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Grid Connected PV System with a Feed-Forward Control to Improve Power Quality in Distribution Grid

Vadela Mahesh
GVPCE (A)
K. Ravi Kumar
GVPCE (A)

ABSTRACT

Distributed energy resources (Solar PV arrays, Wind energy, battery system, etc,) are used to reduce the use of non-renewable energy resources. Harmonics arise in power system due to the Integration of renewable energy resources with the grid. Single phase ac/dc converters are usually employed as the utility interface in the grid tied renewable energy resource system. In this work, a 1kW PV array is integrated with grid using bidirectional ac/dc converter which operates in both rectifier and inverter operating modes to maintain bidirectional power flow in grid tied micro grids as per the requirements. A fuzzy based MPPT controller is used to extract the maximum power point of the PV array. A feed forward controller is implemented for the bidirectional ac-dc converter to reduce the harmonics in AC line current.

KEYWORDS

DERs- Distributed Energy Resources, PV- Photo Voltaic, MPPT- Maximum Power Point Tracking, THD- Total Harmonic Distortion, FLC- Fuzzy Logic Control, FFT- Fast Fourier Transform, PWM- Pulse Width Modulation, UPWM- Unipolar PWM, BPWM- Bi-polar PWM

I. INTRODUCTION

Different technical problems arise in grid tied micro grid systems [8], the major problem is harmonic distortion. An AC/DC bidirectional converter is used to interconnect the distributed energy resources with AC grid [1] to maintain bidirectional power flow in the micro grid, to use the distributed energy resources (DERs) effectively and regain power system stability. The functional block diagram of the proposed grid tied PV system is shown in Fig1. When distributed energy resources have sufficient power, the power from the DERs can be transferred to the AC grid using AC/DC bidirectional converter. During the minimum generation or off time of, DERs can't provide electricity to dc load connected at the dc bus, the converter can change the direction of power flow quickly to transfer power from the AC grid to DC bus. Several types of converter control techniques are used to control the bidirectional converter. PWM method is used to reduce the switching losses in inverters and rectifiers. Unipolar PWM and bipolar PWM methods [1] introduces higher harmonics in AC grid current when compared to hybrid PWM technique. The instantaneous power of converter consists of ripple power and constant power. An alternative ripple energy storage element is provided the way to avoid the effect of ripple power on the dc load, and it should act as a ripple filter. A conventional hysteresis current controller has the drawback of a variable switching frequency, and has bad harmonic performance [3]. A DC-DC converter is necessary to step up to the essential voltage level. The power and current characteristics of PV array are effected by the weather conditions, irradiance. PV array characteristics are highly nonlinear. Therefore, a control is needed for maximum power point tracking (MPPT) to eliminate such conditions and make the PV to operating at maximum operating power point [4]. The existing techniques differed in time response, accuracy, cost, simplicity, and other aspects. A voltage based MPPT control method, which uses the ratio between the maximum power voltage and open circuit voltage under different atmosphere conditions. Since, this technique is dependent on approximation constant ratio, the extracted power of PV is below the MPP causes losses in available power [4]. Hence, this technique is failure in tracking the MPP. A customized hill-climbing fuzzy logic based MPPT method is implemented to eliminate these drawbacks.

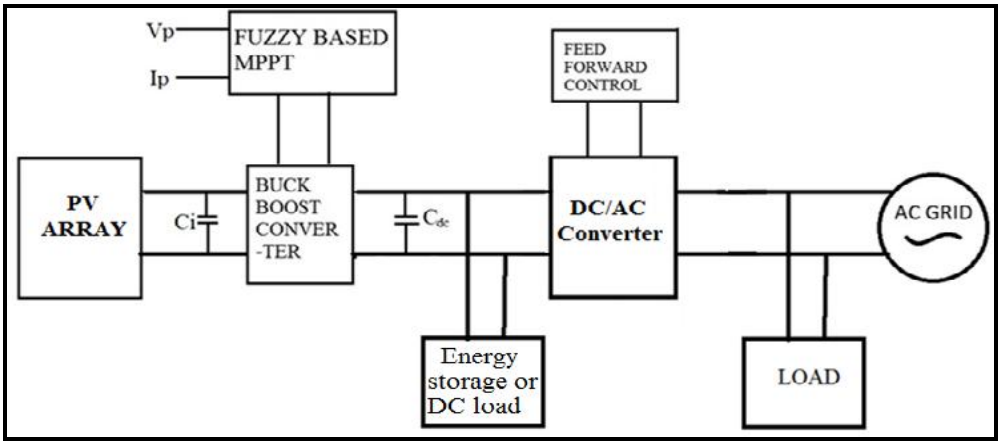

Fig 1: Schematic block diagram of the grid tied PV system

The AC/DC bidirectional converter in gridconnected PV systems need some requirements such as providing the power factor correction, low distortion in AC line currents, less ripple in DC voltage at dc link, and power flow capability in both the directions. PWM generators are suitable for grid-tied systems. In this proposed work a PWM strategy with feedforward controller scheme is implemented for the AC/DC bidirectional converter and it is compared with a dual loop predictable controller. In section II presented the PV grid-connected system and fuzzy based MPPT controller, section III and IV presents the conventional controller and feed forward controller, its operation respectively whereas Section V shows the simulation results and VI concludes the paper.

II. PV GRID-CONNECTED SYSTEM MODEL

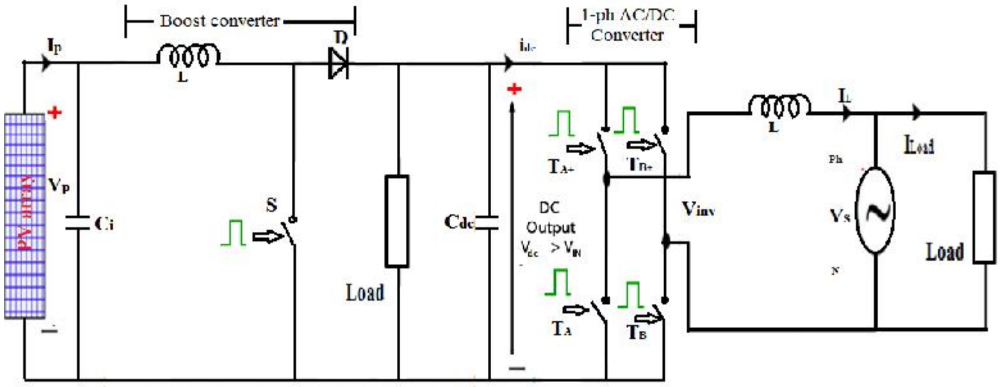

Fig 2: Circuit diagram of the proposed grid-connected PV system

In this paper a grid connected PV system is implemented as shown in the Fig 1, the power is transferred from PV to AC grid during maximum generation of PV, during no power or minimum power generation conditions of PV array, the AC/DC converter can operated in the rectifier mode to maintain bidirectional power flow in the micro grid systems.

PV PANEL MODEL

In general, PV array is a combination of a number of PV cells in series and parallel [2],[5]. Each PV cell is a p-n junction. A practical single diode model of the PV cell is shown in Fig 3. Where R_S and R_{Sh} are the series and shunt resistances connected across diode as in Fig 3. I_s is the short-circuit current of the PV cell, I_D diode current, I_p is the PV cell output current and V_p is the PV cell output voltage. The mathematical model for the PV cell is expressed in fallows.

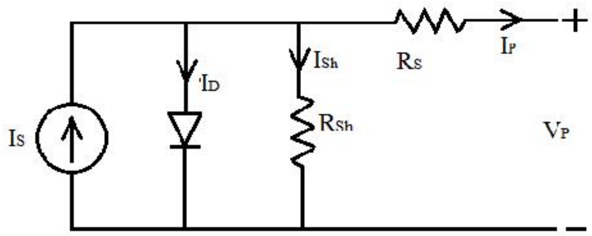

Fig 3: Equivalent of the PV panel

Table 1.Parameters of the proposed system

COMPONENT	VALUE
PV Array rating	1kW (four panels each 250W) Each panel has V_{oc}=38.91V I_{sc}=8.91A V_{MPP}=30.4V I_{MPP}=8.23A
Boost converter	C_i =0.2mF, L=7.9375mH, C_{dc}=2mF Switching frequency f_s=4kHz
Inverter rating	1kW, Switching frequency F_S=40kHz
AC Grid	230V, 50Hz
Non-linear load	R=150 ohm, L=1mH

The characteristics of PV cell current are defined as

$$I_P = N_P I_S - N_P I_0 \left[e\left(\frac{q(V_P + R_S I_P)}{N_S aKT} \right) - 1 \right] - N_P \left(\frac{V_P + R_S I_P}{N_S R_{Sh}} \right) \quad (1)$$

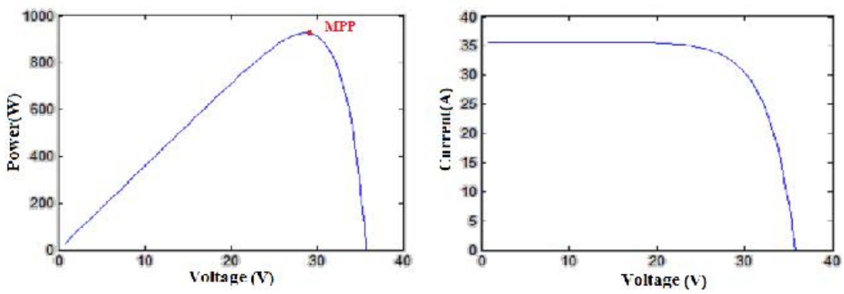

Fig 4: P-V & I-V characteristics of 1kW PV array

In this project, a PV having a total power rating of 1kW is implemented that consisting four panels of rating 250W each. Each panel has the manufacturing characteristics expressed in Table 1. The P-V and I-V characteristics of the designed PV with solar irradiation 1000W/m^2 and temperature of 25°C are simulated and shown in the Fig. 4.

FUZZY BASED MPPT CONTROLLER DESIGN

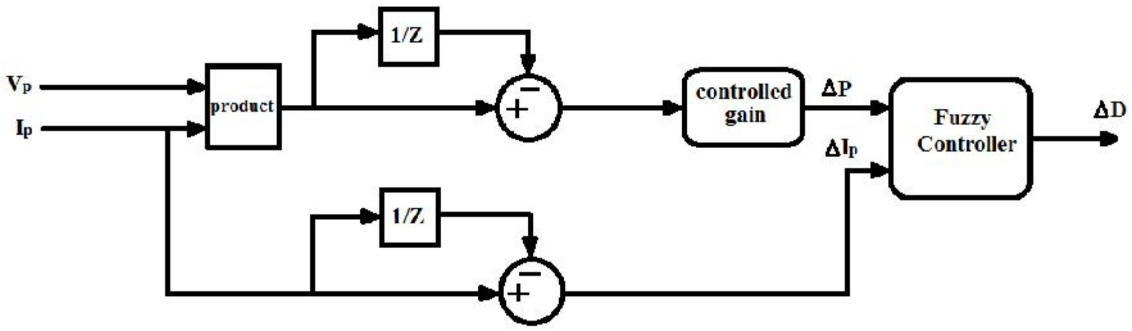

Fig 5: Block diagram of the Fuzzy based MPPT controller

A hill-climbing fuzzy based MPPT technique is implemented to obtain the maximum operating power point of PV array. This method has an advantage of simplicity and eliminating the problems of slow converging to the optimum power point, power losses due to the oscillations of the PV power around the maximum power point and moving of operating power point away from the maximum power point during cloudy weather conditions [6], [7]. The block diagram of fuzzy based MPPT control is shown in Fig 5. The power and currents of the PV array are taken as the references of the controller. The power error and current error are calculated and taken as two inputs to the fuzzy logic controller.

Where the power error and current error are defined as,

$$\Delta P_P = P_P(K) - P_P(K-1) \quad (2)$$

$$\Delta I_P = I_P(K) - I_P(K-1) \quad (3)$$

The change in power (ΔP_P) and the change in current (ΔI_P) given to the fuzzy controller, the output of the fuzzy controller is duty cycle error and is defined as

$$\Delta D = D(K) - D(K-1) \quad (4)$$

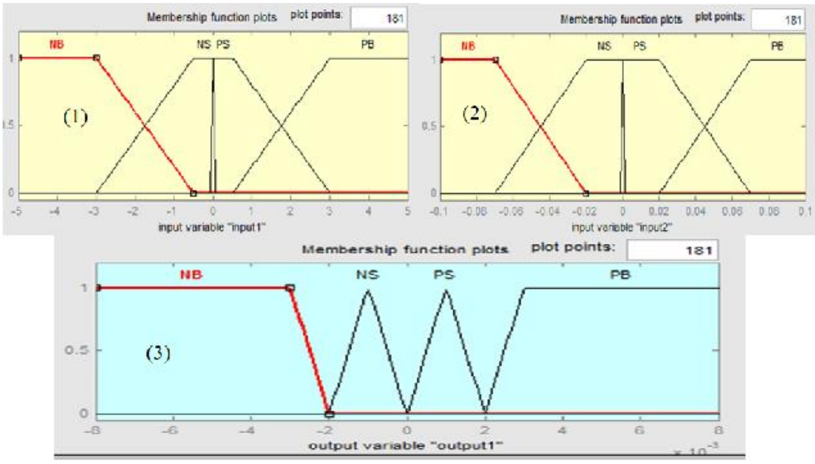

Fig 6: Input (1)(2) and Output(3) membership functions of fuzzy controller

The PV array may not operate at the optimum power point because of the variable weather conditions, to ensure this problem the change in power (ΔP_P) is given to fuzzy controller through gain controller to reverse the direction of power.

The inputs and output of the fuzzy controllers are divided into four fuzzy membership functions and are NB- Negative Big, PB- Positive Big, NS- Negative Small and PS- Positive Small. With input and output membership functions of fuzzy controller 16 fuzzy rules are developed depending on the control algorithm of hill climbing method. Here Mamdani's method with max-min is used for Fuzzification. For Defuzzification

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the Centre of Area algorithm(COA) is used to convert the fuzzy set values into crisp value that is duty cycle change(ΔD)

$$\Delta D = \frac{\sum_i^n \text{«}(D_i) D_i}{\sum_i^n \text{«}(D_i)} \quad (5)$$

Where ΔD is the output of the fuzzy controller and D_i is the center of max-min method compositions at output membership function. The fuzzy logic controller calculates the variable step sizes to a decrement or increments the duty cycle, hence time is taken to track the MPP is short and the Performance of the system is better than the other MPPT techniques in the meanwhile of steady-state conditions.

Table 2. Fuzzification rules of the fuzzy controller

	Input1(ΔP)	Input2(ΔI_p)	Output (ΔD)
If ΔP_P >0 and If ΔI_P >0	PB	PB	PB
	PB	PS	PB
	PB	NB	NB
	PB	NS	NB
	PS	PB	PS
	PS	PS	PS
	PS	NB	NS
	PS	NS	NS
If ΔP_P <0 and If ΔP_P >0	NB	PB	NB
	NB	PS	NB
	NB	NB	PB
	NB	NS	PB
	PS	PB	NS
	PS	PS	NS
	PS	NB	PS
	PS	NS	PS

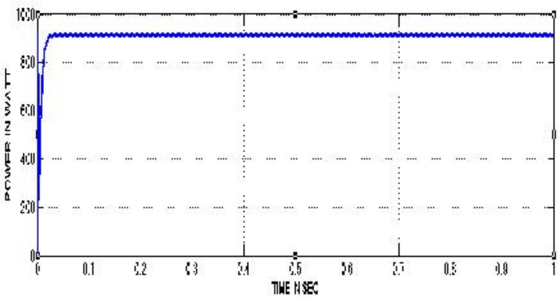

Fig 7: Simulation results of PV array power with Fuzzy based MPPT controller

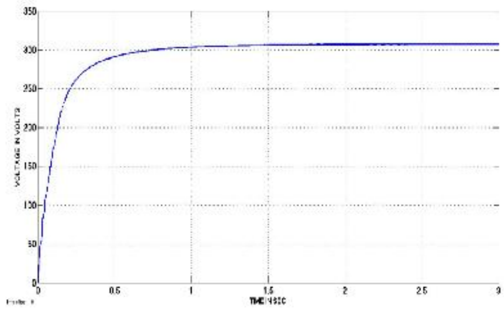

Fig 8: Simulation results of the boost converter output voltage

From the simulation results of PV array, it is observed that the PV array operated at the maximum power of 930W using fuzzy-based MPPT controller. The simulation results boost converter is shown in Fig 8. It is observed that the voltage obtained from the PV array is boosted to the 330V dc to meet the load requirements.

III. CONVENTIONAL CONTROL SCHEME

The conventional controller applied to the bi-directional AC/DC converter has two loops inner current loop and outer voltage loop as shown in Fig 9. A dc voltage reference of 300V is taken as reference signal Vdc and the DC link voltage Vdc measured across the DC link capacitor is taken to compare with the DC reference signal to generate voltage error.

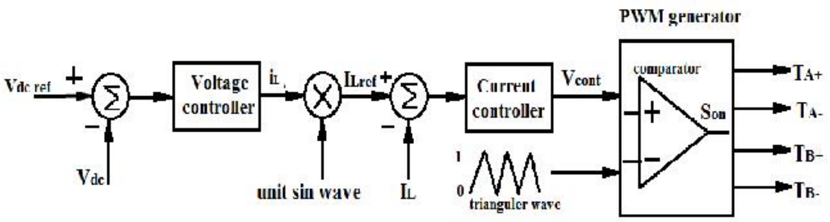

Fig. 9: Conventional control scheme for single-phase bidirectional AC/DC converter

A voltage controller is used to convert voltage error to the current command. The current command obtained from the voltage controller is multiplied with a unit sine wave obtained from PLL which gives AC reference current signal. This reference signal is compared with the AC line current (I_L), the generated current error is given to PI controller called current controller. The output of the current controller is the control voltage which is compared to the triangular waveform to generate the pulses for the gate terminals of the inverter switches. To achieve the voltage regulation at DC side and power factor correction at AC side a PI controller is taken as a voltage controller and current controller.

IV. PROPOSED FEED-FORWARD CONTROL SCHEME

The conventional controller has the drawback of higher harmonic distortion and it is unable to maintain good AC current shaping, hence it has low efficiency. A feed-forward control scheme is implemented to reduce the total harmonic distortion in AC line current and to maintain DC voltage regulation.

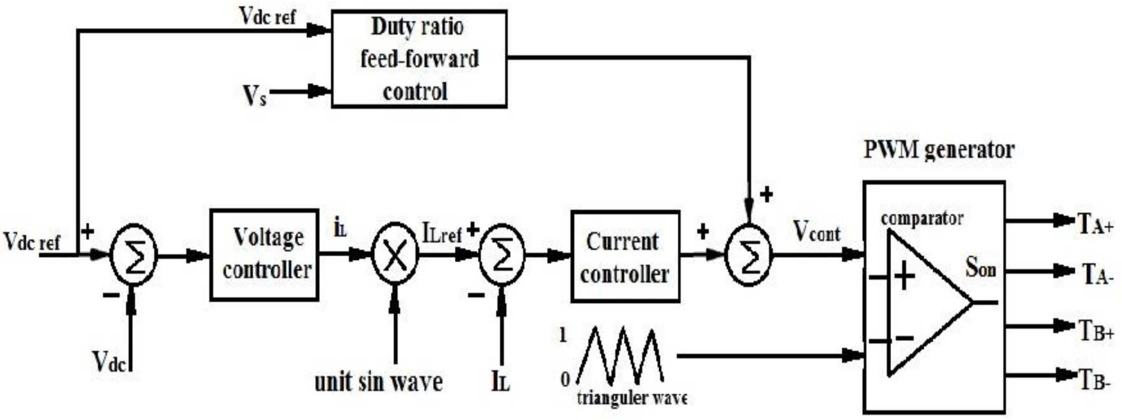

Fig 10: Conventional control scheme for single-phase bidirectional AC/DC converter

OPERATION OF THE PROPOSED FEED-FORWARD CONTROL SCHEME

In the proposed feed-forward controller a duty ratio control is added to the control voltage as shown in the below Fig 10. The duty ratio D_{on} can be defined as

$$D_{on} = \frac{T_{on}}{T} \tag{6}$$

Where the T_{on} is the time duration of the switch when it is turned on, S_{on}=1 and

T is the total time period of the carrier wave.

When the converter is operated in rectifier mode, while the AC grid voltage source is operating in the positive half cycle ($V_S > 0$), switches T_{B+} and T_{A-} are conducted, the inductor current is increased in this condition

The voltage can be obtained by using the Kirchhoff's law

$$V_S - L\frac{d}{dt}I_L = 0 \tag{7}$$

In this state, the inductor is in discharging state. The relationship between the voltages is derived using Kirchhoff's law

$$V_S - L\frac{d}{dt}I_L - V_{dc} = 0 \tag{8}$$

The voltage across the inductor is V_S-V_{dc}. The state-space equation for the controller can be written as

$$V_S - (1 - D_{on})V_{dc} = 0 \tag{9}$$

The DC link voltage and the DC reference voltages are equal ($V_{dc} = V_{dc}^*$) in the steady state operation of the converter. The above equation (9) can also written as

$$D_{on} = \left(1 - \frac{V_S}{V_{dc}^*}\right) \tag{10}$$

While the AC grid voltage source is operating in the negative half cycle ($V_S<0$), switches T_{A+} and T_{B-} are turn on, during this period the relationship between voltages can be derived as

$$V_S - L\frac{d}{dt}I_L = 0 \tag{11}$$

In this condition the current in through the inductor is decreasing, V_S is the voltage across the inductor. In this state, the inductor is in discharging state. The relationship between voltages is derived as

$$V_S - L\frac{d}{dt}I_L + Vdc = 0 \tag{12}$$

The voltage across the inductor is V_S+V_{dc} means the inductor is in charging state. The corresponding duty ratio can be derived as

$$V_S + D_{on}V_{dc} = 0 \tag{13}$$

The DC link voltage is equal to the DC reference command $V_{dc} = V^*_{dc}$ while the converter is operated in steady state, the duty ratio can also be written as

$$D_{on} = -\frac{V_S}{V_{dc}^*} \tag{14}$$

From the properties of the pulse width modulation, the duty ratio can be defined as the ratio of the control signal (v_{cont}) to peak value of the triangular waveform (V_{tri})

$$D_{on} = \frac{v_{cont}}{V_{tri}} \tag{16}$$

It is defined as the duty ratios for both the positive half cycle ($V_S > 0$) and negative half cycles ($V_S < 0$) are

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$$V_{cont} = \begin{cases} \left(1 - \dfrac{V_S}{V_{dc}^*}\right) V_{tri} \text{ ------ } if\ (V_S > 0) \\ \\ -\dfrac{V_S}{V_{dc}^*} V_{tri} \text{ -------- } if\ (V_S < 0) \end{cases} \quad (17)$$

While the converter is operated in the inverter mode, the control signal is calculated in the same manner as in the rectifier mode. Finally, we observe that the control voltage calculated in inverter mode is same as in the rectifier mode as derived in the equation (17). The control signal (v_{cont}) is directly proportional to the duty ratio D_{on}, the control signal (V_{cont}) calculated in the equation 5.12. as the feed-forward duty ratio control signal (V_{ff}) to add to the feed back control signal V_{fb} in the conventional control.

V. SIMULATION RESULTS

To verify the validity of the feedforward control Matlab software is used. The system parameters are given in table 4.

Sinusoidal grid voltage:

The simulation results when converter is operating in inverter mode, grid voltage, line current, feedback signal and feed forward signals are shown in Fig 11(a)- (b) respectively using conventional control. Similarly the simulations results using feedforward control are shown in Fig 12(a)-(d). While the converter operating in rectifier mode using conventional control and feedforward control scheme are shown in Fig 13 and Fig 14 respectively.

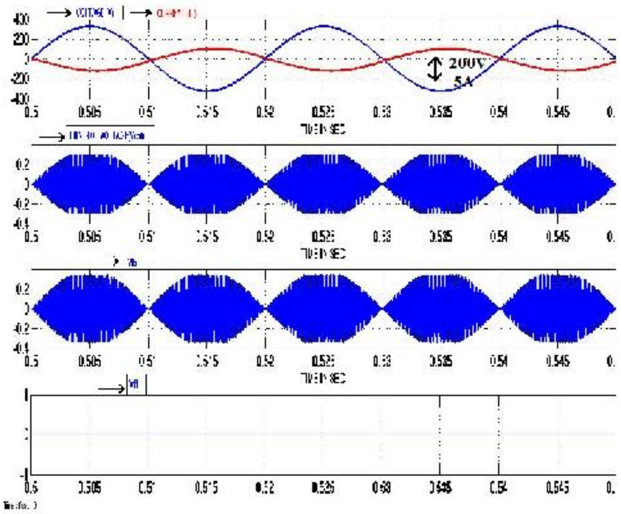

Fig 11: Simulation results with pure sinusoidal grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in inverter mode using conventional control

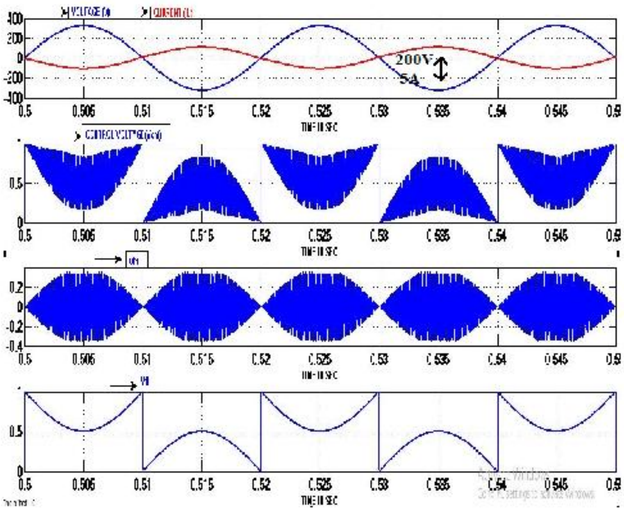

Fig 12: Simulation results with pure sinusoidal AC grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in inverter mode using feedforward control

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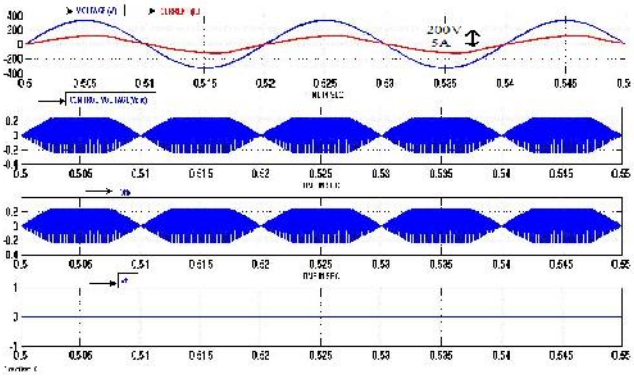

Fig 13: Simulation results with pure sinusoidal grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in rectifier mode using conventional control

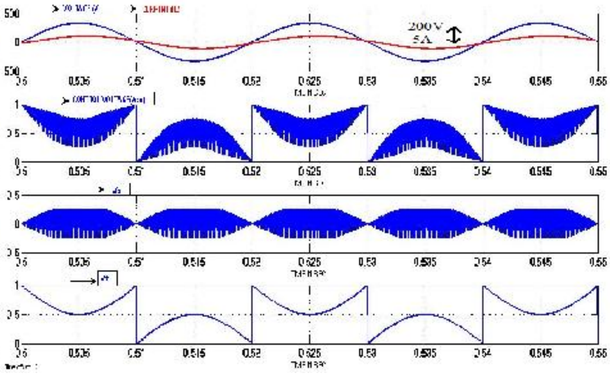

Fig 14: Simulation results with pure sinusoidal grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in rectifier mode using feedforward control

Distorted sinusoidal grid voltage:

THD		= 5.00%	
0 Hz	(DC):	0.00%	0.0°
50 Hz	(Fnd):	100.00%	0.0°
100 Hz	(h2):	0.01%	-55.0°
150 Hz	(h3):	3.32%	42.2°
200 Hz	(h4):	0.09%	105.8°
250 Hz	(h5):	1.62%	175.1°
300 Hz	(h6):	0.00%	-7.6°
350 Hz	(h7):	0.58%	-20.2°
400 Hz	(h8):	0.00%	61.6°
450 Hz	(h9):	0.30%	46.9°
500 Hz	(h10):	0.00%	0.0°
550 Hz	(h11):	0.61%	170.7°
600 Hz	(h12):	0.00%	0.0°
650 Hz	(h13):	0.11%	258.9°
700 Hz	(h14):	0.00%	252.0°
750 Hz	(h15):	3.25%	29.1°
800 Hz	(h16):	0.00%	25.5°
850 Hz	(h17):	0.14%	121.8°
900 Hz	(h18):	0.00%	0.0°
950 Hz	(h19):	0.00%	0.0°

Fig 15: Harmonic components considered in AC grid voltage measured in matlab

Consider the AC grid voltage as distorted sinusoidal voltage with the total harmonic distortion of 5%. The harmonic components of AC grid voltage are considered are listed in above Fig 15. The simulation results when converter is operating in inverter mode, grid voltage, line current, feedback signal and feed forward signals are shown in Fig 16(a)- (b) respectively using conventional control. Similarly the simulations results using feedforward control are shown in Fig 17(a)-(d). While the converter operating in rectifier mode using conventional control and feedforward control scheme are shown in Fig 18 and Fig 19 respectively.

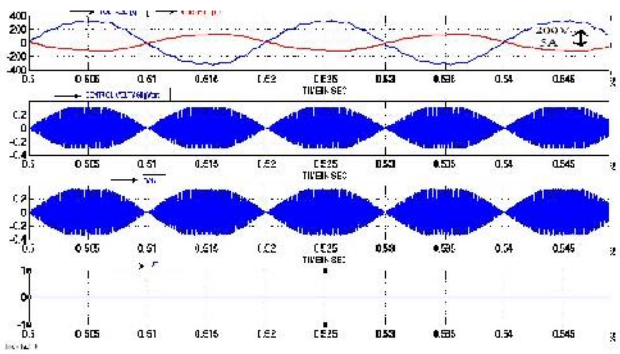

Fig 16: Simulation results with distorted AC grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in inverter mode using conventional control

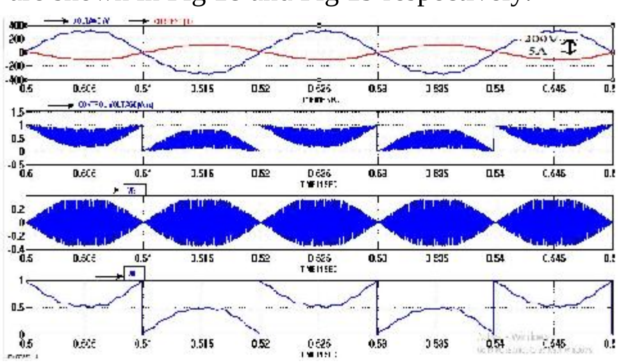

Fig 17: Simulation results with distorted AC grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in inverter mode using feedforward control

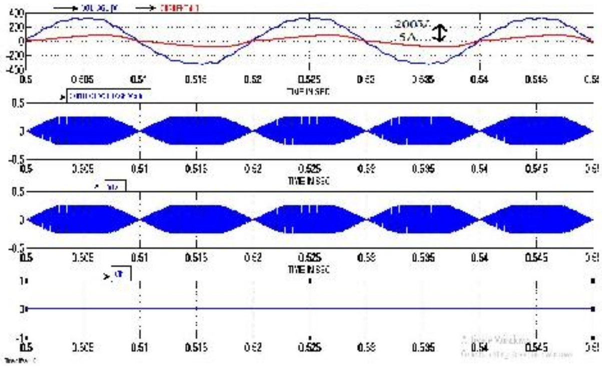

Fig 18: Simulation results with distorted AC grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in rectifier mode using conventional control

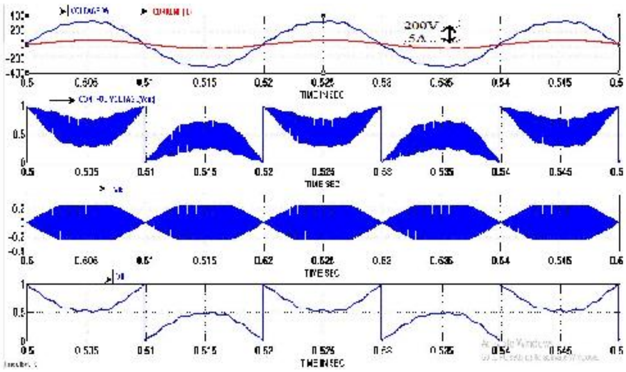

Fig 19: Simulation results with distorted AC grid voltage: Grid voltage and line current, control signal, feedback signal and feedforward signal when converter operated in inverter mode using feedforward control

VI. CONCLUSION

Table 3. Comparison of conventional and feed-forward control schemes with pure sinusoidal AC grid voltage

INVERTER MODE	CONVENTIONAL CONTROLLER	LINE CURRENT	%THD=4.81%
		LOAD CURRENT	%THD=0.45%
	FEED-FORWARD CONTROLLER	LINE CURRENT	%THD=2.41%
		LOAD CURRENT	%THD=0.40%
RECTIFIER MODE	CONVENTIONAL CONTROLLER	LINE CURRENT	%THD=4.8%
		LOAD CURRENT	%THD=2.17%
	FEED-FORWARD CONTROLLER	LINE CURRENT	%THD=2.16%
		LOAD CURRENT	%THD=1.32%

Table 4. Comparison of conventional and feed-forward control schemes with distorted AC grid voltage

INVERTER MODE	CONVENTIONAL CONTROLLER	LINE CURRENT	%THD=6.96%
		LOAD CURRENT	%THD=5.32%
	FEED-FORWARD CONTROLLER	LINE CURRENT	%THD=5.55%
		LOAD CURRENT	%THD=5.23%
RECTIFIER MODE	CONVENTIONAL CONTROLLER	LINE CURRENT	%THD=17.29%
		LOAD CURRENT	%THD=11.29%
	FEED-FORWARD CONTROLLER	LINE CURRENT	%THD=5.25%
		LOAD CURRENT	%THD=4.97%

A fuzzy-based MPPT algorithm is implemented for the boost converter to force the PV array to operate at the maximum power point with a simple approach. The fuzzifying rules are written based on the hill climbing search method to reduce the drawbacks of conventional hill climbing MPPT approach. The proposed fuzzy-based MPPT control approach gives fast converging and fewer oscillations around maximum power point during the steady-state conditions. The total harmonic distortion in AC line current and load current connected at PCC are measured for both inverter and rectifier modes using conventional and feedforward control schemes. From the tables 5 and 6 it is concluded that the feed forward control has the better performance than the conventional control and provides low harmonic distortion. Both AC current shaping and DC voltage regulation are achieved in inverter and rectifier modes. Another advantage is that the larger fundamental output voltage availability in inverter mode than the UPWM, BPWM.

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