4-Leg Shunt Active Power Filter with Hybrid Predictive Fuzzy-logic Controller

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Abstract— **Distribution networks commonly utilize three-phase four-wire systems, especially for low-voltage industrial and residential customers. Due to the rapid increase of nonlinear and unbalanced reactive loads in such systems, several power quality issues arise. Among them, line current harmonics, unbalanced load currents, noticeable neutral current and low power-factor. This paper presents a 4-leg shunt active power filter (APF) featuring reactive power compensation, line current harmonics mitigation, neutral-current reduction and system load-currents balancing. The authors propose hybrid controller for the 4-leg shunt APF: Fuzzy Logic Control (FLC) for the DC-link voltage and predictive control for the grid current. The DC-link voltage FLC handles the system uncertainties and nonlinearities, hence improving the transient performance. In addition, the proposed predictive current control technique features phase locked loop (PLL) independency. Moreover, the proposed hybrid controller necessities sensing only the grid voltage and current, hence less number of sensors are required.In addition, implementation simplicity and cost reduction are achieved. The proposed controller is simulated using Matlab/Simulink® package. For effectiveness verification, system performance is investigated under several loading conditions**

Keywords- 4-leg shunt active power filter, power quality, fuuzy logic control, predictive current control, and harmonic compensation.

I. INTRODUCTION

Three-phase four-wire systems are being used widely in practical power grid, especially in low-voltage industrial and residential systems [1]. Due to the rapid increase of nonlinear/unbalanced reactive loads; line currents distortion, unbalanced load currents, and reactive power problems occur. As a result; low power factor, weakening efficiency, over heating of motors and transformers, and malfunction of sensitive devices. are encountered [2-3]. Domestic single phase nonlinear loads, such as computer equipment, electronic devices, and switching mode power supplies lead to zero-sequence current increase collected in the neutral line. Thus, the neutral line current contains not only fundamental, but also harmonic components. Occasionally, neutral line current may even exceed phase currents amplitude.

Improvement of power quality has been given considerable attention due to the increase of the power quality issues in addition to the limitations required by international standards such as IEEE519-1992, IEC1000-3-2, and IEC1000-3-4 [5-6]. Those limitations were set in order to limit the disturbances and avoid major problems in distribution power systems.

Conventionally, passive filters are used for current harmonics mitigation while capacitor banks are utilized for power factor correction. Neither of them solves the problem in a suitable way, and usually causes other problems, such as resonances. Moreover, their performance depends on system impedance and also suffers from filter passive components aging effect [7].

Shunt active power filters (APF) have attracted considerable attention as an efficient way to perform power conditioning tasks such as harmonic elimination, reactive power compensation, load balancing, and neutral current elimination [7-8]. Also APFs offer high efficiency [9] and perform effectively on lower-order harmonics such as 3rd, 5th, 7th which are generated by the nonlinear loads [10].

Four-wire shunt APFs has been presented in three-phase four-wire systems under three main typologies [11-14] namely; (i) split-capacitor or (capacitor midpoint), (ii) four-leg and (iii) three single-phase bridge configuration or (three full-bridge topology). However, recent research indicates that although less semiconductor devices are required in split-capacitor topology, four-leg topology has higher DC-link voltage utilization ratio, more control flexibility and higher capacity to cancel neutral line current [12-14].

The three full-bridge topology allows lower filter-side voltage but uses higher number of semiconductor devices and three single-phase isolation transformers are recommended [11].

The APF have three control aspects; harmonics current extraction technique, current control technique and DC-link voltage controller. Among the harmonics current extraction techniques; the instantaneous reactive power theory [15], the Synchronous Reference Frame (SRF) [11], *p-q-r* theory [12] Fast Fourier Transform (FFT) [16], Discrete Fourier Transform [17], Adaptive control algorithm [18], and capacitor-voltage-control [19-20]. Different current controllers can be used such as hysteresis [21], PI-controller [22], or predictive controller [20, 22].

Shunt APF's DC-link voltage must be kept constant in order that it can compensate both of harmonics, reactive power and mitigates the neutral current effectively. Because of their simple implementation and tuning, PI controller gains extensive application in the DC-link voltage controllers for

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shunt APFs [11-12]. However, PI controllers require exact system mathematic model and also offer poor robustness in transient state. Occasionally, DC-link voltage overshoot and inrush source current occur, which may result to protection tripping or even semiconductors failure when APF's operation is started [23]. Recently, Fuzzy Logic Controller (FLC) has received a noticeable attention regarding their application as APFs' controller [24-26]. FLCs offer strong robustness to variable parameters, good dynamic response and limited overshoot in the transient response [25-26].

In this paper, a hybrid predictive fuzzy-logic controller is proposed for a 4-leg shunt APF serving a three-phase four-wire unbalanced load. The proposed FLC for the APF's DC-link voltage improves the transient performance, decreases the settling time and reduces the overshoot. The predictive grid-current proposed controller enhances the APF's performance with minimal required sensors. The proposed system is modeled using MATLAB/Simulink and the performance is tested for starting and load variation conditions.

The paper is arranged as follows: Section II describes the system under investigation. The proposed predictive current controller is presented in section III. The classical PI and the proposed DC-link voltage FLC are investigated in section IV. In section V, performance analysis of the proposed hybrid controlled 4-leg APF is carried out via a MATLAB simulation model. In addition, the results for the classical and proposed controllers are compared at variable loading conditions. Finally, a conclusion is given in section VI.

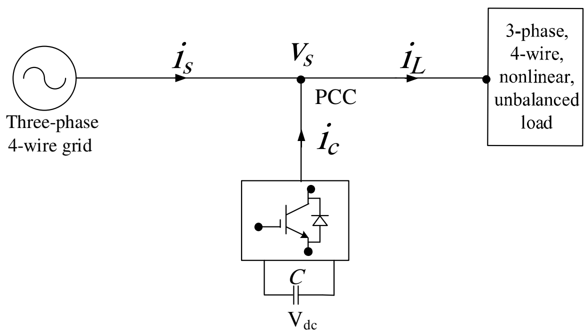

Fig. 1. Block diagram of a three-phase 4-wire system with shunt APF

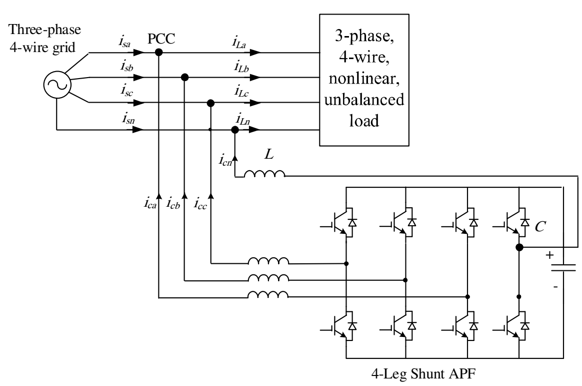

Fig.2. 4-leg APF connected to the system under study.

II. System Under Investigation

The power system under study consists of a three-phase four-wire grid; connected to a three-phase four-wire non-linear unbalanced load as shown in Fig. 1.

This system suffers from line-current harmonics, low power factor, unbalance and excessive neutral current. A shunt 4-leg APF is connected at the point of common coupling (PCC), via interfacing inductances, as shown in Fig.2 to improve the system power quality. The power system neutral wire is tied to the APF fourth leg in order to effectively mitigate the neutral current. The utilized 4-leg APF incorporates capacitor-voltage-control technique for line-current's harmonic extraction and predictive current control for grid connection.

III. Proposed Pridictive Current Controller

The proposed 4-leg APF hybrid controller is shown in Fig. 3 featuring a DC-link voltage controller and grid current controller. The authors propose a predictive controller for the grid current and FLC for the DC-link voltage.

The APF reference currents are computed using capacitor-voltage-control technique [19-20]. No grid voltage harmonics are considered.

The proposed predictive controller requires measurement of the grid voltage v_s, and grid current i_s at PCC. The measurement of the load current and the injected APF current are not required. The output of the DC-link voltage controller and per-unit grid voltage signals forms the required reference supply-current signals. Measured grid current, PCC voltage and reference current are used to predict the required the APF gating pulses.

The relation between the APF current, i_c, inverter output voltage, v_c, and grid voltage at PCC, v_s, is defined in the discrete form by:

$$v_c^*(k+1) = L_i\big(i_c^*(k+1) - i_c(k)\big)/T_s + v_s(k) \quad (1)$$

where L_i is the interfacing inductance, T_s is the sampling time, $i_c^*(k+1)$ and v_c^*(k+1) are the reference inverter current and the predicted reference output voltage of the APF at sampling instant ($k+1$), respectively.

The APF current at sampling instant k is

$$i_c(k) = i_L(k) - i_s(k) \quad (2)$$

where i_L is the load current. Since the sampling instant (k + 1) is not available, $i_c^*(k+1)$ is assumed to be equal to $i_c^*(k)$. This introduced a one sample time delay which is less significant if the sampling frequency is relatively high [27].

The inverter reference current is

$$i_c^*(k) = i_L(k) - i_s^*(k) \quad (3)$$

Hence by substitution of (2) and (3) in (1), the predicted APF output voltage can be expressed in terms of the reference and actual grid currents by

$$v_c^*(k+1) = L_i\big(i_s(k) - i_s^*(k)\big)/T_s + v_s(k) \quad (4)$$

In addition to supply current harmonics mitigation, the inverter is controlled to achieve the balance of the three-phase currents.

The load neutral current is given by

$$i_{Ln}(k) = i_{La}(k) + i_{Lb}(k) + i_{Lc}(k) \quad (5)$$

Similarly for the APF forth-leg

$$v_{cn}^{*}(k+1) = L_i\left(i_{cn}^{*}(k+1) - i_c(k)\right)/T_s + v_{sn}(k) \quad (6)$$

$$i_{cn}(k+1) = i_{sn}(k+1) - i_{Ln}(k) \quad (7)$$

$$i_{cn}^{*}(k+1) = i_{sn}^{*}(k+1) - i_{Ln}(k) \quad (8)$$

where i_{sn}, i_{sn}^{*}, i_{cn}, i_{cn}^{*}, i_{Ln} and v_{sn} are grid neutral current, grid reference neutral current, APF neutral current, APF reference neutral current, load neutral current and grid voltage at neutral point respectively. Then

$$v_{cn}^{*}(k+1) = L_i\left(i_{sn}^{*}(k+1) - i_{sn}(k)\right)/T_s + v_{sn}(k) \quad (9)$$

But

$$i_{sn}^{*}(k+1) = 0 \quad (10)$$

$$v_{sn}(k) = 0 \quad (11)$$

$$i_{sn}(k) = i_{sa}(k) + i_{sb}(k) + i_{sb}(k) \quad (10)$$

Then

$$v_{cn}^{*}(k+1) = -L_i\left(i_{sa}(k) + i_{sb}(k) + i_{sb}(k)\right)/T_s \quad (12)$$

Equation (4) and (12) are used to predict the required the modulating signals, necessary to generate the APF pulse width modulation (PWM) for the three-phase and the forth-leg power switches, consequently the switching decision that forces the actual current to track its reference.

The predictive control method proposed for the 4-leg shunt APF can compensate for both the grid current harmonics and line-currents' unbalance, thus mitigating the neutral current and improves the power factor. It offers simple implementation, less number of required sensors and does not require complex PLL.

IV. Proposed DC-link Voltage Controller

APF DC-link voltage controller is conventionally implemented using simple PI. Classical PI controllers offer simple implementation and tuning yet their performance is degraded specially during the star-up and transient load variation. The PI performance is enhanced to a great extent with the aid of exact control system modeling which is not available in many cases. In this paper, the authors propose a FLC for the APF DC-link voltage instead of the classical PI controller.

The Mamdani's type FLC [26] is adopted in this paper. The actual DC-link voltage V_{dc} is compared with the reference value V_{dc}^{*}. The error (E) and the change of error (CE) signals can be computed

$$E = V_{dc} - V_{dc}^{*} \quad (13)$$

then processed through a fuzzy controller as shown in Fig.4. FLCs are independent of system model. The design is mainly based on the intuitive feeling and designer experience of the process. The rules are expressed as: If (error E is X and change of error *CE* is Y) then (control output is O).

The controller fuzzy petitioned subspaces negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB) are used. These seven membership functions are same for inputs and output. FLC rules are summarized in Table 1.

The proposed FLC blocks; fuzzification, rule-base, inference and de-fuzzification, are shown in Fig.5. The membership functions for the error, change of error and the output variables are shown in Fig. 6, Fig. 7 and Fig. 8 respectively.

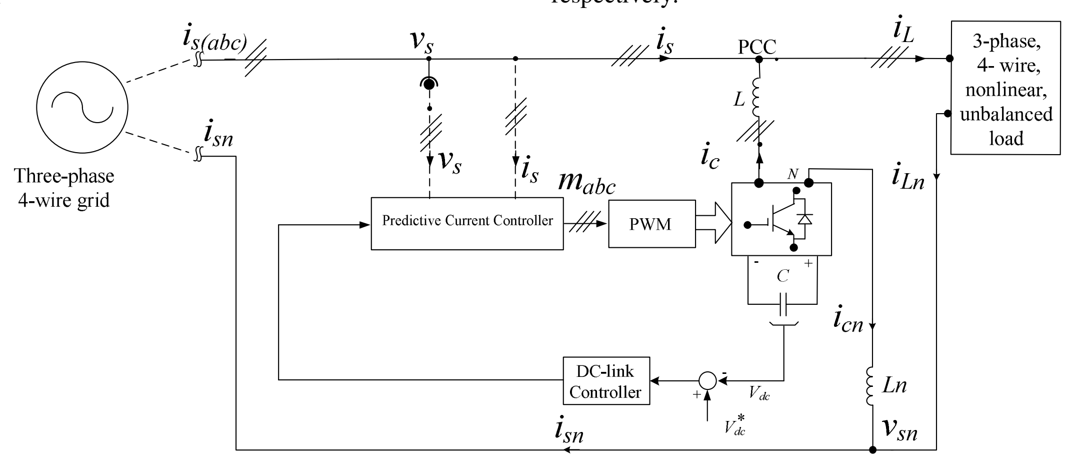

Fig. 3. 4-leg shunt APF proposed hybrid controller

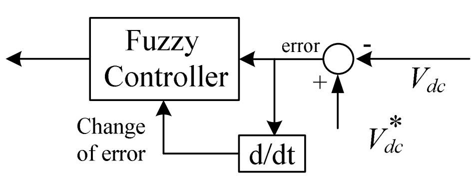

Fig. 4. Proposed DC-link voltage FLC

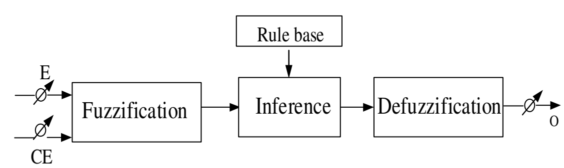

Fig. 5. FLC block diagram

Table 1: Fuzzy rules base

E CE	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PB	PS	PS	Z
NM	PB	PB	PM	PM	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NM
Z	PM	PS	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	ZM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	NS	NS	NM	NM	NB	NB

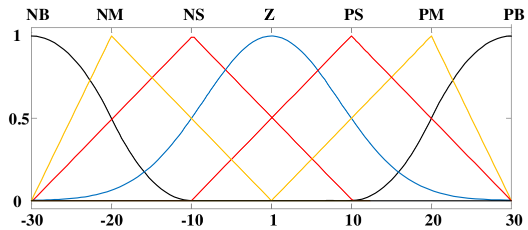

Fig. 6. Proposed FLC error membership function

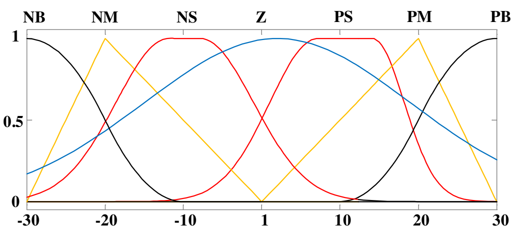

Fig. 7. Proposed FLC change of error membership function

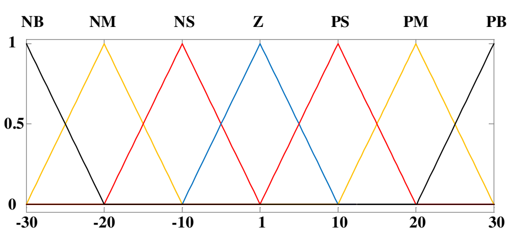

Fig. 8. Proposed FLC output membership function

V. Performance Investigation of the Proposed System

The proposed system, shown in Fig. 3, is simulated using a MATLAB/Simulink model to investigate its performance. The point of common coupling (PCC) voltage is 380 V. The non-linear load is represented by a three-phase diode rectifier feeding an inductive load consists of resistor R_{L1}= 30 Ohm and inductor L_{L1}=150 mH acting as a harmonic current producing source. The load unbalance is presented by connecting an inductive load with phase A only consists of resistor R_{LN}= 15 Ohm and inductor L_{LL}=50 mH. The resistance and the inductance of the APF coupling inductor, are R_i = 0.01 Ω and L_i = 4 mH respectively. A DC-link capacitor of 3.0 mF is used.

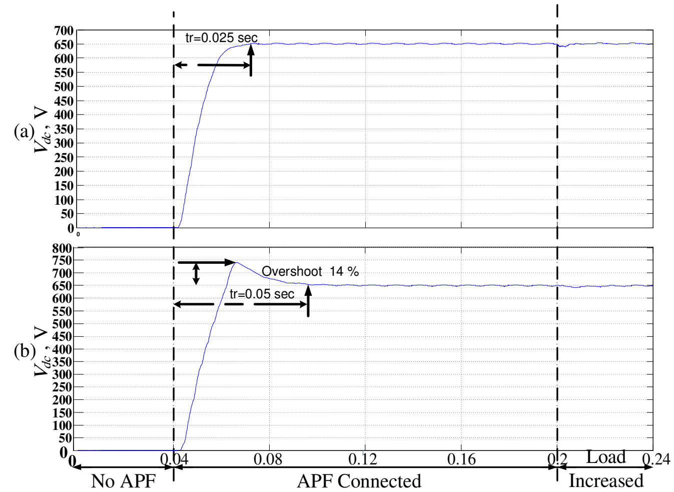

Fig. 9. DC-link capacitor voltage simulation results using: (a) proposed FLC and (b) conventional PI controller.

The DC-link reference voltage is set at 650V and the inverter switching frequency, f_s, is 5 kHz.

From time 0s to 0.04s, no APF is operating. The APF is switched on at t=0.04 sec. At t=0.2s, the load is increased by connecting an inductive load consists of resistor R_{L2}= 50 Ohm and inductor L_{L2}=50 mH in parallel to the existing load, R_{L1} and L_{L1}.

Fig. 9(b) shows the DC-link voltage under conventional PI controller where the performance suffers from critical over-shoot of 14 % in addition to the relatively long settling time. On the contrary, the proposed FLC enhance the performance of the DC-link voltage control loop. Results shown in Fig. 9(a) illustrate no over-shoot, better settling time in case of the proposed FLC.

Typical system performance waveforms are illustrated in Fig. 10. The three-phase grid voltage waveform at the PCC is shown in Fig. 10(a) while the non-linear load current, i_L, is shown in Fig. 10(b). It is shown that the load current is distorted and unbalanced because of the bridge rectifier loading effect and the parallel unbalanced load.

The APF current and the supply current waveforms are illustrated in Fig 10 parts e and f respectively when conventional PI controller is utilized as the DC-link voltage controller. For the proposed FLC hybrid with predictive current controller, the APF and supply currents are shown in Fig. 10 parts c and d respectively.

As shown in Fig. 10 (e, f), the APF with conventional PI controller manages to attain balanced supply currents with THD compliant with IEEE standards. The proposed hybrid controller allows the APF to mitigate the supply line harmonics and offer better THD than that in the conventional PI case. Also, the APF current suffers critical overshoot in the case of the conventional PI controller mainly as a reflect to the DC-link voltage overshoot occurs.

The load neutral current is minimized using the APF with the proposed hybrid controller that enables fast response and accurate tracing as shown in Fig. 11.

The proposed APF hybrid controller enables reactive power compensation for the grid. It can be shown from Fig. 12 that the grid supplies only the load active power need while the load reactive power is presented by the APF. The small portion of active power drawn by the APF is due to the utilized inverter losses.

VI. Conclusion

A hybrid predictive fuzzy-logic controller is proposed for 4-leg shunt APF. Despite the existence of non-linear unbalanced load, the APF succeeds in attaining supply line currents with IEEE compliant THD, minimizes the supply neutral current, and operates near unity power factor. The proposed hybrid controller is compared with the classical PI controller under various operating conditions. The performance superiority of the proposed controller is verified during both transient and steady-state. Moreover, the proposed controller does require neither the load nor the APF current measurement, in addition to its PLL independency operation.

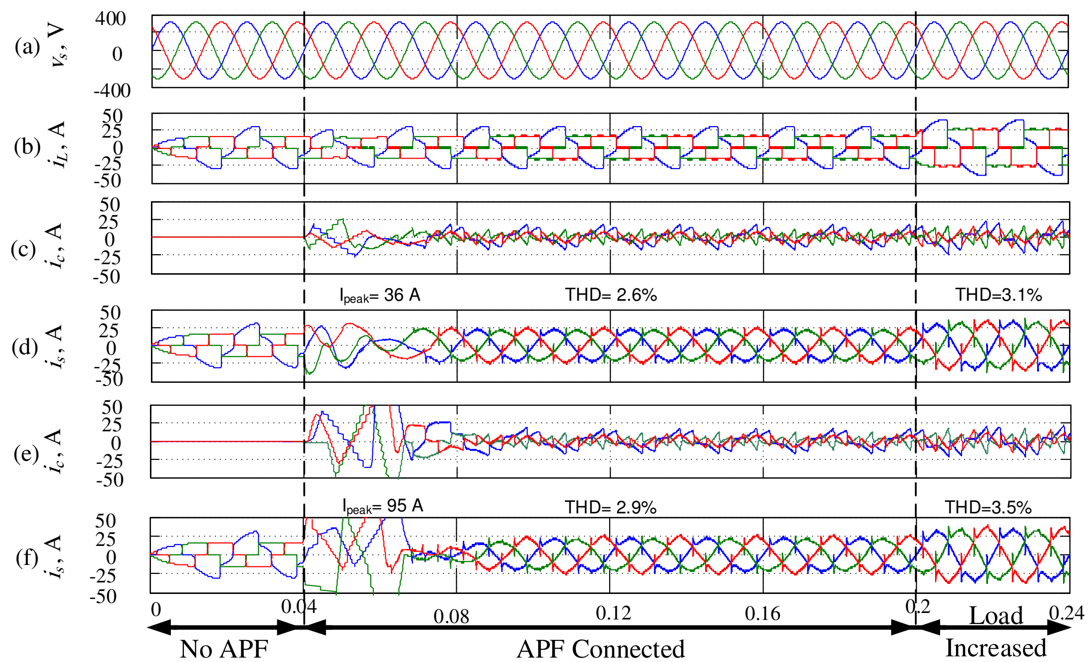

Fig. 10. Simulation results: (a) supply voltage, v_s, (b) load current, i_L, (c) APF current with predictive fuzzy controller, i_c, (d) supply current with predictive fuzzy controller, i_s, (e) APF current with predictive PI controller, i_c and (f) supply current with predictive PI controller, i_s.

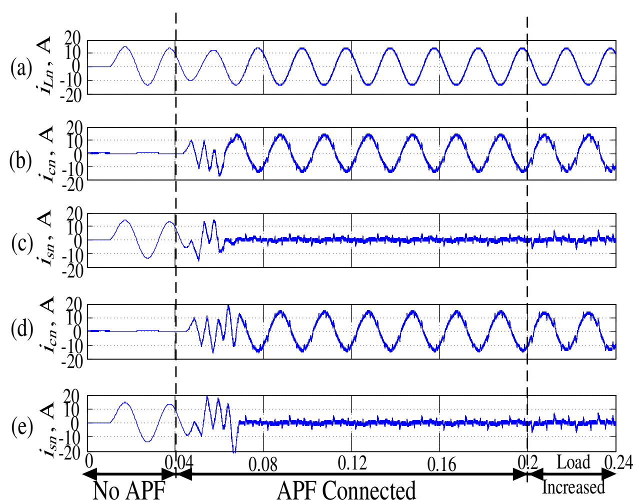

Fig.11. Neutral current simulation results: (a) load neutral current, i_{Ln}, (b) APF neutral current with predictive fuzzy controller, i_{cn}, (e) supply neutral current with predictive fuzzy controller, i_{sn}, (d) APF neutral current with predictive PI controller, i_{cn} and (e) supply neutral current with predictive PI controller, i_{sn}

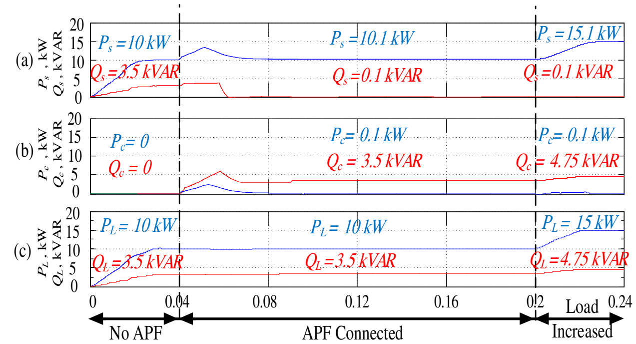

Fig. 12. Active and reactive power simulation results: (a) grid active and reactive power, P_s and, Q_s , (b) APF active and reactive power, P_c and, Q_c and (c) load active and reactive power, P_L and, Q_L

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