A Simple Control Scheme for Single-Phase Shunt Active Power Filter with Fuzzy Logic Based DC Bus Voltage Controller

H. Doğan, R. Akkaya

***Abstract*—In this paper, a simple control scheme of single-phase shunt active power filter for current harmonics and reactive power compensation of linear and non-linear loads, is proposed. Simplicity of the proposed control scheme is based on uncomplicated reference source current generation and fuzzy logic based dc bus voltage regulation methods. Thus, complex computations are not needed. To indicate reactive power and current harmonics compensation capability in both transient and steady state, leading and lagging power factor linear loads and uncontrolled rectifier and thyristor based ac regulator non-linear loads are connected to the system. The effectiveness of the proposed control technique is verified by the simulation results.**

***Index Terms*—active power filter, fuzzy logic controller, hysteresis current controller, reference source current.**

I. INTRODUCTION

In recent years with the development of power semiconductor technology power electronics based devices such as static var compensators (SVCs), adjustable speed drives (ASDs) and uninterruptible power supplies (UPSs) are widely employed in various applications. Because of their nonlinear V-I characteristics these devices draw current with harmonic content and reactive power from ac mains. Current harmonics drawn by nonlineer loads disturb the waveform of the voltage at the point of common coupling (PCC) and lead to the voltage harmonics that the other linear loads and sensitive electronic equipments have to deal with.

Conventionally, to reduce harmonics passive LC filters and to improve power factor of the ac loads capacitor banks were used. However these solutions have the demerits of large size and weight, fixed compensation design, increased operating losses and risk of resonance occurrence [1]. Power system and power electronics engineers made an effort to develop dynamic and adjustable solution to these power quality problems and a concept of active power filter (APF) –also called active power line conditioner (APLC) or active power quality conditioner (APQC)– was introduced first a couple of decade ago by Gyugi and Strycula [2].

Since then many researches have been done on active power filters and their practical applications. With the emergence of semiconductor devices IGBTs and MOSFETs which have the advantage of fast switching capability and the availability of digital signal processors (DSPs), field programmable gate arrays (FPGAs), hall effect voltage/current sensors at reasonable cost usage of active power filters has become widespread. Today modern active power filters are superior in filtering performance, smaller in physical size and more flexible in application compared to traditional passive filters. However the APFs have still the disadvantages of higher cost and complexity of control [3].

Among the active power filter configurations, shunt APF is the most important and most widely used in industrial processes. It is connected in parallel with the non-linear load as shown in Fig. 1, thus can easily be adapted to existing plants. Main purpose of the filter is to cancel the load current harmonics injected to the supply but it can also implement reactive power compensation and three phase currents balancing [4].

Active power filters can be divided into single phase and three phase active filters. Single phase APFs have attracted less attention than three phase APFs because they are limited to low power applications. However, installing low power single phase APF near each single phase non-linear load may be sometimes a better solution than installing one medium power three phase APF at the point of common coupling due to simplicity of control without complex heavy mathematical equations and decreasing cost of APF from medium to low power.

In this paper, a simple control scheme of single-phase shunt active power filter for harmonic and reactive power compensation of linear and non-linear loads, is proposed. Proposed APF consists of two major parts; power circuit and control circuit. Power circuit comprises a voltage source single phase converter that works bidirectionally in two modes; inverter and charger, an energy storage capacitor at the dc side and a filter inductor at the ac side. Control circuit comprises a reference current generator, a hysteresis current controller and a fuzzy logic based dc bus voltage controller. Outputs of control cicuit are the gating signals for the power switches. Leading and lagging power factor linear loads and uncontrolled rectifier and thyristor based ac regulator non-linear loads are considered to be compensated for current harmonics and reactive power by the proposed shunt APF. To indicate the steady state and transient performance, some simulation results are presented.

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H. Doğan is with the Selcuk University, Dept. of Elect.&Electronics Eng., 42075, Konya, TURKEY (e-mail: huseyindogan@selcuk.edu.tr).
Phone: 90-332-2232056 Fax: 90-332-2410635

R. Akkaya, is with the Selcuk University, Dept. of Elect.&Electronics Eng., 42075, Konya, TURKEY (e-mail: akkaya@selcuk.edu.tr).

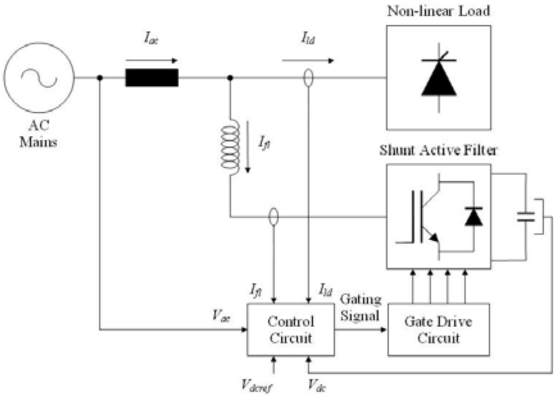

Fig. 1. Block diagram of shunt active power filter

II. ACTIVE POWER FILTER TOPOLOGY

Block diagram of the proposed shunt APF is shown in Fig. 1. It comprises a voltage source single phase IGBT based full bridge converter with an energy storage capacitor at the dc side and connected in parallel with the linear or non-linear load through a filter inductor at the ac side.

To represent reactive power compensation capability, leading and lagging power factor linear loads and to represent both reactive power and current harmonics compensation capability uncontrolled rectifier and thyristor based ac regulator non-linear loads are connected to the system. Load types mentioned above are shown in Fig. 2.

Operating principle of shunt APF depends on providing reactive and harmonic components of load current. By this way, filter and load together behaves like a resistive load and only fundamental component of load current in phase with voltage is drawn from ac mains.

III. CONTROL STRATEGY

A. Reference Source Current Generation

In order to determine harmonic and reactive component of load current, reference source current generation is needed. Thus, reference filter current can be obtained when it is substracted from total load current. For better filter performance, generation of reference source current should be done properly. For this purpose several methods such as pq-theory [5]-[8], dq-transformation [9], multiplication with sine function [10]-[12] and fourier transform [13]-[14] have been introduced in literature. In this paper multiplication with sine function method is used for extraction of reference source current as shown in Fig. 3. This method requires very less computation time compared to the other methods. It can also provide a response time of half cycle for load containing odd harmonics only [15].

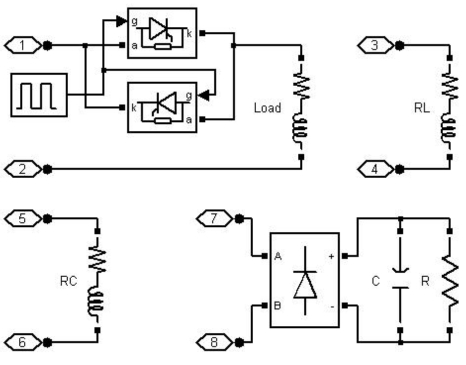

Fig. 2. Different types of linear and non-linear loads

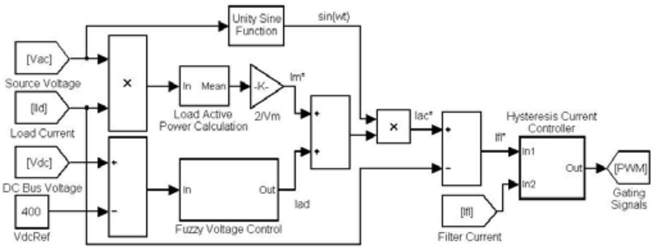

Fig. 3. Block diagram of proposed control scheme

In this method it is assumed that after compensation the source current (2) will become sinusoidal in phase with voltage (1). Then, instantaneous power drawn by load is calculated as in (3);

$$v_{ac}(t) = V_m \sin(wt) \tag{1}$$

$$i_{ac}(t) = I_m \sin(wt) \tag{2}$$

$$p_L(t) = v_{ac}(t) i_{ac}(t) = V_m I_m \sin^2(wt) \tag{3}$$

Average of (3) over one cycle gives the active power drawn by load as in (4) and (5);

$$P_L = \frac{1}{2\pi} \int_0^{2\pi} V_m I_m . \sin^2(wt) dwt \tag{4}$$

$$P_L = \frac{V_m I_m}{2} \tag{5}$$

Therefore, if active power of load before and after compensation, are equalized, peak value of reference source current can be calculated;

$$I_m^* = \frac{2P_L}{V_m} \tag{7}$$

After multiplication of peak value of reference source current and unity sine function, reference source current can be found;

$$i_{ac}^*(t) = I_m^* \sin(wt) = \frac{2P_L}{V_m} \sin(wt) \tag{8}$$

And finally reference filter current is calculated by substracting load current from reference source current as in (9);

$$i_{fl}^*(t) = i_{ac}^*(t) - i_{ld}(t) \tag{9}$$

B. Fuzzy Logic Based DC Bus Voltage Controller

APF dc bus capacitor voltage is an important parameter to be controlled. If this control is not done properly, source current will deteriorate and lapse from sinusoidal waveform.

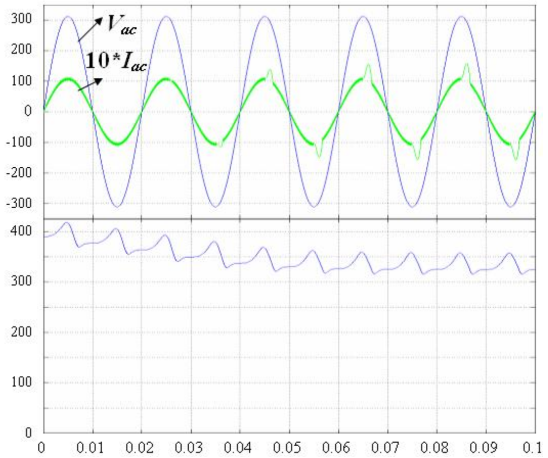

Fig. 4. Source current deterioration according to capacitor voltage decrease.

In Fig. 4, occurance of swells in the source current when capacitor voltage decreases below the peak value of source voltage is shown. In this paper, a fuzzy logic based dc bus voltage controller is used to regulate the dc bus voltage of the APF.

Since fuzzy control rules are derived from a heuristic knowledge of system behavior, neither precise mathematical modelling nor complex computations are needed [16]. Simplicity of fuzzy control is based on using human like linguistic terms in the form of IF-THEN rules to capture the non-linear system dynamics [17]. This approach is potentially able to extend the control capability even to operating conditions where linear control techniques fail

Block diagram of the fuzzy logic controller which is used to regulate the dc bus capacitor voltage of the APF is shown in Fig. 3. Capacitor voltage is sensed using a voltage sensor and compared with the set reference voltage (V_{dcref}). Input variables of the fuzzy controller are capacitor voltage error (e) and change in voltage error (Δe) at the k-th sampling time as given below;

$$e(k) = \alpha\left(V_{dc}(k) - V_{dcref}\right) \tag{10}$$

$$\Delta e(k) = \beta\left(e(k) - e(k-1)\right) \tag{11}$$

where α and β are input scaling factors. Output of the fuzzy controller is the change of adjustment current (ΔI_{ad}) and actual adjustment current is determined as below;

$$I_{ad}(k) = I_{ad}(k-1) + \gamma.\Delta I_{ad}(k) \tag{12}$$

where γ is output scaling factor. This adjustment current will supply the losses in the converter and will be added to peak value of reference source current (I_m^*). If (8) is recomposed, new reference source current is computed as below;

$$i_{ac}^*(t) = \left(I_m^* + I_{ad}\right)\sin(wt) = \frac{2P_L}{V_m}\sin(wt) \tag{13}$$

The input membership functions are shown in Fig. 5. Arrangemet of triangular membership functions ensures that for any combination of (e) and (Δe), maximum four rules are applied. In this way the computation time can be reduced.

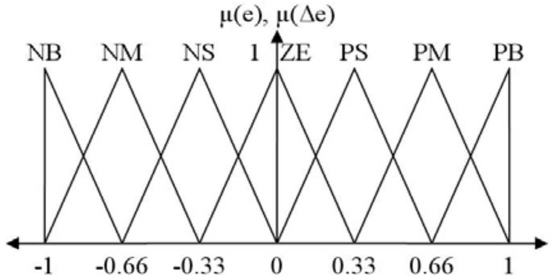

Fig. 5. Membership functions for (e) and (Δe)

To ensure converter output voltage stable near the set point 49 rules are derived as seen in Table I. Fuzzy rules of the controller are in the fallowing form;

IF $e(k)$ is X_i AND $\Delta e(k)$ is Y_i THEN $\Delta I_{ad}(k)$ is Z_i

where X_i and Y_i are input membership functions and weighted linear output function of the fuzzy controller computed as;.

$$Z_i = w_i\left(a_i.e(k) + b_i.\Delta e(k) + c_i\right) \tag{14}$$

$$w_i = AndMethod\left(X_i\left(e(k)\right), Y_i\left(\Delta e(k)\right)\right) \tag{15}$$

where a_i, b_i and c_i are output function coefficients and w_i is firing strength of the rule. For any combination of (e) and (Δe) the final output of the system is the weighted average of all rule outputs, computed as;.

$$FinalOutput = \frac{\sum_{j=1}^{N} Z_j}{\sum_{j=1}^{N} w_j} \tag{16}$$

TABLE I
RULE TABLE OF THE FUZZY CONTROLLER

e \ Δe	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	ZE
NM	PB	PM	PM	PS	PS	ZE	NS
NS	PM	PM	PS	PS	ZE	NS	NS
ZE	PM	PS	PS	ZE	NS	NS	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NS	NS	NM	NM	NB
PB	ZE	NS	NS	NM	NM	NB	NB

C. *Hysteresis Band Current Controller*

The third stage of the shunt APF control circuit is generating appropriate gating signals for the power switches that forces the filter current follow derived reference current. The goal is to reduce the current error.

In this paper, hysteresis band current control method is used because implementation of this control is not expensive and the dynamic answer is excellent. It allows a fast current control. Unfortunately, in this control it is not possible to fix the commutation frequency. However, this disadvantage is not ever critical and current controllers based on this method are now standart in most APF control schemes.

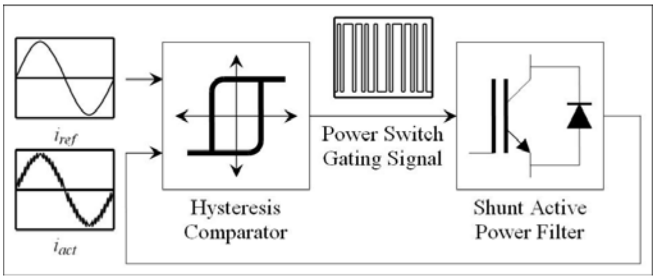

Fig. 5. Block diagram of hysteresis band current controller

The operating principle of the hysteresis band current controller which is shown in Fig. 5, depends on comparing of measured APF output current with its reference by the hysteresis comparator. The outputs of the comparator are the power switch gating signals.

If the measured filter current is bigger (half of the band value) than the reference one, it is necessary to commute the corresponding power switches to decrease the output current, and it goes to the reference. On the other hand, if the measured current is less (half of the band value) than the reference one, the switches commute to increase output current and it goes to the reference. As a result, the output current will be in a band around the reference current as shown in Fig. 6.

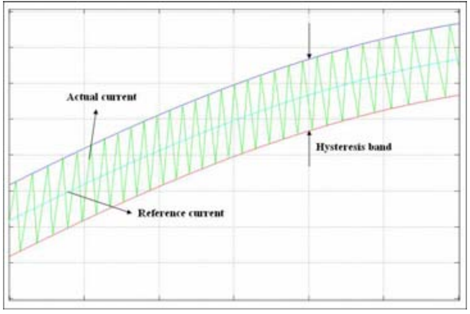

Fig. 6. Reference and actual filter currents for hysteresis band controller

IV. SIMULATION RESULTS

Performance of the shunt active power filter with the proposed control scheme is demonstrated in from Fig. 7 to Fig. 10 which are obtained by MATLAB/Simulink software. Circuit parameters of the shunt APF and different types of loads are listed in Table II.

TABLE II
CIRCUIT PARAMETERS OF ACTIVE POWER FILTER

Source voltage (peak value)	311 V
Source frequency	50 Hz
Coupling inductor	2 mH
DC bus capacitor	470 µF
DC bus reference voltage	400 V
Resistance of all types of loads	50 Ω
Inductance of inductive load	2 mH
Capacitance of capacitive load	470 µF
Inductance of ac regulator	2 mH
Capacitance of uncontrolled rectifier	470 µF

Fig. 7 and Fig. 8 shows reactive power compensation capability of APF for inductive and capacitive linear loads. Loads draw leading and lagging currents from ac mains and APF injects contrary currents resulting in a source current in phase with the source voltage.

Fig. 9 and Fig. 10 shows both reactive power and current harmonics compensation capability of APF for uncontrolled rectifier and thyristor based ac regulator non-linear loads. Loads draw harmonic and reactive component containing currents from ac mains. If APF provides these components only fundamental component of load current in phase with voltage is drawn from ac mains.

Also, from Fig. 7 to Fig. 10 it can be seen that proposed APF has a fast transient response during addition and removal of load. Source current settles smoothly to a new steady-state value within a time of one cycle. DC bus voltage settles its reference value within a time of a few cycles after small oscillation during load change.

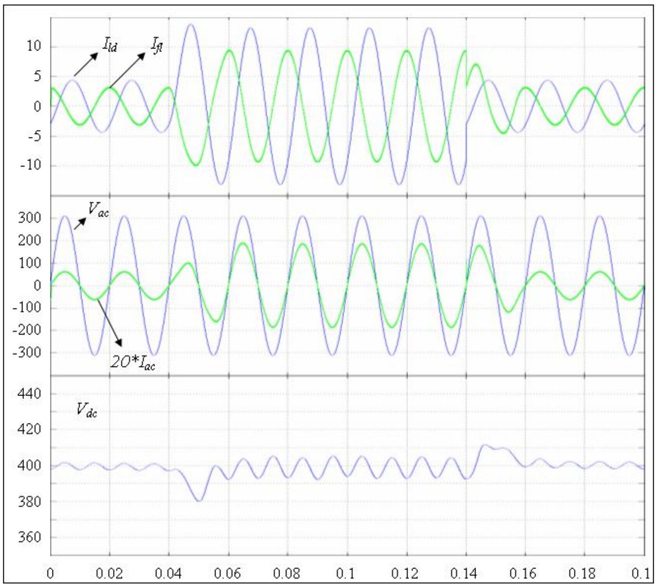

Fig. 7. Variation of load and filter currents (top), source voltage and current (middle), dc bus voltage (bottom) under inductive linear load for active power change from 482 W to 1444 W to 482 W.

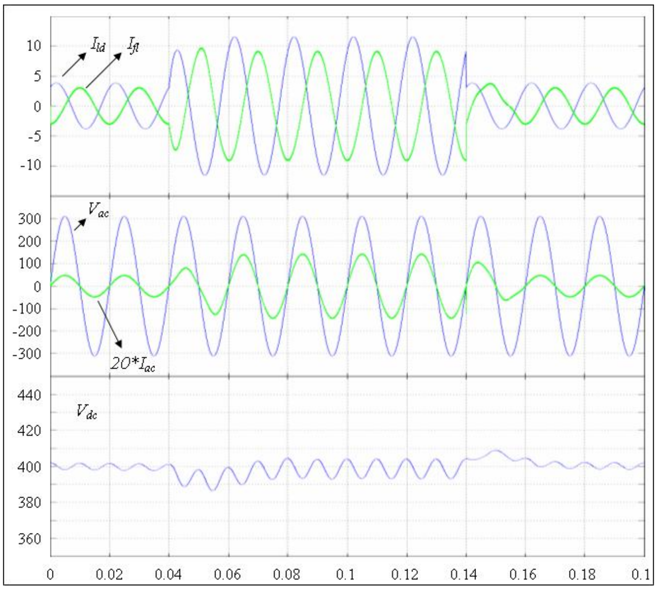

Fig. 8. Variation of load and filter currents (top), source voltage and current (middle), dc bus voltage (bottom) under capacitive linear load for active power change from 370 W to 1108 W to 370 W.

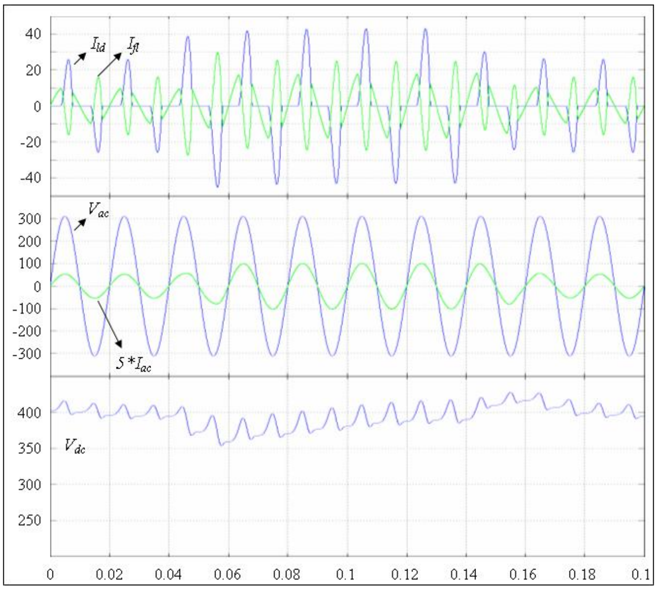

Fig. 9. Variation of load and filter currents (top), source voltage and current (middle), dc bus voltage (bottom) under uncontrolled rectifier non-linear load for active power change from 1662 W to 3156 W to 1662 W.

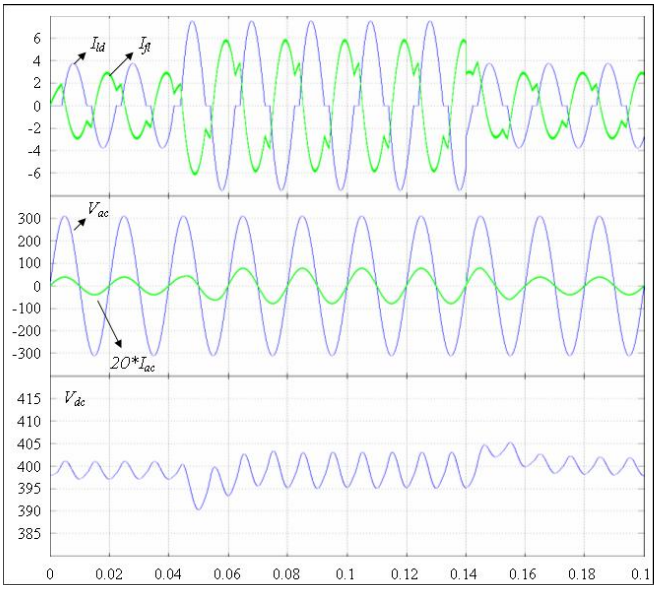

Fig. 10. Variation of load and filter currents (top), source voltage and current (middle), dc bus voltage (bottom) under ac regulator non-linear load for avtive power change from 307 W to 613 W to 307 W.

V. CONCLUSION

In this paper, a simple control scheme for a single phase shunt active power filter to compensate current harmonics and reactive power of linear and non-linear loads, is proposed. Advantage of the proposed control sheme is that it comprises an uncomplicated reference source current generator and a fuzzy logic based dc bus voltage controller using human like linguistic terms in the form of IF-THEN rules without need of complex computations. As for obtaining gating signals of the power switches a standart hysteresis current controller is employed. Different types of linear and non-linear loads for reactive power and current harmonics compensation are connected to the APF to indicate steady-state and transient performance. Validity of the proposed control technique is verified by the presented simulation results.

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