

Development of fuzzy logic controller for photovoltaic integrated shunt active power filter

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Abstract. This paper presents the design, modeling, and implementation of a photovoltaic (PV) integrated shunt active power filter (SAPF) for clean power generation along with power quality improvement. The system uses fuzzy logic control (FLC) for maximum power point tracking (MPPT) and SAPF control. The proposed system implements synchronous reference frame theory based direct power control strategy using hysteresis control. The system performance is evaluated in real-time under-balanced/unbalanced and nonlinear load conditions using field-programmable gate array (FPGA) based computational engine with different controllers. The performance is observed to be better with FLC as compared to traditional controllers.

Keywords: Photovoltaic array, maximum power point, fuzzy logic control, shunt active power filter, power quality

1. Introduction

Smart grid realization poses one of the major issues towards power quality. To compensate for it, shunt active power filter (SAPF) is preferred over passive filters because of their fast and dynamic compensation. Power quality concerns such as harmonics, low power factor and unbalanced loads are quite common in power distribution systems. Low power factor increases the utilization expenses. Load unbalance results from different power utilization in each phase which leads to unwanted high neutral current and unreliable power supply. Utilization of non-linear loads is the main cause of harmonics, which thereby leads to problems in system stability and brings larger influence on devices and feeder de-rating. They also

contribute as one of the major factors in larger heating losses in transformer, mains voltage blinking, audible noise in system components, electromagnetic interference, shorter existence of natural protection, incorrect operation of voltage sensitive devices and above all malfunction of protective relaying systems. Thus, harmonics elimination is of utmost importance and can be realized using filters. Conventional passive filter is replaced by SAPF because of better dynamic performance. SAPF provides compensating current to nullify the AC side harmonics. This employs a controller to extract reference-current while regulating DC-link voltage of the voltage source inverter (VSI) [1, 2]. The traditional controllers like PI and PID require exact mathematical models which are complex to tune and also underperform during varying load conditions [3].

They are replaced with a new strategy like FLC which offers a better solution. Fuzzy-PI based controllers used in distribution static compensator

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(D-STATCOM) has nonlinear, robust and faster transient response as compared to traditional PI controller [4]. The FLC based SAPF reduces the current harmonics and improves the steady state performance under dynamic load changes [5–10]. Direct power control based on high selectivity filters (low pass filter) has been presented [11]. They have used instantaneous reactive power theory (IRPT) for unbalanced load with non-sinusoidal source voltage to improve the power quality.

Energy demand is rising very fast due to increased industrial and household energy consumption. The conventional resources are limited and their usage is also responsible for environmental problems. Solar energy may provide a sufficient solution to this problem. Amid the many renewable energy sources namely, solar, wind, tidal, geothermal, biomass, bio-fuel and small hydro; solar energy is the best green energy resource. As the V-I characteristics of PV array changes with irradiation and temperature, MPPT schemes are needed to extract its maximum energy. Numerous MPPT strategies such as P&O, incremental & conductance (I&C), fractional open voltage and fractional short circuit current are developed and actualized [12]. Ansari et al. [13] presented the fuzzy based MPPT controller which demonstrates an accurate and fast response. They did not use any DC-DC converter and fed the MPPT output directly to VSI. The proper design of DC-DC converter helps in boosting PV panel output and thus the efficiency. Adaptive P&O-fuzzy MPPT techniques are applied in [14] which provides faster response and better stability over traditional algorithms. AI based fuzzy logic is implemented to improve control performance and to detect MPP [15]. Alajmi et al. [16] presented the FLC based hill climbing technique which is fast and accurately converges the MPP during steady-state and varying weather conditions. [17] showed that FLC based MPPT reduces the oscillation around MPP. Fuzzy based MPPT results in high tracking efficiency under all weather conditions [18].

The PV integrated SAPF operates during sunlight to provide power and power quality enhancement [19]. Amid the night and no-daylight periods, the power required by the loads is taken from the distribution system while SAPF simply provides reactive power compensation and harmonic elimination.

The operation of PV integrated SAPF consisting DC-DC boost converter is presented in [20–25]. They used P&O algorithm to extract the highest power and utilized the instantaneous reactive power theory (IRPT) for harmonic mitigation. M. Vijaykumar

et al. [26] described the PV integrated hybrid SAPF to eliminate the voltage and current harmonics. The author does not describe the MPPT operation. R. Balamurugan et al. [27] introduced the second-order generalized integrator to control the PV-SAPF. This topology does not need voltage sensor on AC and DC side and the presented scheme is implemented for single-phase PV-SAPF. G. Vijaykumar et al. [28] presented the $I \cos \phi$ based control scheme used for the estimation of reference supply currents PV integrated SAPF. This work used P&O algorithm to track maximum power which gave satisfactory results. Geury et al. [29] introduced the single stage PV integrated SAPF using sliding mode control for minimizing the harmonics distortion and power factor correction. Zainuri et al. [30] presented the adaptive linear neuron based control algorithm for PV-SAPF to minimize the harmonic distortion. Tuyen et al. [31] demonstrated the operation of PV integrated SAPF. They used I&C method to extract MPP and applied IRPT to control SAPF. IRPT has disadvantages of slower response and large computational burden on the system as compared to SRF theory. This strategy is inefficient for dynamic load changes. Kannan et al. [32] presented a PV based D-STATCOM to improve power quality using SRF theory. It provides better control for reactive power compensation, minimizes the voltage variations and yields better utilization of solar energy. Dionne Soto et al. [33] extended the PV integrated SAPF operation for islanding detection. H. Calleja et al. [34] presented a single-phase grid associated PV integrated SAPF to compensate reactive power, to minimize the harmonic distortions and also to extract maximum power from PV module. PV integrated UPQC was proposed in [35] which has various advantages like enhancing power quality of the grid, protecting critical loads from grid side disruption and increasing the fault ride through capacity of the converter during transients. PV integrated SAPF using artificial intelligence has been reported in [36]. The majority of the work available in the literature concentrates on MPPT operation of PV array, design of inverter topologies and performance of inverter in grid integration.

The literature review reveals that the PV integrated SAPF has many advantages such as harmonic elimination, constant DC-link voltage and better control of reactive power compensation over traditional methods. Solar energy has dependably helped in reducing global warming and greenhouse effects. In this article, a PV integrated SAPF is proposed which is controlled using soft-computing based FLC for

varying load conditions. The major objectives and contributions of this paper are:

- Design and mathematical formulation of PV-SAPF.
- Design of FLC based MPPT controller to extract maximum power from PV module.
- Design of FLC to control SAPF.
- Smooth regulation of DC-link voltage.
- System performance evaluation based on the MATLAB/Simulink and then validation in real-time.

The paper organization is as follows: Section 1 introduces the article. Section 2 presents the system configuration of PV integrated SAPF, corresponding mathematical modeling and proposed control scheme. In Section 3, the real-time results and discussions are enumerated. Finally, the conclusion is drawn in Section 4.

2. System configuration of PV-SAPF

The power circuit of PV integrated SAPF is shown in Fig. 1. The boost converter is connected with VSI which is linked at point of common coupling (PCC) with balanced/unbalanced and nonlinear loads. The

proposed system consists of two stages; in the first stage, MPPT control is used to track the maximum power of the PV module using the DC-DC boost converter. The second stage is used to control a three-phase grid-tied VSI which has six insulated-gate bipolar transistors (IGBT) grid-interfaced VSC, also operating as a SAPF. The proposed strategy is based on SRF theory.

2.1. Modeling of SAPF

As per Fig. 1, one can build up the dynamic model of three-phase SAPF. As per circuit theory and KVL, we can acquire Equations (1) to (3) [37]

$$V_{pa} = L_c \frac{di_{ca}}{dt} + R_c i_{ca} + V_{1M} + V_{MN} \quad (1)$$

$$V_{pb} = L_c \frac{di_{cb}}{dt} + R_c i_{cb} + V_{2M} + V_{MN} \quad (2)$$

$$V_{pc} = L_c \frac{di_{cc}}{dt} + R_c i_{cc} + V_{3M} + V_{MN} \quad (3)$$

where L_c and R_c are the inductance and resistance of the SAPF respectively. The V_{MN} is the voltage

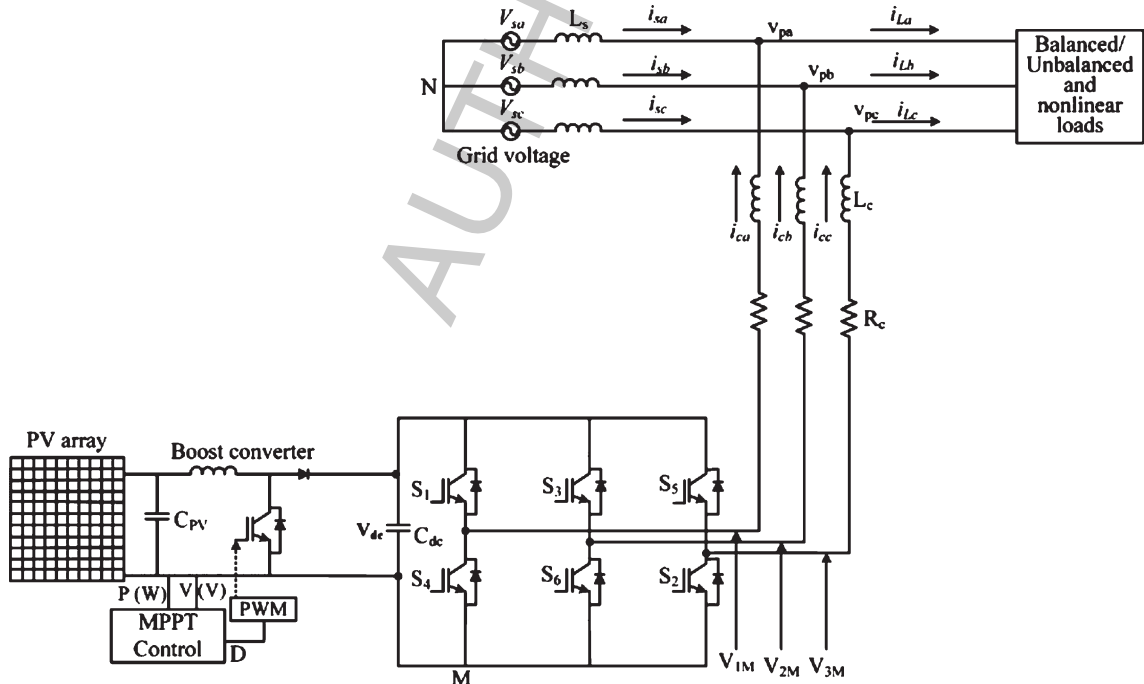


Fig. 1. Power circuit of PV integrated SAPF.

between M and N expressed as in Equation (4).

$$V_{MN} = -\frac{1}{3} \sum_{m=1}^3 V_{mM} \quad (4)$$

The ON/OFF status of the devices in the IGBT bridge is denoted by a switching function g_n and is given in Equation (5).

$$g_n = \begin{cases} 1, & \text{if } s_n \text{ is On and } s_{n+3} \text{ is Off} \\ 0, & \text{if } s_n \text{ is Off and } s_{n+3} \text{ is On} \end{cases} \quad (5)$$

where, $n=1,2,3$.

As $V_{MN} = g_n V_{dc}$, the Equation (1), (2), (3) becomes

$$\frac{di_{ca}}{dt} = -\frac{R_c}{L_c} i_{ca} + \frac{V_{pa}}{L_c} - \frac{V_{dc}}{L_c} \left(g_1 - \frac{1}{3} \sum_{m=1}^3 g_m \right) \quad (6)$$

$$\frac{di_{cb}}{dt} = -\frac{R_c}{L_c} i_{cb} + \frac{V_{pb}}{L_c} - \frac{V_{dc}}{L_c} \left(g_1 - \frac{1}{3} \sum_{m=1}^3 g_m \right) \quad (7)$$

$$\frac{di_{cc}}{dt} = -\frac{R_c}{L_c} i_{cc} + \frac{V_{pc}}{L_c} - \frac{V_{dc}}{L_c} \left(g_1 - \frac{1}{3} \sum_{m=1}^3 g_m \right) \quad (8)$$

Now, d_n can be defined as:

$$d_n = g_n - \frac{1}{3} \sum_{m=1}^3 g_m. \quad (9)$$

It is clear that d_n depends on the switching function g_n , i.e. nonlinearity in the system. From Equation (9) and taking eight permissible switching states of the IGBT, one can obtain that

$$\begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}. \quad (10)$$

Then equation (13), (14), (15) becomes

$$\frac{di_{ca}}{dt} = -\frac{R_c}{L_c} i_{ca} + \frac{V_{pa}}{L_c} - \frac{V_{dc}}{L_c} d_1 \quad (11)$$

$$\frac{di_{cb}}{dt} = -\frac{R_c}{L_c} i_{cb} + \frac{V_{pb}}{L_c} - \frac{V_{dc}}{L_c} d_2 \quad (12)$$

$$\frac{di_{cc}}{dt} = -\frac{R_c}{L_c} i_{cc} + \frac{V_{pc}}{L_c} - \frac{V_{dc}}{L_c} d_3 \quad (13)$$

$$\text{Define } \begin{cases} x_1 = i_n \\ x_2 = i_{n1} \end{cases} \quad (14)$$

where, $i_n = [i_{ca}; i_{cb}; i_{cc}]$

Putting equation (14) into (11), (12), (13), we have

$$x_1 = i_n = -\frac{R_c}{L_c} i_n + \frac{V_n}{L_c} - \frac{V_{dc}}{L_c} d_n \quad (15)$$

$$x_2 = i_{n1} = -\frac{R_c}{L_c} i_n + \frac{1}{L_c} \frac{dV_n}{dt} - \frac{1}{L_c} \frac{dV_{dc}}{dt} d_n \quad (16)$$

$$= -\frac{R_c^2}{L_c^2} i_n - \frac{R_c}{L_c^2} v_n + \frac{1}{L_c} \frac{dV_n}{dt} + \left(\frac{R_c}{L_c^2} V_{dc} - \frac{1}{L_c} \frac{dV_{dc}}{dt} \right) d_n. \quad (17)$$

Then Equation (17) becomes

$$x_2 = ba(x) + Mz \quad (18)$$

where, $ba(x)$ and Mz represented the state control.

$$ba(x) = \frac{R_c^2}{L_c^2} i_n - \frac{R_c}{L_c^2} v_n + \frac{1}{L_c} \frac{dV_n}{dt},$$

$$M = \frac{R_c}{L_c^2} V_{dc} - \frac{1}{L_c} \frac{dV_{dc}}{dt}$$

$$z = d_n, v_n = [V_{pa}; V_{pb}; V_{pc}],$$

$$d_n = [d_1; d_2; d_3] \quad (18)$$

2.2. Fuzzy logic controller based strategy

The PV system has non-linear V-I characteristics which changes with solar irradiation and temperature. FL base strategy provides solutions to uncertainties and nonlinearity problems in an effective manner. The implementation of FL based tracking is simple, as it does not need mathematical modelling of the system. Further, it results in better dynamic response and high convergence rate.

Figure 2 shows the basic structure of the fuzzy process, which comprises fuzzification, inference engine and defuzzification. A brief description of the processes is given below:

Fuzzification: The process of converting a numerical variable (real number) to a linguistic variable

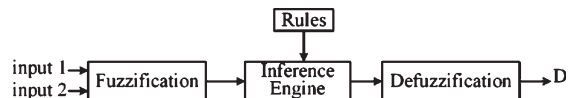


Fig. 2. Basic structure of Fuzzy process.

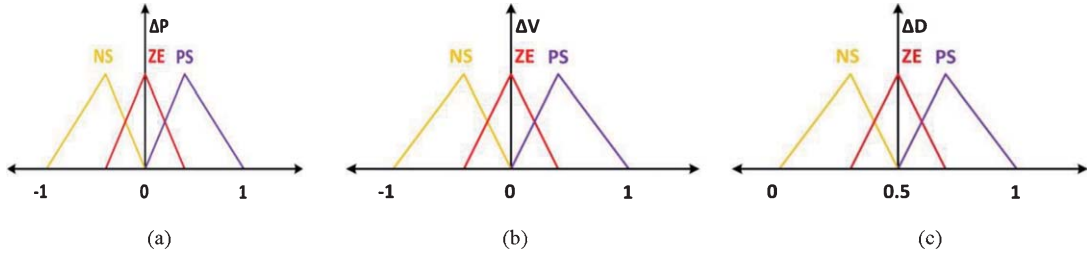


Fig. 3. Membership functions (a) input variable (ΔP) (b) input variable (ΔV) (c) output variable (ΔD).

(fuzzy number) is called fuzzification.

Inference engine: The input and output variables are assigned with linguistic variables.

Defuzzification: is the process of transforming linguistic variables in to real number.

2.2.1. Fuzzy logic controller based MPPT

The FLC MPPT controller extracts utmost power from the PV system at variable irradiance and ambient temperatures. To generate constant DC-link voltage, the boost converter IGBT is controlled using FLC MPPT type with PWM technique. This boost converter has two functions: to step up the voltage generated at PV terminals to DC-link voltage and to extract maximum available power from solar PV using MPPT control. Operating point setting is a tough task which is done using fuzzy and P&O algorithms that further controls the boost converter. The inputs to the planned controller are variations in power (ΔP) and voltage (ΔV). (ΔD) is the corresponding variation in output duty cycle.

The shape of the MF is important for a particular problem since they effect the fuzzy inference system. In this work, different membership function (MF) like triangular, Gaussian and trapezoidal are tested with rules 3*3, 5*5 and 7*7. In real-time implementation, the triangular MF with 3*3 (Fig. 3) rules is adopted here as it imposes lesser computational burden. Mamdani's method is used as a fuzzy decision rule base that is based on the max-min composition.

The linguistic variables are represented as:

NS: negative small, ZE: zeros and PS: positive small. The proposed fuzzy MPPT will contain 3*3 (nine) different rules as depicted in Table 1.

The results for FL and P&O (conventional) based control algorithm for MPPT are compared and it is found that FL based methods are superior. The detail results are given in section 3.

Table 1
Rule base for planned FLC based MPPT

$\Delta P \backslash \Delta V$	NS	ZE	PS
NS	PS	NS	NS
ZE	NS	ZE	ZE
PS	NS	PS	PS

2.3. Fuzzy logic control of the SAPF

In this work SRF based SAPF is used. The functional diagram of SRF based control method is shown in Fig. 4. The feedback signals are sensed from the load current, grid and DC-link voltages of SAPF.

The load currents from abc axis are converted to $dq0$ axis using the following Equation (19)

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \times \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (19)$$

A three-phase, phase lock loop (PLL) is used to synchronize these signals with the grid voltage. Figure 5 shows the block diagram of PLL including phase detector, low-pass filter (LPF) and voltage control oscillator (VCO). The phase detection in PLL is implemented by applying the Clarke's transformation and then the Park's transformation to three-phase input signals. The q-axis output of the phase detector which contains the phase error information, is passed through the LPF (the PI controller). The resultant signal, which is an estimated frequency, is fed to VCO which yields an estimation of the phase angle.

DC-link voltage (V_{dc}) is sensed and compared with reference voltage ($V_{dc \text{ ref}}$). The error (E) and change

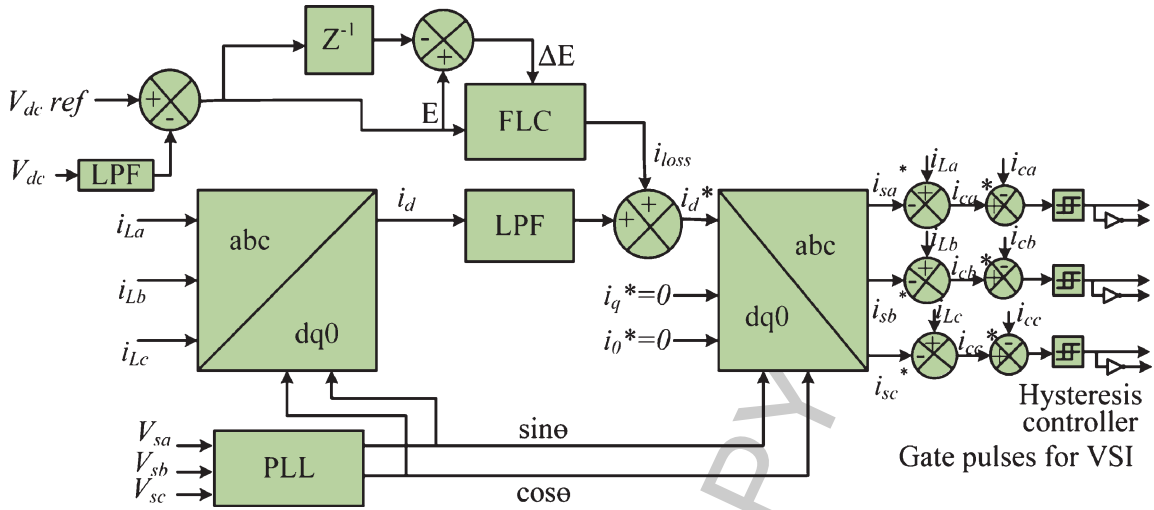


Fig. 4. Block diagram of FLC based control technique.

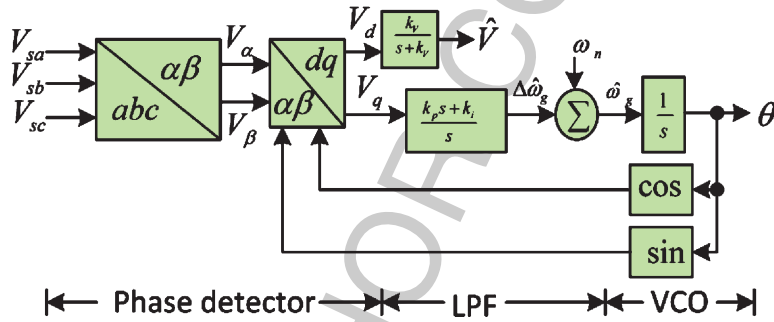


Fig. 5. Block diagram of PLL.

in error (ΔE) are supplied to the controller (PI or Fuzzy). The output of the controller is an active power component which is used to maintain V_{dc} at a reference value and then the reference source current is compared with the load current to generate a reference compensating current. The reference compensating current is compared with actual compensating current and the difference is fed to hysteresis current controller to finally minimize the harmonics and draw the pure sinusoidal currents from the utility.

The fuzzy controller MFs are shown in Fig. 6. Fuzzy control-based system has two inputs which are assumed as a number of linguistic values represented by a fuzzy set. Seven linguistic variables chosen for this work are: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big).

In the transient state, large error needs coarse control and requires coarse input/output variables.

In steady state, little error needs superior control which requires fine input/output variables. In view of this, FLC rules are displayed in Table 2.

The results for FL and PI based control algorithm to control SAPF are compared and it is found that FL based methods provide better results. The detail results are given in section 3.

3. Real-time results and discussion

Real-time technology is a necessary part of the design and test procedure of various types of electric systems like power grids, adjustable speed drives and power converters. The latest approaches mitigate the risks through the wide use of technologies like hardware in the loop (HIL) simulation and model-based design approach. Real-time lab permits the user to readily convert Simulink to real time workshop and then to conduct real-time simulation of

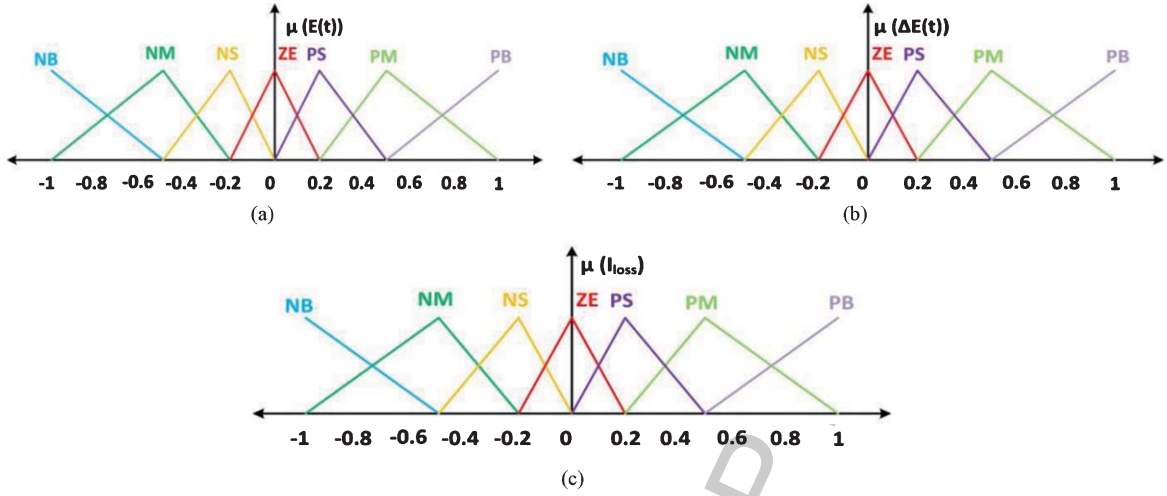


Fig. 6. Membership functions (a) input variable error 'E' (b) input change in error 'ΔE' (c) output variable reference current 'I_{loss}'.

Table 2
Fuzzy rule base

ΔE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

those models executed on a multiprocessor hardware design. To accommodate the outputs, scale is decreased by a factor of 1000 voltage and current measurement respectively.

The real-time work bench used to carry out the validation of the proposed work is given in Fig. 7. This system has two parts: one is host computer and another is OPAL-RT. The host computer has three basic purposes such as: Simulink model; model compilation with RT-LAB and user interface.

The performance of combined PV integrated SAPF system is validated in OPAL-RT 4510. The impact of balanced/unbalanced and nonlinear load is investigated here. Three-phase diode rectifiers represent the nonlinear load. The parameters used are: three phase grid voltage 400 V; frequency 50 Hz; compensating inductance 4 mH; DC-link capacitor 5750 μF and PV array voltages 300 V. The results are obtained under standard climatic conditions (1000 W/m² and 30°C).

Figure 8 shows signature of V_{dc} of the combined PV-SAPF system under variable irradiance and

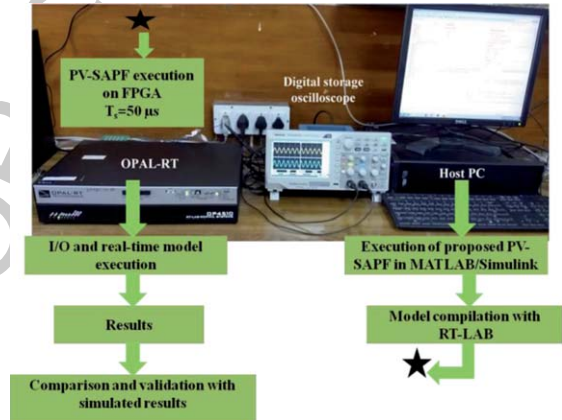


Fig. 7. Real-time laboratory set up.

temperature. It can be observed that it has very less deviation from V_{dc} ref.

Figure 9 depicts the output voltage of the combined system with boost converter for i) FLC in SAPF and for MPPT, ii) PI in SAPF and P&O for MPPT and iii) without MPPT. It also provides the PV array voltage without boost converter for reference. This figure indicates that the FLC based MPPT settles earlier than P&O based method and has lesser overshoots and lesser variation in DC-link voltage i.e. it offers better transient response.

Therefore, the FLC based MPPT and SAPF controller is used in this work and the results for different load combinations are given below.

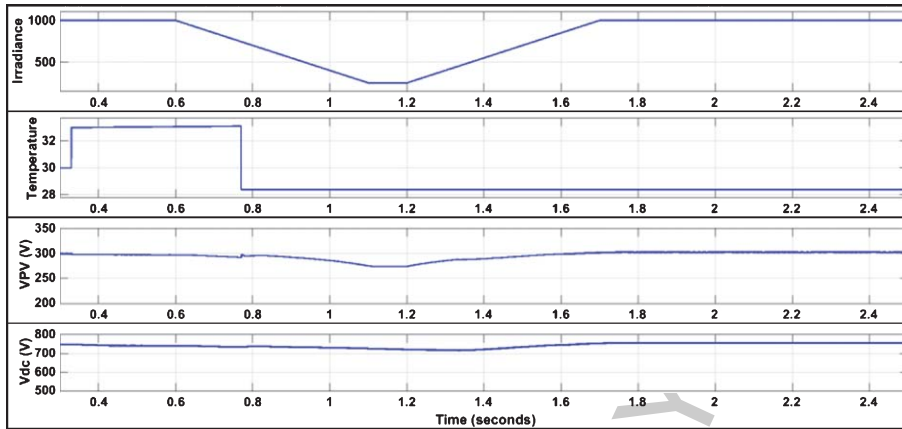


Fig. 8. Dynamic response of PV array at varying irradiance and temperature.

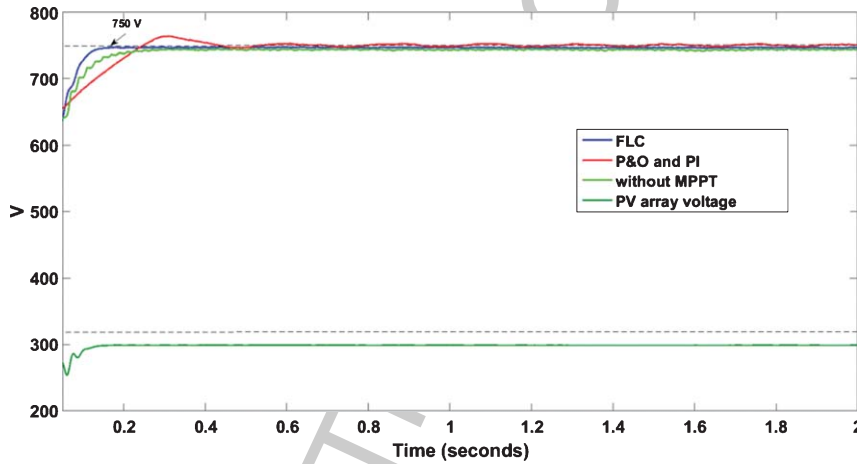
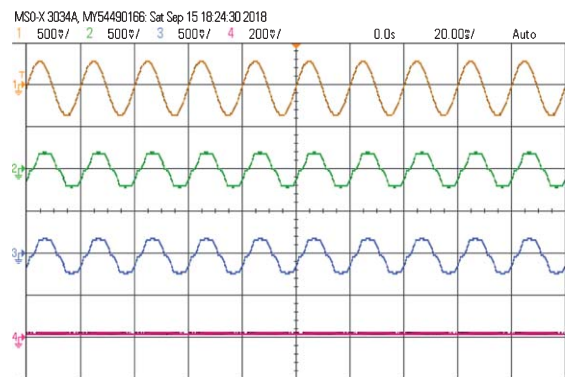


Fig. 9. Transient response of DC-link voltage.

3.1. Performance of system under balanced and nonlinear load conditions

Figure 10 shows source voltage, source current, load current and compensating current when PV-SAPF is OFF (i.e. SAPF does not receive gate pulse). Figures 11, 12, 13 and 14 depict the source voltage, source current, load current and compensating current respectively for all three phases when PV-SAPF is ON. It can easily be inferred that the source current is sinusoidal which was not so when SAPF was OFF. Figure 15 and 16 display the harmonic spectrums of source currents without and with compensation respectively. The THD is minimized from 17.74 % to 1.67 %.

Fig. 10. System performance without PV-SAPF. Scale-CH1 V_{sa} : 500 V/div, CH2 i_{sa} : 500 A/div, CH3 i_{la} : 500 A/div, CH4 i_{ca} : 200 A/div.

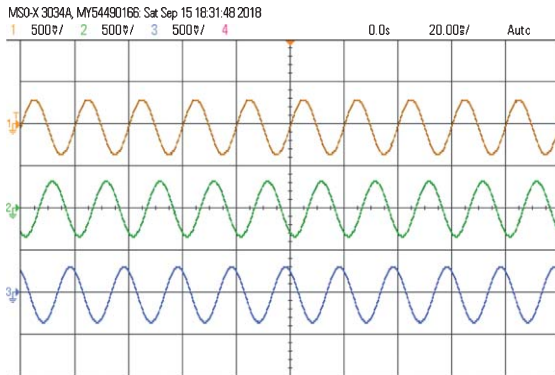


Fig. 11. Waveform of grid voltage. Scale-CH1: V_{sa} :500 V/div, CH2 V_{sb} : 500 V/div, CH3 V_{sc} : 500 V/div.

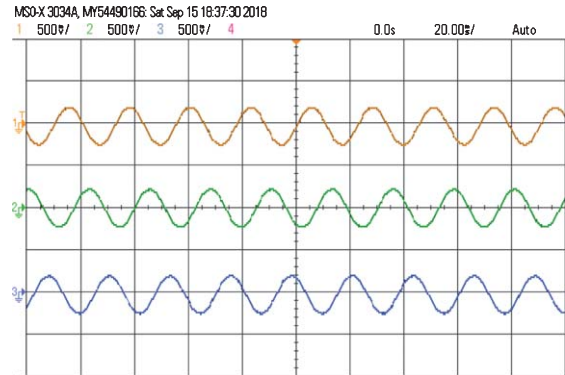


Fig. 13. Waveform of grid current. Scale-CH1: i_{sa} :500 A/div, CH2 i_{sb} : 500 A/div, CH3 i_{sc} : 500 A/div.

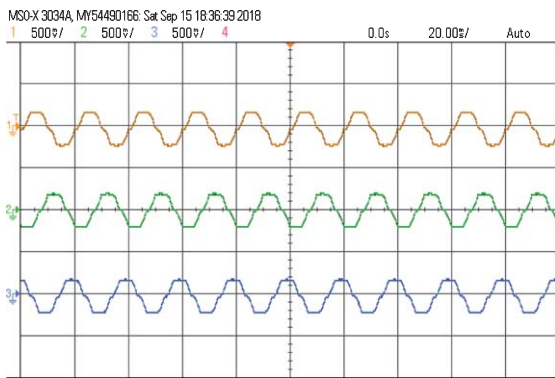


Fig. 12. Waveform of load current. Scale-CH1: i_{La} :500 A/div, CH2 i_{Lb} : 500 A/div, CH3 i_{Lc} : 500 A/div.

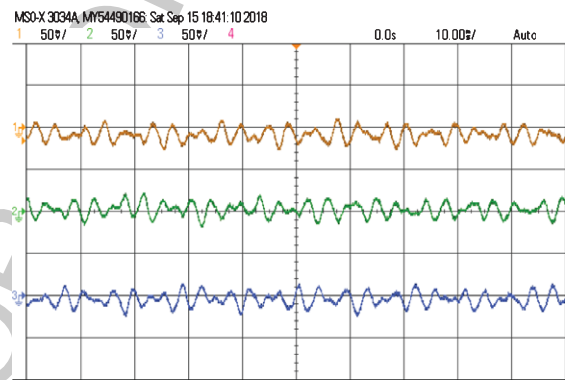


Fig. 14. Waveform of compensating current. Scale-CH1: i_{ca} :50 A/div, CH2 i_{cb} : 50 A/div, CH3 i_{cc} : 50 A/div.

3.2. Performance of system under unbalanced and nonlinear load conditions

Figure 17 shows the grid voltage, grid current, load current and compensating current respectively when unbalanced and nonlinear load is applied. Figures. 18 and 19 provide the harmonic spectrum of source current and load current respectively.

3.3. Performance comparison of conventional and proposed algorithm

A comparative study of the proposed and existing methods under balanced/unbalanced and nonlinear load conditions has been carried out and the performance of the proposed system is found better. Table 3 represents the comparison in terms of steady state

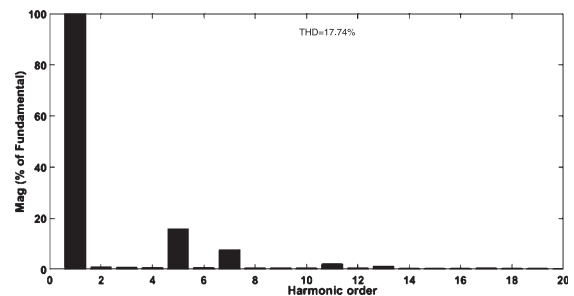


Fig. 15. Harmonic spectrum of source current without PV-SAPF.

conditions, overshoot, rise time and THD. It infers that the proposed FLC based technique extracts out the harmonics from the distorted grid current effectively.

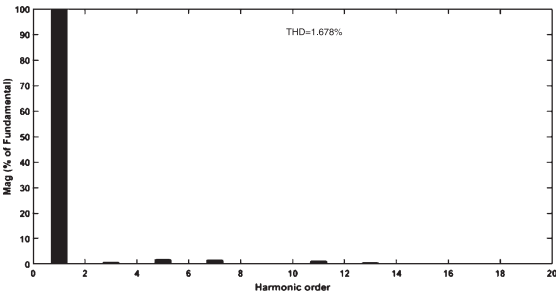


Fig. 16. Harmonic spectrum of source current with PV-SAPF.

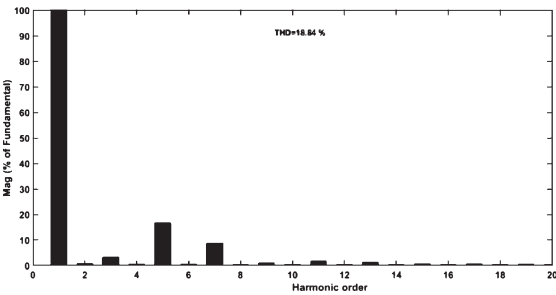


Fig. 19. Harmonics spectrum of load current.

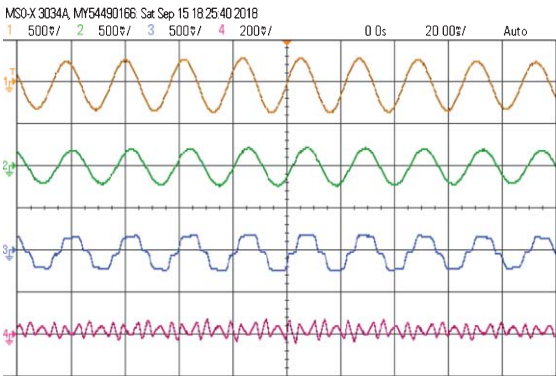


Fig. 17. Waveform of grid voltage. Scale-CH1: V_s :500 V/div, i_s :500 A/div CH3 i_L : 500 A/div, CH4 i_c : 200 A/div.

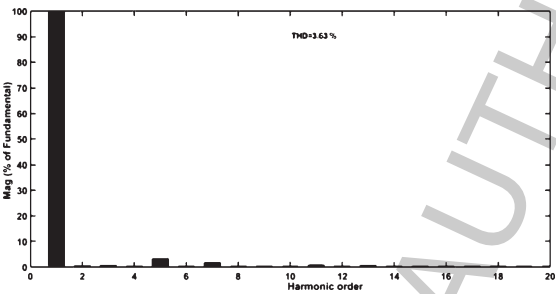


Fig. 18. Harmonics spectrum of grid current.

4. Conclusion

This paper provides the design and analysis of PV integrated shunt active power filter. Fuzzy logic and perturb & observe based MPPT techniques are designed to extract maximum power from PV array. Further, synchronous reference frame theory-based PI and FL controllers are used to control the SAPF. A detailed comparative analysis is made for these control strategies. FLC provides better response over traditional techniques for MPPT and control of SAPF and also involves lesser complexity. PV integrated SAPF systems are found superior in performance as they are cost-effective, provide better control of reactive power compensation, reduce current harmonics, minimize voltage variation problems, improves power factor and do not need additional grid tied inverter.

The PV integrated SAPF using FLC has better transient response over conventional PI controllers under load variations. The performance of this system is validated using OPAL-RT hardware controller. In case of balanced & nonlinear load, the THD is minimized from 17.74 % to 1.678 % and for unbalanced & nonlinear load, the THD is minimized from 18.84 % to 3.63 %. The PV integrated SAPF using FLC is found to be an efficient solution to improve the power qual-

Table 3
Performance comparison of conventional and proposed algorithm

Authors	Control Technique	% Overshoot in DC-link voltage	Balanced & nonlinear load		Unbalanced & nonlinear load	
			%THD in source current	Power Factor	%THD	Power Factor
Geury et al.	Sliding mode	–	3.59	0.99	6.07	0.96
Geury et al.	Adaptive linear neuron	–	4.52	–	–	–
Tuyen et al.	PI	–	3.67	1	–	–
Kannan et al.	PI	43	5.38	–	–	–
Proposed	FLC	No overshoot	1.67	0.96	3.63	0.95

ity which further motivates the use of PV integrated energy systems.

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Appendix

C_{pv}	capacitance of PV array	PCC	point of common coupling
C_{dc}	DC-link capacitor	P&O	perturb & observe
D	duty cycle	PLL	phase lock loop
DSTATCOM	distribution static compensator	PV	photovoltaic
FLC	fuzzy logic control	SAPF	shunt active power filter
FPGA	field programmable gate array	SRF	synchronous reference frame
i_c	compensating current	THD	total harmonic distortion
I&C	incremental and conductance	UPQC	unified power quality conditioner
i_{La}, i_{Lb}, i_{Lc}	load currents	V_{sa}, V_{sb}, V_{sc}	source voltages
IRPT	instantaneous reactive power theory	V_{dc}	dc link voltage
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	reference source currents	V_{dc}^*	reference dc link voltage
i_{sa}, i_{sb}, i_{sc}	actual source current	V_{pv}	PV array voltage
i_d, i_q	direct and quadrature axis current	VSI	voltage source inverter
k	overloading factor	Δi_L	ripple filter inductance
m_i	modulation index	ΔD	duty cycle variation
MF	membership function	ΔP	power variation
MPPT	maximum power point tracking	ΔV	voltage variation
n	n^{th} harmonic order		