phases of the APF. The main objective of the APF is to compensate harmonics, reactive power, neutral current and unbalancing of non-linear loads locally such that ac mains supplies only unity power-factor sinusoidal balanced three-phase currents.

The block diagram of the proposed control scheme is shown in Fig. 2. AC mains supplies active power component of load currents and other active power components of current to maintain the average voltage of the dc bus capacitor to a constant value. This second component of supply current feeds losses in the VSI bridge such as switching losses, leakage current of capacitor, etc. under steady state conditions and to regulate the stored energy on the dc bus of the APF under transient conditions imposed on the system. This component of peak of supply currents (I_{m}}) is computed by using average dc bus voltage, value of the capacitor and required reference value of dc bus voltage (I_{m}) (v_{dc}). The main component of peak of supply currents (I_{m}) to feed load currents is computed using sensed load currents and supply voltages. The total peak value of supply currents (I_{m}) is computed by adding these two components (I_{m} + I_{m}). Three-phase instantaneous reference supply currents (i_{a}^{*}, i_{b}^{*} and i_{c}^{*}) are computed by multiplying this peak magnitude (I_{m}) with unit current templates (i_{a}, i_{b} and i_{c}) derived in phase with supply voltages (v_{a}, v_{b} and v_{c}). Three-phase instantaneous reference currents of an APF (i_{a}^{*}, i_{b}^{*} and i_{c}^{*}) are computed by subtracting load currents (i_{a}, i_{b} and i_{c}) from reference supply currents (i_{a}^{*}, i_{b}^{*} and i_{c}^{*}). A hysteresis rule based carrierless PWM current control technique is employed over the current errors of the three-phase sensed and reference currents of the APF to derive gating signals to the IGBTs of the VSI bridges. The APF draws the required currents from the ac mains to feed harmonics, reactive power, neutral
current and for balancing of load currents locally and causes balanced sinusoidal unity power-factor supply currents under all operating conditions.

3. Modeling of the APF system

Different components of the system are modeled separately and integrated to develop the overall model for the simulation of steady state and transient behavior.

3.1. Control scheme

The operation of the control scheme, shown in Fig. 2, has been discussed in an earlier section. Different steps in the scheme are modeled as follows.

3.1.1. Computation of peak reference current of the supply

The reference current has two components ($I_{a}^*$ and $I_{sm}^*$) and the first component $I_{sm}^*$ corresponding to load is computed from instantaneous load power. The instantaneous load power is

$$p_i = v_{sa}i_a + v_{sb}i_b + v_{sc}i_c$$

where $i_a$, $i_b$, and $i_c$ are three-phase load currents, of which some may be zero; $v_{sa}$, $v_{sb}$, and $v_{sc}$ are three-phase line to neutral voltages of the mains; under ideal conditions,

$$v_{sa} = V_{sa} \sin \omega t; \quad v_{sb} = V_{sa} \sin(\omega t - 2\pi/3);$$

$$v_{sc} = V_{sa} \sin(\omega t + 2\pi/3)$$

(2)
where \( V_{sm} \) is the peak value of phase voltage and \( \omega \) is the frequency in rad s\(^{-1}\).

The average power of the load \( (p_L) \) to be supplied by the ac mains can be computed by averaging \( p_1 \) and expressed as

\[
p_L = (3/2)V_{sm}I_{ml} \cos \phi_1 = (3/2)V_{sm}I_{sm}^* \tag{3}
\]

where \( I_{ml} \) is the peak of fundamental supply current and \( \cos \phi_1 \) is the fundamental power-factor (displacement factor) of the load.

From Eq. (3) the supply peak current \( I_{sm}^* \) for unity power-factor corresponding to load average power is computed as

\[
I_{sm}^* = p_L/(3V_{sm}) = I_{ml} \cos \phi_1 \tag{4}
\]

The second component of supply reference current \( I_{sm}^* \) to restore the energy on dc bus for regulating its voltage to constant value, is computed based on energy balance. In the present work, the losses in APF, being very small, are neglected. The nominal stored energy \( (e_{dc}^*) \) on the dc bus of the APF is

\[
e_{dc}^* = C_{dc}(v_{dc}^*)^2/2 \tag{5}
\]

where \( v_{dc}^* \) is the reference voltage across the dc bus capacitor \( C_{dc} \).

But, the actual average stored energy on dc bus is

\[
e_{dc} = C_{dc}v_{dc}^2/2 \tag{6}
\]

where \( v_{dc} \) is the average value of the actual dc bus voltage.

Thus energy loss of dc bus capacitor is

\[
\Delta e_{dc} = e_{dc}^* - e_{dc} = C_{dc}((v_{dc}^*)^2 - v_{dc}^2)/2 \tag{7}
\]

This energy difference, encountered in the APF, must be supplied by the three-phase ac mains. The corresponding peak value of supply current \( I_{sm}^* \) is computed as

\[
I_{sm}^* = \int_0^T \left[ v_{sm}^* \left( at + v_{dc}^* \right) \sin (ot + 2\pi/3) + v_{dc}^* \sin (ot + 2\pi/3) \right] dt = \Delta e_{dc}/(3TV_{sm}) \tag{8}
\]

where \( T \) is the half cycle period of the supply frequency over which the averaging is carried out. The net peak value of supply currents \( I_{sm}^* \) from Eq. (4) and Eq. (8) is

\[
I_{sm}^* = I_{sm}^* + I_{sm} \tag{9}
\]

3.1.2. Computation of instantaneous reference supply currents

The instantaneous three-phase reference supply currents are computed using Eq. (9) as

\[
i_{sm}^* = I_{sm}^* u_{sa}^*; \quad i_{sb}^* = I_{sm}^* u_{sb}^* \quad \text{and} \quad i_{sc}^* = I_{sm}^* u_{sc}^* \tag{10}
\]

where \( u_{sa}^* \), \( u_{sb}^* \) and \( u_{sc}^* \) are unit current vectors obtained from Eq. (2) and peak supply voltages as

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

3.1.3. Computation of instantaneous reference APF currents

The APF currents are computed using Eq. (10) and sensed load currents \( i_{a}, i_{b} \) and \( i_{c} \) as

\[
i_{a}^* = i_{a} - i_{sa}; \quad i_{b}^* = i_{b} - i_{sb} \quad \text{and} \quad i_{c}^* = i_{c} - i_{sc} \tag{11}
\]

3.1.4. Hysteresis rule based carrierless PWM current controller

The APF comprises of three single phase VSI bridges isolated with unity turns ratio transformers [11] and connected to a common dc bus capacitor. The current controllers of the three-phases are designed to operate independently. Each current controller determines the switching signals to its VSI bridge. The switching logic for ‘phase-a’ is formulated as: if \( i_{sa} < (i_{a}^* - h_{a}) \) upper switch is OFF and lower switch is ON in the left leg of ‘phase-a’ and SAL = 0; if \( i_{sa} > (i_{a}^* + h_{a}) \) upper switch is ON and lower switch is OFF in the left leg of ‘phase-a’ and SAL = 1.

The right leg devices of ‘phase-a’ bridge are switched in a complementary manner to left leg devices, i.e. SAL is the complement of SAR.

In the same fashion, the switching of ‘phase-b and c’ devices are derived using \( h_{b} \) the width of hysteresis band.

3.2. Active power filter (APF)

The unity turns ratio transformer in each phase has equivalent inductance \( (L_e) \) and resistance \( (R_e) \) at ac input. The common dc bus capacitor is \( C_{dc} \). These APF may be modeled by the following state space equations.

\[
p_i = - (R_e/L_e)i_i + (v_i - v_{dc})/L_e \tag{12}
\]

\[
p_i = - (R_e/L_e)i_i + (v_i - v_{dc})/L_e \tag{13}
\]

\[
p_i = - (R_e/L_e)i_i + (v_i - v_{dc})/L_e \tag{14}
\]

\[
p_i = (i_{ead} + i_{ead})/C_{dc} \tag{15}
\]

where \( p \) is the differential operator \( (d/dr) \) and \( t_{ead} \) and \( t_{ead} \) are the charging currents to the dc bus of the APF from the three single phase VSI bridges. The currents depend on the switching logic and are expressed as

\[
i_{ead} = i_{ead}(\text{SAL} - \text{SAR});
\]

\[
i_{ead} = i_{ead}(\text{SBL} - \text{SBR}) \quad \text{and} \quad i_{ead} = i_{ead}(\text{SCL} - \text{SCR})
\]

where SAL, SAR, SBL, SBR, SCL, SCR are the switching functions.
Fig. 3. Performance of APF system for load change from three-phase (5.82 kW) to two-phase (3.95 kW) to single phase (1.98 kW) to two-phase (3.95 kW) to three-phase (5.82 kW).

Voltages $v_{ca}$, $v_{cb}$ and $v_{cd}$ are the three-phase PWM voltages reflected on the ac input side computed as

$$v_{ca} = v_{dc}(SAL - SAR);$$

$$v_{cb} = v_{dc}(SBL - SBR) \text{ and } v_{cd} = v_{dc}(SCL - SCR)$$

The neutral current ($i_{na}$) of the APF is computed by adding the three APF currents $i_{ca}$, $i_{cb}$ and $i_{cd}$.

3.3. Non-linear loads on the system

Three non-linear loads are connected in the ac mains one across each phase and the neutral. Each load consists of an input impedance $(L_a, R_a)$, diode bridge and resistive-capacitive $(R_c, C_l)$ dc side loading. The non-linear load draws non sinusoidal current from ac mains. Two operating modes are possible depending on the conduction state of the diodes. In the first mode, when diodes are in conduction, the ac mains is connected to the load and the equation for ‘phase-a’ load is

$$R_{i_{ia}} + L_{i_{ia}}i_{ia} + v_{ia} = i_{ia}$$

which may be expressed in state space form as

$$p_{i_{ia}} = (v_{ia} - v_{ia} - R_{i_{ia}}i_{ia})/L_{i_{ia}}$$

and the charging equation is

$$p_{v_{ia}} = (i_{ia} - i_{ia})/C_{i_{ia}}$$

where $v_{ia}$ is the voltage across dc load capacitor $C_{i_{ia}}$. Current $i_{ia}$ is the load current drawn from ac mains and $i_{ia}$ is the magnitude of $i_{ia}$, $i_{ia}$ is the dc load current ($i_{ia}$).

When diodes are not conducting, $i_{ia}$ and $i_{ia}$ will be zero and charged capacitor ($C_{i_{ia}}$) with voltage $v_{ia}$ will feed the dc load $(R_{i_{ia}})$ and Eq. (17) will be modified accordingly.

Similar equations can be derived for phases $b$ and $c$ non-linear loads. The neutral current of the load $(i_{na})$ is estimated by adding the three ac load currents $i_{ia}$, $i_{ib}$ and $i_{ia}$.

The set of first order non-linear differential Eqs. (12)–(17) with additional four equations for the other two phase loads along with other essential expressions define the dynamic model of the APF system. When any phase is not being loaded, the model equations are modified appropriately. These equations are integrated
using fourth order Runge–Kutta method to simulate the transient and steady state behavior of the APF system. A standard FFT package is used to estimate harmonic spectrum and THD of the ac load current, neutral current of the load and supply currents.

4. Performance of APF system

Performance characteristics of the APF system with new control method are shown in Figs. 3 and 4 illustrating the steady state and transient behavior. The harmonic spectrum of supply, load and neutral currents for single phase, two-phase and three-phase non-linear loads are also presented.

The essential parameters of the system are given in the Appendix A. From these results, the following observations are made.

Fig. 3 shows the supply, load, neutral and APF currents for a pattern of load variations. Initially, the load is 5.82 kW and then varies to 3.95, 1.98, 3.95 kW and finally back to 5.82 kW. The APF has a fast dynamic response and the supply currents, APF currents and dc bus voltage settle down to new values within a cycle of supply frequency after a change in load. Supply currents remain sinusoidal and balanced and are lower than load currents under steady state as well as transient conditions even while feeding unbalanced non-linear loads. The neutral current of the APF ($I_{n}$) is exactly out of phase and equal in magnitude to load neutral current ($I_{n}$), resulting in zero neutral current in supply neutral conductor for all operating con-
ditions. DC bus voltage has a dip of 8.4% (to 204 V) and rise of 7% (to 242 V) following sudden application and removal of load.

Fig. 4 shows the harmonic spectrum of supply currents (a, b, c) load current (d) and load neutral currents (d, e, f) under single phase, two-phase and three phase loading conditions. Fig. 4(a) shows the harmonic spectrum of supply currents (5.15 A rms) under single phase non-linear load (1.98 kW). The APF has reduced the THD to 0.65% from 38.7% of load current (16.85 A rms) and the harmonic spectrum is shown in Fig. 4(d). Fig. 4(b) shows the harmonic spectrum of supply currents (10.98 A rms) under two-phase non-linear load (3.95 kW). The APF is effective to reduce its THD to 2.28% from 38.7% of load current as shown in Fig. 4(d). Fig. 4(c) shows the harmonic spectrum of supply currents (15.22 A rms) while feeding three-phase non-linear loads (5.82 kW). The THD of supply currents has reduced to 0.27% from 38.7% of load current (16.85 A rms) as shown in Fig. 4(d). Fig. 4(d) shows the harmonic spectrum of load current (16.85 A rms) which is also the neutral load current. The new APF is used in the distribution system with good results in reducing harmonic distortion and THD.

The performance of the APF is observed to be excellent and it has maintained balanced sinusoidal supply currents at unity power-factor at different types of unbalanced non-linear loads. The APF is found effective in reducing supply neutral current to almost zero value.

5. Conclusions

The new control approach for the three-phase APF has been demonstrated to result in sinusoidal, unity power-factor, balanced supply currents. Performance of the APF is observed to be excellent as it leads to reduced harmonics, reactive power burden and neutral currents. The unbalancing caused by unbalanced non-linear loads is also remedied at the supply mains. The supply currents always remain below load currents resulting in increased loading capability of the distribution system. The APF enhances the system efficiency as it avoids harmonic injection, reactive power burden and neutral currents.

Appendix A

\[
I_c (\text{rms/phase}) = 127 \text{ V}, \quad F = 60 \text{ Hz}, \quad R_c = 0.1 \Omega, \quad L_c = 2.5 \text{ mH}, \quad C_f = 470 \mu\text{F}, \quad R_s = 1 \Omega, \quad L_s = 0.25 \text{ mH}, \quad C_{dc} = 3000 \mu\text{F}, \quad R_i = 8 \Omega.
\]

References


