Unified Fuzzy-Logic Based Controller for Dual Function 4-Leg Shunt APF with Predictive Current Control

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Abstract

Due to the rapid increase of nonlinear and unbalanced reactive loads in 4-wire distribution systems, various power quality issues such as harmonics current, unbalanced load currents, neutral current and low power factor occur. The need for green and renewable energy sources increases daily due to increase in demand for electrical power. Photovoltaic (PV) energy is an important renewable technology that requires an inverter to interface with the electrical distribution systems. Conventionally, shunt active power filter (APF) is connected in parallel to perform power conditioning tasks such as harmonic elimination, reactive power compensation, load balancing, and neutral current elimination. This paper presents a unified Fuzzy-Logic based Controller for a 4-leg APF preforming as a dual-function converter. The presented system achieves power quality tasks like: (i) reactive power compensation, (ii) harmonics current elimination, (iii) neutral current mitigation and (iv) system line-currents balance in addition to transfer locally generated renewable energy to the grid utilizing only one power electronic based converter.

I. INTRODUCTION

In three-phase four-wire distribution systems, there exist several power quality problems, such as, increased voltage/current distortion levels due to the widespread use of power electronics based non-linear loads. Further, three phase four-wire distribution systems possesses considerable amount of neutral currents and current unbalance due to the uneven distribution of nonlinear/linear single-phase reactive loads. These cause unbalance in supply voltages resulting in excessive neutral current, increased voltage and current harmonics, unbalance in supply voltages and currents, poor power factor, increased losses, reduced overall efficiency and degraded the performance of the neighbouring loads [1-6].

Four-wire shunt APF has been utilized in three-phase four-wire distribution systems featuring three main topologies: (i) split-capacitor, (ii) 4-leg and (iii) three single-phase bridge configurations [7-20]. Split-capacitor configuration offers inverter with only three legs and less complicated controller [4, 20]. However, the zero-sequence component in the APF compensation currents flow through the DC-link capacitors. This current gives rise to unbalanced capacitor voltage sharing. Such unbalance in the DC voltages deteriorates the dynamic capability of the APF to follow fast changes in the current references [19]. For better compensation capability, 4-leg inverter connected as a shunt APF can be used [17]. In this configuration, the compensated neutral current is provided through a fourth leg, allowing better controllability and dynamic stability than the 3-leg with split-capacitor configuration. However, a fourth-leg with its associated controller is required [19, 17].

Recently, Fuzzy Logic Controllers (FLCs) have received a considerable attention in regards to their application to APFs as they do not require an exact mathematical model of the controlled object [24-26]. It has strong robustness to variable parameters, which give a good dynamic response and limitation of overshoot. Hence it can be considered as a viable solution for power system which suffers high non-linearity [25-26]. The demand for green and renewable energy sources such as Fuel cells, Wind and Solar energy are increasing due to the increase in demand for electrical power [27]. Photovoltaic (PV) energy is an important renewable technology due to its offered benefits like minimized maintenance requirements and direct conversion to electric power [28]. PV system requires an interfacing converter, conventionally a VSI, for grid connection purposes [29].

In this paper, a 4-leg inverter is proposed to operate as a dual-function converter to perform as shunt APF for power quality tasks such as reactive power compensation, harmonics current elimination, neutral current mitigation and system balancing in addition to connect PV array power to the grid. Unified Fuzzy Logic Control (FLC) is used as a robust controller for both DC-link voltage control and PV MPPT technique. The proposed control technique can handle the system uncertainties and nonlinearities. For the APF, a predictive current control technique is proposed which does not require a phase locked loop (PLL). The controller requires sensing only the grid voltage and current. Hence, reduced number of sensors is required in addition to its offered simplicity and ease of practical implementation. The proposed system is modelled using MATLAB Simulink® and the performance is tested for various loading and environmental conditions.

The paper is arranged as follows: Section II describes the overall system under investigation structure. The proposed predictive current controller is presented in section III. The proposed unified fuzzy logic controller is discussed in section IV. In section V, performance investigation of the proposed system is carried out via a MATLAB simulation model. Finally, a conclusion is given in section VI.

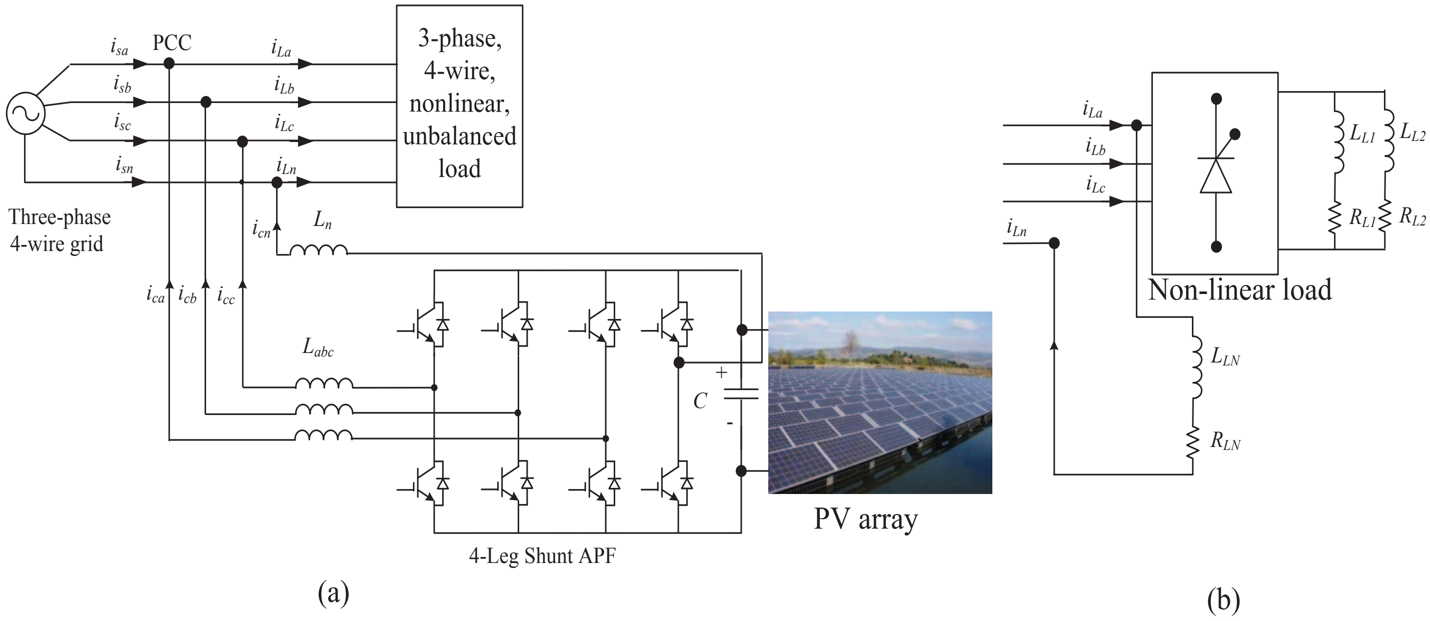

Fig. 1. System under investigation: (a) topology, and (b) load arrangement.

II. OVERALL SYSTEM STRUCTURE

The system under investigation incorporates a three-phase four-wire grid supplying three-phase four-wire non-linear unbalanced reactive load. This system suffers from harmonics current, low power-factor, line-currents unbalance and neutral current existence. The PV system requires an interfacing inverter for grid connection. A 4-leg inverter is proposed for dual function operation to perform as shunt active power filter for power quality tasks in addition to interface the PV array power to the grid as shown in Fig. 1.

A two-stage grid-connected PV system, shown in Fig. 2, consists of a PV array followed by step-up DC/DC converter, which feeds a 4-leg voltage source inverter (VSI) acting as an APF that feeds current into a three-phase 4-wire grid. The shunt 4-leg inverter is connected at PCC to a three-phase four-wire grid through interface inductances for compensation of load current harmonics, power factor improvement and system balancing in addition of transferring the PV power to the grid as shown in Fig.3. The power system neutral wire is tied to the fourth leg in order to effectively mitigate the neutral current. The harmonic extraction technique and the current control techniques used are capacitor voltage control and proposed predictive control respectively while the DC-link voltage controller uses a proposed FLC.

III. THE PROPOSED PREDICTIVE CURRENT CONTROLLER

The proposed predictive current controller is shown in Fig. 3. The APF reference currents are calculated from sensing grid currents which are drawn by nonlinear and unbalanced loads connected at PCC to the grid. The reference currents are computed by using capacitor DC-link voltage control [19-20]. The 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 inverter current are not required. The output of the unified FLC and per-unit grid voltage forms the reference supply current.

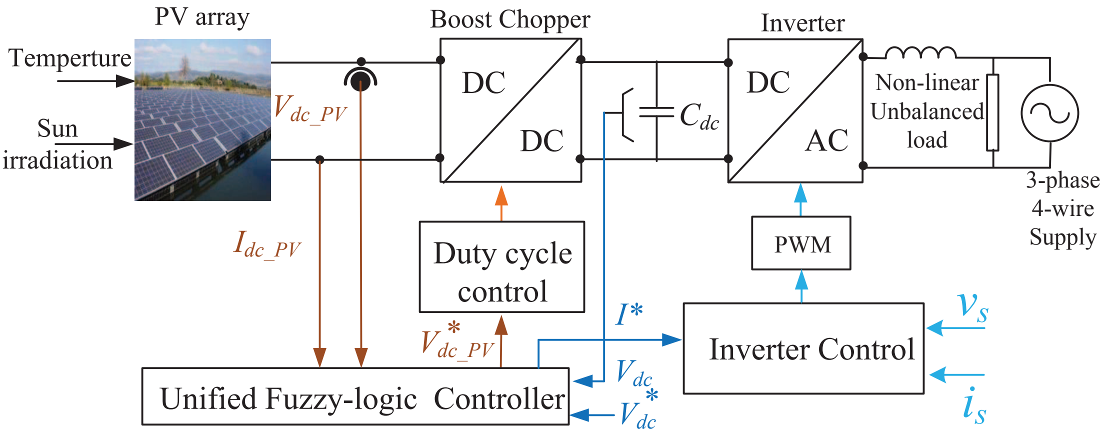

Fig. 2. Proposed APF dual function operation

The predicted inverter output voltage for the phases can be expressed in terms of the reference and actual grid currents by

$$v_c^*(k+1)= L_i/T_s\left(i_s(k)-i_s^*(k)\right)+v_s(k) \tag{1}$$

where L_i is the interfacing inductance, T_s is the sampling time, v_s is grid voltage at PCC, i_s is the grid current, $i_s^*(k)$ and $v_c^*(k+1)$ are the grid current and the predicted reference output voltage of the APF at sampling instant (k) and ($k+1$) respectively. In addition to compensate supply current harmonics, the inverter is controlled to achieve the balance of the three-phase currents.

$$v_{cn}^*(k+1)= -L_i/T_s\left(i_{sa}(k)+i_{sb}(k)+i_{sb}(k)\right) \tag{2}$$

where $v_{cn}^*(k+1)$ is the reference output voltage for the fourth-leg

Equation (1) and (2) are used to predict the required modulating signals, necessary to generate the APF PWM for the three-phase and the forth-leg. Consequently the switching decision forces the actual current to track its reference. Hence, supply current and voltage becomes in phase. As a result, the grid supplies only active power and the neutral current are effectively mitigated [17].

IV. THE PROPOSED UNIFIED FUZZY LOGIC CONTROLLER

The Mamdani's type [26, 35] of fuzzy controller is used in this paper for the DC-link voltage control of the APF with Max-Min operation combination.

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 are processed through a unified FLC as shown in Fig.4.

$$E= V_{dc} - V_{dc}^* \tag{3}$$

This contributes to zero steady-state error in tracking the reference current. In addition, the controller limits the overshoot and the inrush current during transient state [17]. The output power of PV arrays varies with environmental conditions; solar irradiation and atmospheric temperature. Therefore, real-time MPPT control for extracting maximum power from the PV panel becomes indispensable in the PV generation systems [21, 22].

The proposed Unified FLC is shown in Figure 4. It has four inputs and two outputs. Two inputs of FLC-MPPT part variables are the error and the change of error for the PV power variation with respect to array voltage E_{PV} and CE_{PV} respectively at sampled times k defined by

$$P_{PV} = V_{dc-PV} * I_{dc-PV} \tag{4}$$

$$E_{PV}(k) = \frac{P_{PV}(k) - P_{PV}(k-1)}{V_{dc\_PV}(k) - V_{dc\_PV}(k-1)} \tag{5}$$

$$CE_{PV}(k) = E(k) - E(k-1) \tag{6}$$

where P_{PV}, $I_{dc\text{-}PV}$, $V_{dc\text{-}PV}$ are the PV power, current and voltage respectively at instant k. E_{PV} (k) shows that if the load operating point at the instant k is located either on the left or on the right of the maximum power point on the P-V characteristic where it is equals to zero at MPP. The change of error of the PV CE_{PV} (k) expresses the moving direction of this point where the control action duty cycle D, used for the tracking of the MPP, triggers a fly-back boost converter [36].

The proposed unified FLC is independent of system model, hence the design is mainly based on the intuitive feeling for and experience of the process. The rules are expressed like If (error E is X and change of error CE is Y) then (control output is O). The main parts of FLC are; fuzzification, rule-base, inference and defuzzification. The membership functions for the error, change of error and the output variables are shown in Fig. 5 as surface and Fig. 6. as 3-D illustration

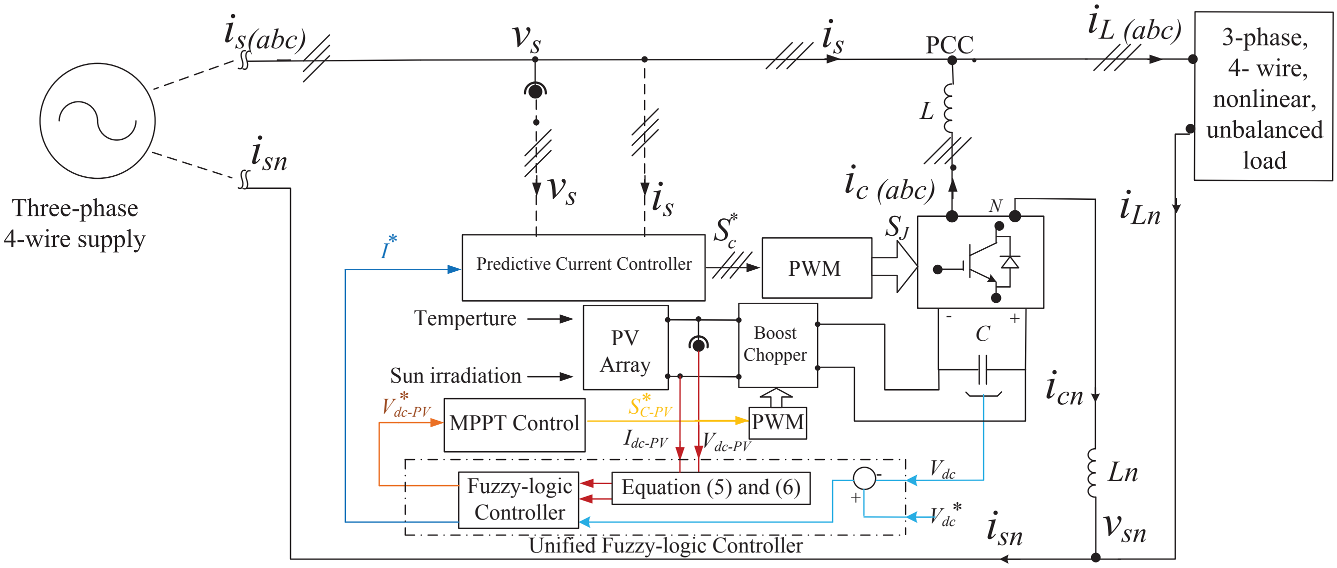

Fig. 3. Block diagram of the proposed control system

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

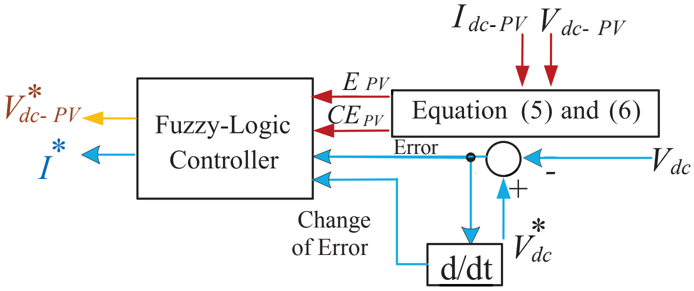

Fig. 4. Proposed unified fuzzy logic controller

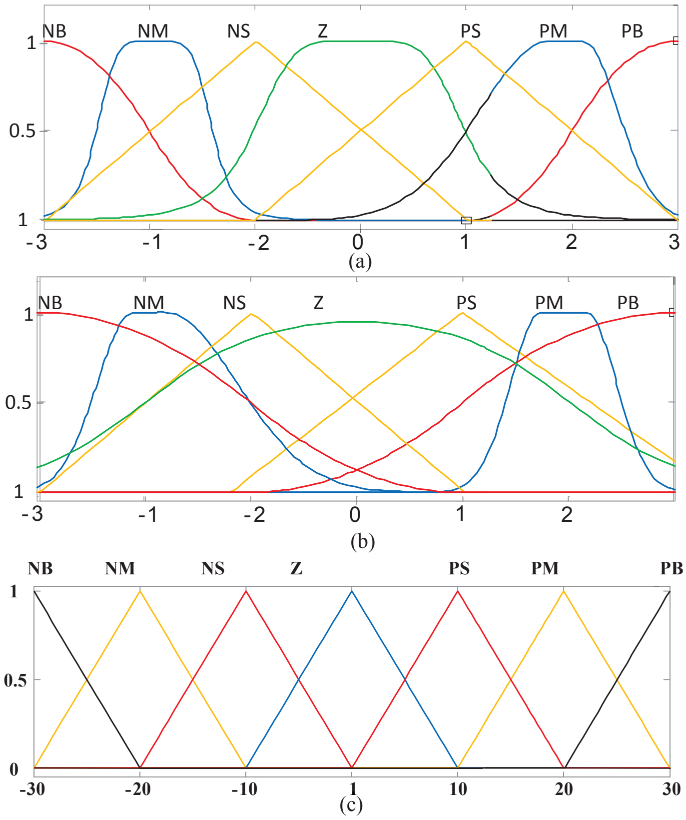

Fig. 5. Proposed FLC Surface: (a) FLC Error, (b) FLC Change of Error, and (c) FLC Outputs

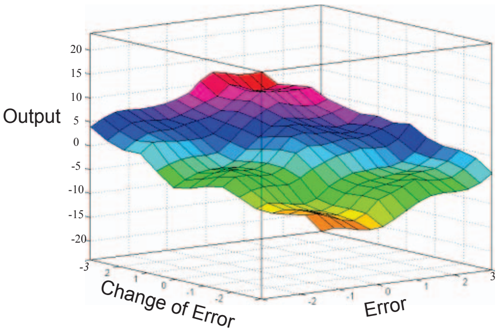

Fig. 6. Proposed Unified fuzzy logic 3-D illustration

V. PERFORMANCE INVESTIGATION OF THE PROPOSED SYSTEM

The proposed system shown in Fig. 1 and its components which are illustrated in Fig.2, Fig.3 and Fig.4 are simulated using a MATLAB/Simulink® model to investigate its performance. The 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 Ω and inductor L_{L1}=150 mH acting as a harmonic current producing source. The resistance and the inductance of the inverter coupling inductor, are R_i = 0.01 Ω and L_i = 4 mH respectively. A DC-link capacitor of 3.2 mF is used. The reference DC-link voltage is set at 650V and the inverter switching frequency, f_s, is 5 kHz.

The PV system parameters are presented in Table 2 and the fly-back high-frequency (HF) transformer parameters are presented in Table 3.The APF is switched on at 0s and the load are increased at 0.04s by connecting an inductive load consists of resistor R_{L1}= 50 Ω and inductor L_{L1}=150 mH in parallel to the existing load. The current unbalance is presented by connecting an inductive load with phase A, only consists of resistor R_{LN}= 15 Ω and inductor L_{LN}=30 mH at 0.08s. The load are increased again at 0.12s by connecting an inductive load consists of resistor R_{L2}= 15 Ω and inductor L_{L2}=30 mH in parallel to the existing loads. At 0.16s, the atmospheric temperature is increased to 35° C. The DC-link voltage with predictive fuzzy controller is shown in Fig. 7. At starting of the APF operation, the DC-link voltage is build-up to its reference of 650V at 0.02s with no overshoot showing excellent performance. Almost no change in DC-link voltage occurs for the simulated varying loading and environmental conditions.

Table 2: Investigated system parameters

Quantity	Symbol	Values
Rated power	P_{MPPT}	225 W
Rated voltage	V_{MPPT}	26.3 V
Rated current	I_{MPPT}	7.6 A
Open-circuit voltage	V_{OC}	32.9 V
Short-circuit current	I_{SC}	8.21 A
Number of series cell	N_S	54
Number of parallel cell	N_P	1
Number of series modules	N_{Sm}	5
Number of parallel modules	N_{Pm}	3
PV module capacitor	C	4700μF
Nominal Atmospheric Temperature	T_C	25°C
Nominal Solar Irradiation	G_N	1000 W/m^2
Line grid voltage in RMS	V_S	380 V
DC-link reference voltage	V^*_{dc}	650V
Fly-back capacitor	C_F	3.2mF
Grid tied inductor	L_S	4mH
DC-bus capacitor	C_{dc}	5 μF
Sampling frequency	F_{SM}	33kHz
Switching frequency	f_S	5kHz
Line frequency	f	50Hz

Table 3: Fly-back HF transformer parameters

Quantity	Symbol	Values
Inductance	L_{boost}	28μH
DC resistance	DCR Primary	0.008 Ω
DC resistance	DCR Secondary	0.472 Ω
Self-Resonant Frequency	SRF	360 kHz
Saturation current	I_{sat}.	210.5 A
Turns ratio	Pri.: Sec.	1:12

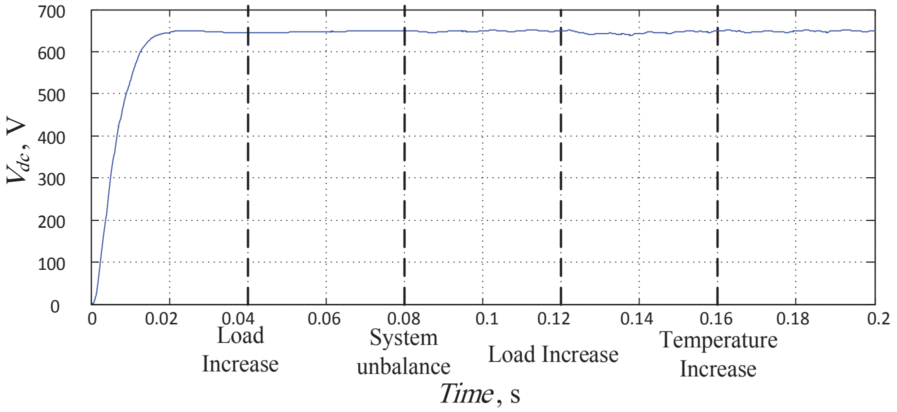

Fig. 7. Capacitor voltage, V_{dc} simulation results with the proposed predictive fuzzy controller under varying loading and environmental conditions.

The active and reactive power of the grid, inverter, and load are shown in Fig. 8 parts (a), (b), and (c), respectively. The load active power, P_L, is increased at 0.04s from 8.8 kW to 13.5KW, while its associated reactive power, Q_L, is increased from 2.5kVA to 4.1 kVA.

The three-phase grid voltage waveforms at the PCC are shown in Fig. 9(a). Typical non-linear load current, i_L, is shown in Fig. 9(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 inverter compensation current with the proposed predictive fuzzy control, i_c, shown in Fig. 9(c) is injected at the PCC. As a result, sinusoidal and balanced grid current, i_s, is achieved as shown in Fig. 9(d). The load neutral current, i_{Ln}, is shown in Fig. 10(a). The inverter neutral current with the proposed predictive fuzzy, i_{cn}, shown in Fig. 10(b) is injected. As a result, the supply neutral current is mitigated as shown in Fig. 10(c).

During the whole simulation period the generated power from the PV arrays (near 3 kW) is injected at PCC, aiding the grid to supply the load demands. Moreover the grid PF is stabilized by the injected reactive power to compensate for the load inductive nature. Hence, the dual-function feature under the proposed controller is validated under varying loading and environmental conditions. The supply current total harmonic distortion, (THD), is compared before and after compensation. The APF improves the THD of the line currents from 17.5%, 29.2%, and 30.1 to 3.1%, 3%, and 2.8% which comply with the IEEE std. 519-1992 [5]. The rms current of the load, inverter, and the grid are shown in Fig. 11(a), (b), and (c), respectively. Hence, the capability of proposed configuration to improve the grid currents, THD and mitigate the neutral current in addition to transfer the PV power to the grid is validated.

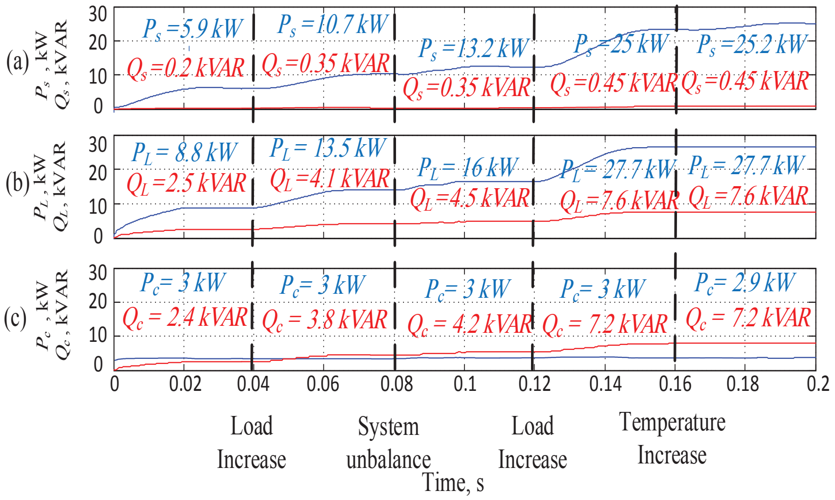

Fig. 8. Simulation results: (a) supply active and reactive power, P_s and, Q_s , (b) load active and reactive power, P_L and, Q_L and (c) Inverter active and reactive power, P_c and, Q_c

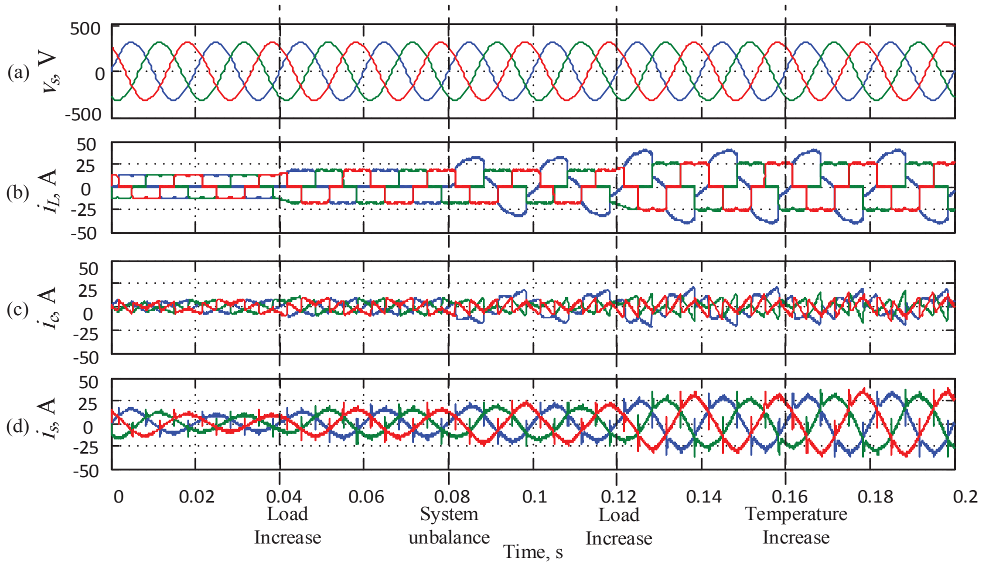

Fig. 9. Simulation results: (a) supply voltage, v_s, (b) load current, i_L, (c) compensation inverter current, i_c, and (d) compensated supply current, i_s,

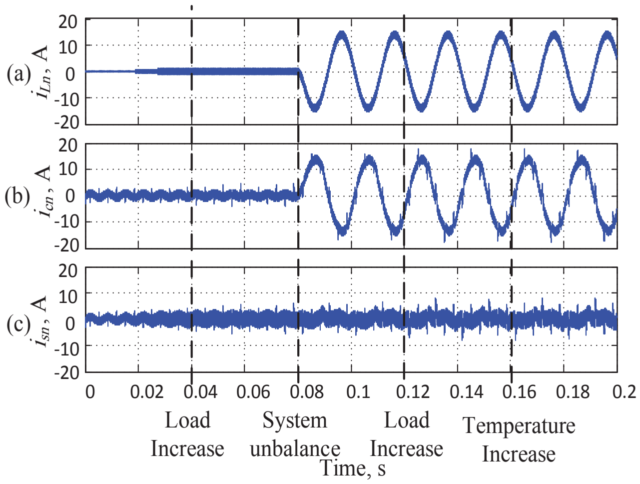

Fig. 10. Simulation results: (a) load neutral current, i_{Ln}, (b) compensation inverter neutral current, i_{cn}, and (c) compensated supply neutral current, i_{sn}.

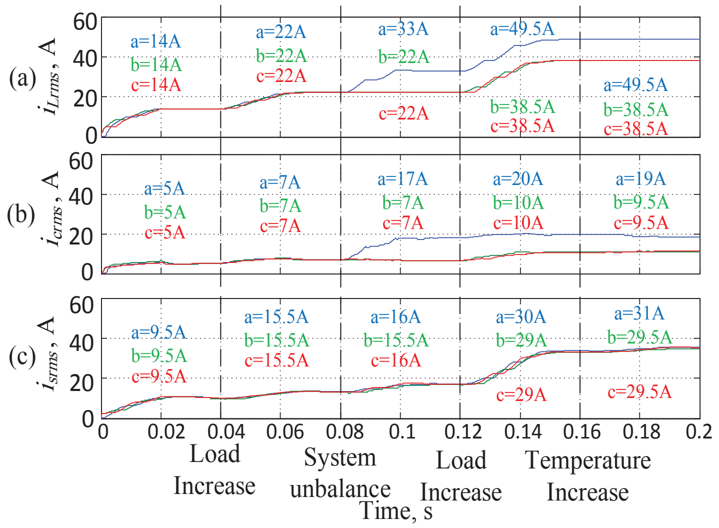

Fig. 11. Simulation results: (a) load rms current, i_{Lrms}, (b) Inverter rms current, i_{crms}, and (c) supply rms current, i_{srms},

VI. CONCLUSION

In this paper, a dual-function APF is proposed. The presented APF offers the capability to: (i) mitigate supply current harmonics, (ii) minimize the neutral current, (iii) attain near unity power factor operation in addition to interfacing a locally generated PV power to the grid. A unified fuzzy logic based controller is proposed to achieve these functions. The presented system attains high performance, system balance, PLL independency, reduced number of required sensors, and ease of implementation. Rigorous simulations have been carried out verifying the proposed techniques effectiveness under varying loading and environmental conditions.

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