PERFORMANCE ANALYSIS OF THREE PHASE PWM RECTIFIER USING FUZZY AND PI HYSTERESIS CURRENT CONTROLLER

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Abstract-*The research work presents hysteresis current controlled 3-phase PWM converter. The switching control is applied on three-phase bi-directional switches, to attain sinusoidal input current at unity pf. such a rectifier can also operate as unity p.f. converter which is presented in this paper. The rectifier input current controller can be operated with either fixed frequency or variable frequency both with their merits and demerits. The current study includes the current controller and voltage controller implementation with: (i) conventional hysteresis current control (random frequency) (ii) fuzzy controller and PI controller. The various design problems and the performance of the current modulation strategies are investigated & then compared. Rectifier performance parameters, that is, THD and PF are computed.The dc-link voltage is controlled by outer loop fuzzy controller and PI controller. The converter can be used for bi-directional power flow. The bi-directional switches operate at low frequency, crossover zero voltage (at turn-on) and conduct for 1/12th of line voltage cycle. The THD analysis of the controlled input phase current shows significant reduction in the THD as compared to the uncontrolled input phase current in Fuzzy HCC and PI HCC. The dc-link voltage follows the reference value.*

Keywords: *Hysteresis current controller, 3-phase pulse width modulation Voltage source rectifier, Fuzzy Controller, PI Controller, Park's transformation, three IGBT based switch*

1 Introduction

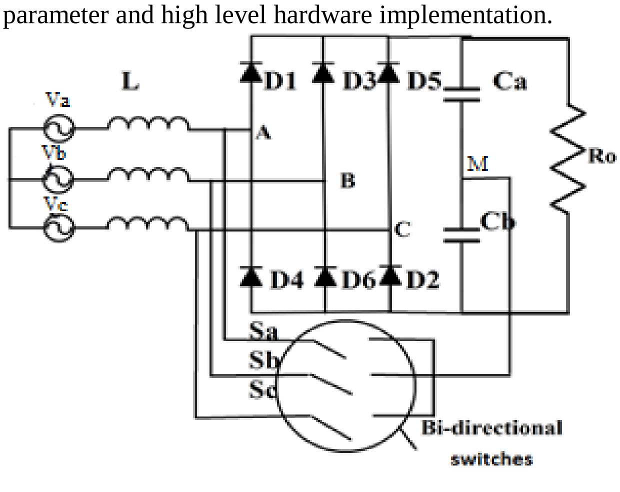
With the advancements in power electronic converter Technology, various kinds of inverters based on Pulse with Modulation (PWM) have been developed. Most of rectifier devices usually use non-controlled or semi controlled rectification technology [1], [2], [3], [9].

The PWM-converters ensures:

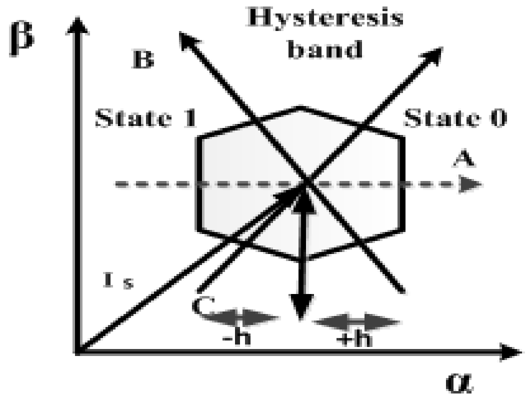
- A sinusoidal current waveform;
- Control the network power factor;

The technical control of 3-phase PWM rectifier is done to reduce current harmonic and improve the pf. in the power grid, by Voltage Orientation Control (VOC) which is based on the voltage estimate. The active power exchange must not be unstable by ensuring a DC voltage is equivalent to its reference voltage so that the PWM rectifier can operate with a better efficiency. This can be done by using a control system which is able to regulate the DC voltage. In this paper, the technique used to control the DC-voltage is fuzzy logic controller and PI controller. In this firstly, the whole system is modeled and then a simulation is performed in Matlab. The comparative study highlights that, the performance using the fuzzy logic controller is somewhat better than that obtained without controller and PI controller. The DC voltage response shows disturbances are rejected in the load with good dynamics. Moreover, the output voltage has less harmonic content reducing the overall THD ratio.

The control devices are used here to attain unity power factor and reduce the system harmonics [4]. There are three control technique: (i) linear proportional – integral controller. (ii) Predictive controller. (iii) Hysteresis current controller. The PI controllers can decrease and put the switching frequency of converter in limit and produce well defined harmonic content. Predictive controller has the most complex method & needs the information of load parameter and high level hardware implementation.



(a)



(b)

Fig. 1. (a) Block diagram (b) switching trajectory.

Hysteresis current controllers have non-complex implementation, very good stability, no presence of tracking error, rapid transient response and intrinsic robustness to load parameter.

In power electronic system particularly diode and SCR based rectifiers are used in the beginning of dc-link power converter or rectifier as a in between interface with the ac line power [10]. The rectifier behave as a nonlinear load on the power system which distort the current having lots of harmonics in it ,which are rich in harmonics and low input power factor & large quantities of harmonics in supply current produces various unwanted effects like line voltage harmonic distortion, overheating of equipment ,bad functioning and may system got damaged .

Power pollution, occurring because of the usage of power converters like harmonic distortion of the line voltage, consequences of which are serious power quality problems in transmission & distribution systems. The figure shows a three-phase diode based bridge rectifier in where below bi-directional switches are connected and operated by getting switching signal from hysteresis band by this technique. A system improves their power factor to unity and current harmonics is reduced.

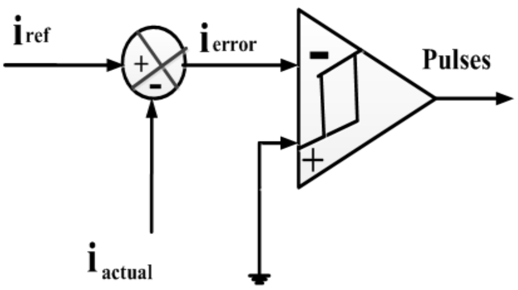


Fig. 2. Hysteresis Current Controller.

S. Kim and P. Enjeti gave a way which improves the p.f. of a 3-phase diode based bridge converter by the three IGBT based Bi-directional switches. Two-level hysteresis controller block diagram and switching trajectory are shown in fig.1.

These switches operated at low frequency and all bi-directional switches are turned ON when the respective voltages cross over zero voltage and conduct for $1/_{12}\ th$ of line Voltage cycle. Low cost, simplicity, and high power applications are main circuit features. The converter needs a connection with the ac system through the neutral wire and because of that connection a pulsed current is developed there on the neutral. Hysteresis current controller is shown in fig.2. It can also be noted that in the circuit there is an increment high voltage pressure on the switches during commutation of switches, because of the energy stored in the inductor [5].

2 Synchronous reference frame based hysteresis current controller

The front end of the rectifier's based circuit arrangement shown in fig. 1.It is made up of a combination of full bridge 3-phase diode based rectifier with 2 identical series connected capacitor used for filterring the rectifier output voltage& three bi-directional switches $S_a, S_b, \&S_c$ which are made up of the combination of two anti parallel connected IGBT.

These 3 bi-directional switches $S_a, S_b, \&S_c$ are used to conform current shape which is coming from the supply, output dc-link voltage regulation & two capacitors are used for voltage votage balancing. Now moving on the topology which is shown in fig.1 can be formulated as below:

$$L\frac{di_a}{dt} = V_a - (V_{am} + V_{mo}) \quad (1)$$

$$L\frac{di_b}{dt} = V_b - (V_{bm} + V_{mo}) \quad (2)$$

$$L\frac{di_c}{dt} = V_c - (V_{cm} + V_{mo}) \quad (3)$$

Where V_{mo} is voltage of point M with respect to O (neutral point) $V_{am}, V_{bm} \& V_{cm}$ are voltages of point A, B, and C refers to the point M.

The expression for the node voltages are:

$$V_{am} = sign(I_a)(1 - S_a)\frac{V_{dc}}{2} \quad (4)$$

$$V_{bm} = sign(I_b)(1 - S_b)\frac{V_{dc}}{2} \quad (5)$$

$$V_{cm} = sign(I_c)(1 - S_c)\frac{V_{dc}}{2} \quad (6)$$

Now sign (I_a), sign (I_b) & sign (I_c) are depended by the polarity of inductor current.

Such that;

$$Sign.(I_a) = \begin{cases} 1, if\ i_a \geq 0 \\ -1\ if\ i_a, < 0 \end{cases} \quad (7)$$

switches S_a, S_b, and S_c denotethe state of switching of all 3 bi-directional switches S_a, S_b, and S_c recspectively.

For example if sign (I_a) is 1 it means that if (I_a) current error vector is greater than or equal to 0. If it shows -1

then the current error vector is less than zero.

Now, for a balanced 3-phase supply system the voltage from switches to node M (V_{mo}) written as

$$V_{mo} = \frac{V_{am}+V_{bm}+V_{cm}}{3} \quad (8)$$

The injected current(i_m) can be written as;

$$i_m = i_a s_a + i_b s_b + i_c s_c \quad (9)$$

Here (i_m) is the total sum of the current which is because of three phase bi-directional switches.

3 Proposed controller

Fig. 3 shows the control strategy for the front-end converter. The currents I_a^*, I_b^* and I_c^* are reference input current to the hysteresis current controller. The angular position of the I/P voltage is defined by PLL circuit which is depicted from fig. 3. Phase lock loop (PLL) is used here to provide angular position to dqo to abc frame by this dc voltage is converted to reference value. The converter's reference current is in three phase co-ordinate are obtained by the dqo to abc park's transformation.

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \quad (10)$$

Current converter I_d & I_q are active & reactive part of the rectifier park's transformation current. The purpose of using parks transformation is to convert dqo rotating frame to three phases abc with the help of (wt) angular position which is given by PLL and PLL takes input as a three phase voltage.

The phase locked loop circuit is provides (wt) which is increasing function of time whose derivative is fixed underneath a given AC I/P voltage. The angle is not sensitive for voltage harmonics & unbalanced voltage source of this transformation.

The dc voltage is also controlled at a fixed level by converter and is attained by action for parks transformation active current (I_d) and the parks reactive current (I_q) should have null or zero value so that an almost unity power factor is attained. It will happen by a non-existent connection b/w AC I/P, the zero series and neutral end of parks transformation always has null value. In this hysteresis current controller model, legible losses are produced in AC I/P source inductance in rectifier based circuit. In a three phase high power factor hysteresis current controller pwm converter [6], [8], [15]. The controller is used here is hysteresis current controller through which a switching signal is generated. Switching signal is given to three phase bi-directional switches to attain unity power factor and to reduce harmonics distortion and THD.

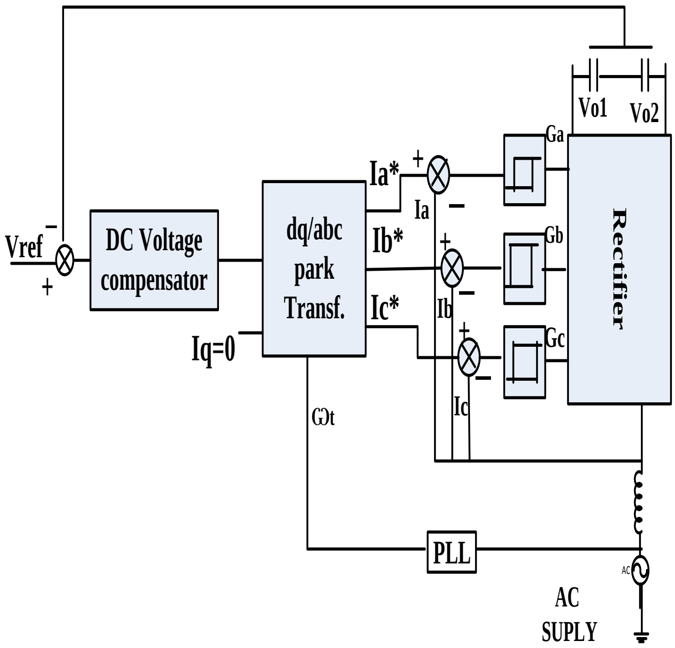


Fig. 3. Converter Model Circuit.

A proposed block diagram representation of front end converter control circuit is shown in fig. 3. It shows the conversion and control scheme for the front end converter. The dc link rectifier output voltage tracks the reference input voltage and it is also constant. It has two feedback loops one is inner control loop is feed forward current loop and second is outer dc voltage loop and ensure that dc-link voltages are fixed at a value and it tracks the reference.

Second inner control loop feeds forward current loop. The supply current is regulated and accomplish by the harness of conventional HCC [12]. It is used in park's transformation abc to dq0 & is expressed for the reference current parameter wt, which is obtained by the PLL circuit which occupies the 3-phase sinusoidal reference currents [13]. The voltage balance is also ensured to be controlled by the voltage of the dc-link midpoint M which is connected by two capacitor c1 and c2 in series.

3.1 Current control

Feedback current is controlled by the method of hysteresis modulation whereas the reference current is tracked by the motor current in a hysteresis band. The conduction period which is generated by hysteresis current controller is to provide switches. The hysteresis control of independent controllers with supply current the switching signal SX(x=123) of the bi directional switches are.

$$\mathrm{Sx} = \begin{cases} 1, & (i_x < i_x^* - h) \text{ and } (i_x > 0) \\ \text{or} & (i_x > i_x^* + h) \text{ and } (i_x < 0) \\ 0, & \text{if } (i_x > i_x^* + h) \text{ and } (i_x > 0) \\ \text{or} & (i_x < (i_x^* - h) \text{ and } (i_x < 0) \end{cases} \quad (11)$$

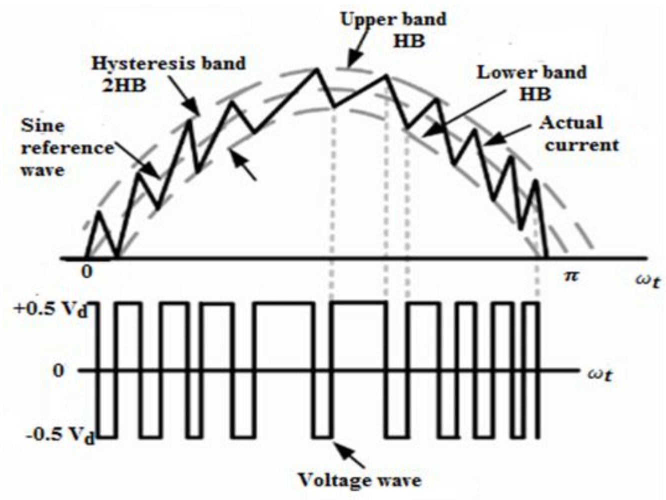


Fig. 4. Switching pattern in HCC.

The switching pattern is generated according fig.4. The voltage is computed from the current signs & switching state of all phases.

3.2 DC voltage control

At any moment summing the rate of change of energy storage the output power is the rectifier input power. Analysis of the system characteristics are done by the mathematical modeling. Taking some condition before approaching mathematical analysis in AC I/P inductance and in the rectifier negligible losses are anticipated.

The power balance equation of controller for synchronous frame based is given.

$$\frac{d}{dt}\left(\frac{1}{2}c_{eq}v_{dc}^{2}\right)+V_{dc}I_{dc}=\sqrt{3}V_pI_d\cos\alpha \;-\; \frac{d}{dt}\left(\frac{1}{2}L_sI_d^{2}\right) \quad (12)$$

Where $c_{eq} = \frac{c}{2}$ (half of the capacitor c_a or c_b which are connected in series)

V_p = Vrms of the supply voltage

Now, solving equation (6) linearization of the above equation of the steady state operating end ($I_{dc}V_{dc}$) is done:

$$C_{eq}V_{dc}s\,\bar{V}_{dc}(s) - I_{dc}\bar{V}_{dc}(s) = (\sqrt{3}\cos\alpha\, V_pI_d(s) - L_sI_ds\, i_d(s) - V_{dc}I_{dc}(s) \quad (13)$$

$$(C_{eq}V_{dc}s - I_{dc})\bar{V}_{dc}(s) = (\sqrt{3}\cos\alpha\, V_p - L_sI_ds)I_d(s) - V_{dc}I_{dc}(s) \quad (14)$$

Now putting Cosα = 1, so the equation transforms as under:

$$(C_{eq}V_{dc}s - I_{dc})\bar{V}_{dc}(s) = (\sqrt{3}V_p - L_sI_ds)I_d(s) - V_{dc}I_{dc}(s) \quad (15)$$

Now solving equation (3.6.4)the steady state working current I_{dc} is computed as under:

$$\sqrt{3}V_pI_d = V_{dc}I_{dc} \quad (16)$$

Two voltage loops are delinked; the outer voltage loop is much slower than the response time in inner current control (ICC) technique [7]. It is assumed that input current command is completely following its output current controller then ICC block IS eliminated and is shown in control block outer voltage control loop.

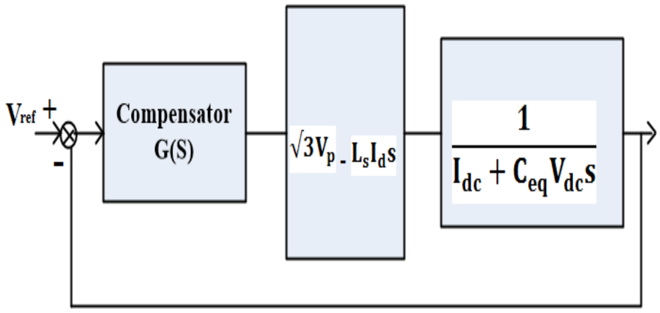


Fig. 5. Simple Voltage Control Scheme.

The dc link output voltage response is improved by using here the current feed-forward control loop for the load disturbance shown in fig.5. By equation (9) it can be see that the system is unbalanced because of the one right half plane zeros present in on system. The open loop T.F. in voltage control loop is given under.

$$L(s) = G_c(s)\frac{L_sI_d}{c_{eq}v_{dc}}\left[\frac{\left(\frac{\sqrt{3v_p}}{L_sI_d}\right)-s}{s+\left(\frac{I_{dc}}{c_{eq}V_{dc}}\right)}\right] \quad (17)$$

On the control system bandwidth, a right hand plane (RHP) zeros imposes fundamental limitations, for stable operation it forces to reach upper limit to the accessible gain cross over frequency. From [11] it can be shown that the systems with one right hand half plane zero at z, shows the max gain cross over frequency which can be achieved of the open loop compensated control system limits and has the value as:

$$\omega_{gc} = tan\left(\frac{\pi}{2} - \frac{\alpha_m}{2} + n_{gc}\frac{\pi}{4}\right) \quad (18)$$

Where α_m is the phase margin of the compensated control system in radians also n_{gc}, the slope on the Bode plot of compensated min phase part of control to O/P of the transfer function at w_{gc} system.

3.3 Balancing dc link capacitor voltage

The dc-link capacitor voltage causes some error in the voltages V_{01} and V_{02} of capacitors c_a and c_b are these voltages have some variation or error which disturb the systems ideal condition. To overcome the voltages of the dc-link capacitor should be balanced.

On the capacitor the V_{01} and V_{02} asymmetry will enhanced stress of voltage and increased the blocking devices. The dc capacitor voltage differences V_m are written:

$$V_m = \frac{1}{2}(V_{01} - V_{02}) = \frac{1}{2c}\int_{t1}^{t2} i_m \, dt \quad (19)$$

Where V_{01} and V_{02} are the voltages across capacitance c_a and c_b respectively, The 3 independent hcc i_m it is total summing current from bi-directional switches is:

$$i_m = i_a s_a + i_b s_b + i_c s_c \quad (20)$$

i_m is not null and it can be see that from equation (20).

3.4 PI-controller

The DC-bus capacitor voltage is sensed and compared with a reference voltage and also calculating the error signal. The error signal $e = V_{dc,ref} - V_{dc}$ at the n^{th} sampling instant is used as input for PI-controller. The error signal passes through first order Butterworth design based Low Pass Filter (LPF) that suppresses higher frequency components and allows fundamental components only. The proportional and integral gains are estimates the magnitude of peak reference current *I*max and control the dc-bus capacitor voltage of the inverter. Its transfer function is

$$H(s) = K_p + \frac{K_i}{s} \quad (21)$$

Where, [$K_p = 0.4$] is the proportional constant that determines the dynamic response of the DC-bus voltage control and [$K_i = 15$] is the integration constant that determines the settling time. This PIcontroller is eliminating the steady state error in the DC-bus voltage of the cascaded multilevel voltage source inverter.

3.5 Fuzzy controller

A fuzzy controller is used for the good performance of the control voltage, particularly in the case of change of DC voltage reference level .The new control structure of the DC voltage ensures the same model adopted when the PI controller was used. These parameters are adjusted in real time according to the disturbance on the system. The fuzzy controller developed in this section is given by Fig .6 which the internal structure of the controller, both input values normalized using the normalization gains.

The error and variation are defined by:

$$\in (k) = V_{dref}(k) - V_{dc}(k) \quad (22)$$

$$\Delta\in (k) = \in (k) - \in (k-1) \quad (23)$$

The output of the fuzzy controller is the change reference current amplitude Δi_dref. the new amplitude adjusted at each sampling moment is defined. The main role of this action is proportional to ensure stability in permanent regime and eliminate the static error in the steady state. The main features of the developed controller are:

- Seven fuzzy set for each input output
- The function of appurtenance is triangular for simplicity
- Inference Min-Max E. Mamdani is used
- The defuzzification process is done by centre of gravity

FLC is comprises four steps.

Step-1: The fuzzification is performed which is the process that converts input data into suitable linguistic values by using suitable fuzzy sets.

Step-2: The knowledge base created which consists of a data base with the necessary linguistic definitions and control rule set.

Step-3: Inference engine simulates the human decision process. Firstly each rule’s conclusion is obtained, by substituting fuzzified input variables into rule base. These rules are aggregated into single fuzzy set by using fuzzy aggregation operators. Maximum, Sum and Probabilistic Sum are some of the commonly used operators. In this paper, Sum operator is used.

Step-4: Output of Step 3 is a single fuzzy set. But we want the output to be a numerical value. So we need to transform fuzzy set into single numerical value. This process is called defuzzification.

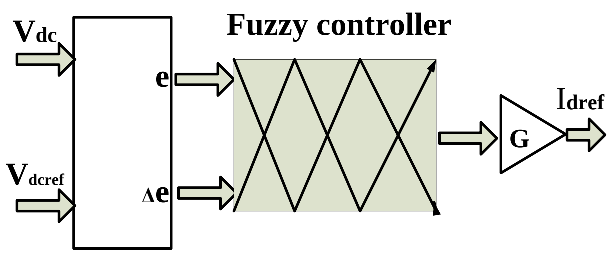


Fig. 6. Fuzzy logic controller.

The membership functions representing the input and the output variables are given by Fig 7, Fig.8 and Fig.9.

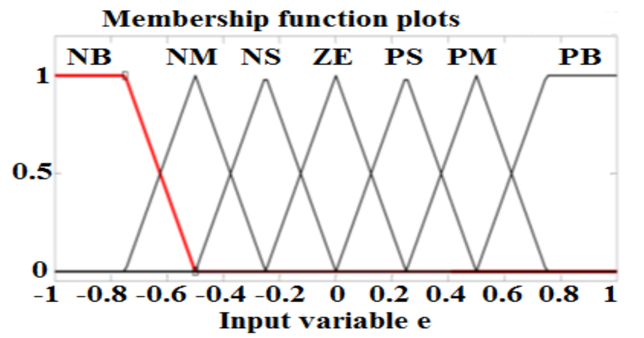


Fig. 7. Input membership function for error e.

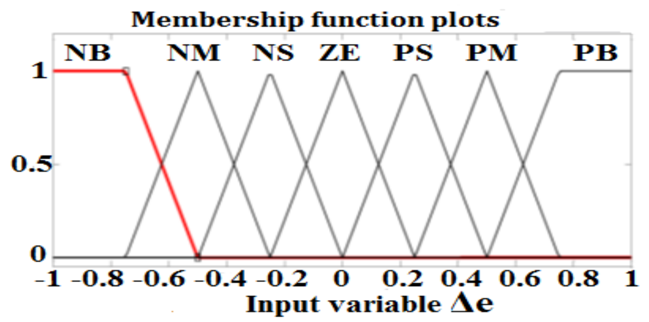


Fig. 8. Input membership function for error Δe.

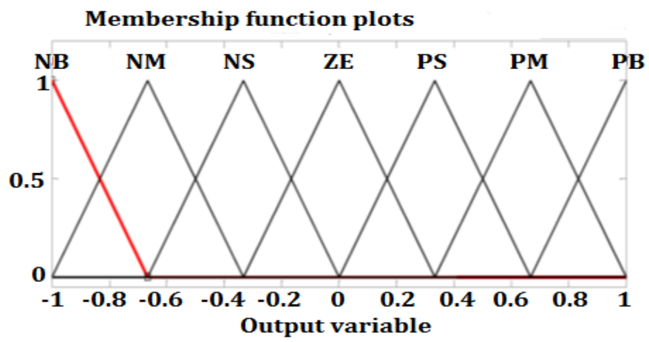


Fig. 9. Output membership function.

Firstly, for the fuzzy controller definition input and output parameters (variables) are chosen. In this paper, the 'error voltage (e)' and 'rate of change of error voltage (Δe)' are defined as input parameters and 'reference current' is the output parameter both of these are variables [14]. The three variables of the FLC, the error, change in error and the reference current, have seven triangle membership functions for each. The fuzzy variables, for which the membership functions are created, are expressed by linguistic variables.

NB: Negative Big;
NM: Negative Medium;
NS: Negative Small;
ZE: Zero;
PB: Positive Big;
PM: Positive Medium;
PS: Positive Small.

Fuzzy rules are gathered in an inference matrix shown in table.

Table 1. Fuzzy rules

	$\in = V_{dref} - V_{dc}$						
Δ∈	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

4 Specification of controller

A hysteresis current controller pulse width modulator voltage source rectifier is used in three-phase diode based rectifier which converts DC from AC power. It is used for the operating DC drive system. In this paper the load is used in rectifier DC load topology which employed here. A set of rules with design is chosen, to show the specification feasibility of the conventional rectifier, which is given below:

line to line supply volt.: 220 V; 50Hz frequency
Reference o/p volt. : 750 V
I/P inductance: 6.5 m H

DC link capacitance $C_a = C_b = 2000\ \mu F$

Load resistance is 100 ohm

Bidirectional switches working freq. 6.6 kHz.

The dc voltage Compensator $G_c(S)$is chosen by a common PI controller $(0.4 + \frac{15}{s})$, according to (12) and (13). The conventional rectifier circuit is evolved by a MATLAB/SIMULINK model. The current & I/P voltage waveform are given away in Fig. 7. The I/P p.f. has founded to be 0.999 also THD 2.67%.

In a Fuzzy controller the dc voltage Compensator $G_c(S)$ is chosen by a fuzzy controller, according to (12) and (13). The conventional rectifier circuit is evolved by a MATLAB/SIMULINK model to present a digital simulation and calibrate the foreshowed results. The current & I/P voltage waveform are given away in Fig. 7. The I/P p.f. has founded to be 0.999 also THD 1.90%.

5 Simulation result

Fig. 1 shows a 3-phase high p.f. PWM rectifier with three parallel connected IGBT based bi-direction switch HCC switches. A simulation diagram is designed to get simulation result and the parameters are used to design simulation diagram as mentioned above. Fig. 10 shows the balanced supply voltages are of three-phase PWM rectifier based circuit having 220 V_{rms} and 50 Hz frequency of each phase and three phases are $\frac{2\pi}{3}$ radian apart each other.

Fig. 11 represents the I/P current and supply voltage of 3-phase rectifier without using current controller and the I/P power factor is observed 0.707. The input current I_a is discontinuous and in each pulse it is zero for some duration.

Fig. 12 is a waveform of supply controlled input voltage and current using PI Hysteresis Current Control technique. The phase difference between voltage and current waveform is zero it represents unity power factor.

Fig. 13 is a waveform of supply controlled input voltage and current using Fuzzy Hysteresis Current Control technique. The phase difference b/w voltage and current waveform is 0 it represents unity p.f.. Fig. 14 shows dc output voltage of three-phase rectifier using PI Hysteresis Current Control. It reaches to steady state at 0.015 sec.

Fig. 15 shows dc output voltage of three-phase rectifier using Fuzzy Hysteresis Current Controller. It reaches to steady state at 0.01 sec.

Now fig. 16 input phase A current without using controller and fig. 17 represents the FFT analysis of phase A input current of 3-phase PWM rectifier without using current control technique. It shows total harmonics of I/P current is 37.78% at 50Hz and the fundamental value of current is 5.596 A at 100 ohm resistance.

Now fig. 18 and fig. 19 represents the FFT analysis of phase A input current of three-phase PWM rectifier with using PI Hysteresis Current Control technique. It represents the total harmonics of input phase A current is 2.67% at 50 Hz frequency and the fundamental value of current is 11.5 A at 100 ohm resistance.

Now fig. 20 and fig. 21 represents the FFT analysis of phase A I/P current of 3-phase PWM rectifier with using hysteresis current control technique. It represents the total harmonics of input phase A current is 1.90% at 50 Hz frequency and the fundamental value of current is 12.05 A at 100 ohm resistance.

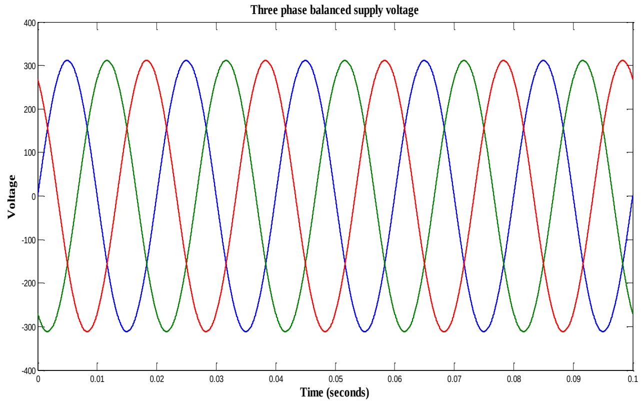


Fig. 10. Three-phase balanced supply voltage.

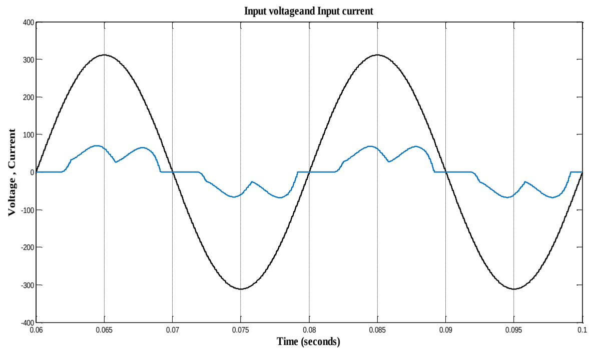


Fig. 11. Input p. f. without current controller.

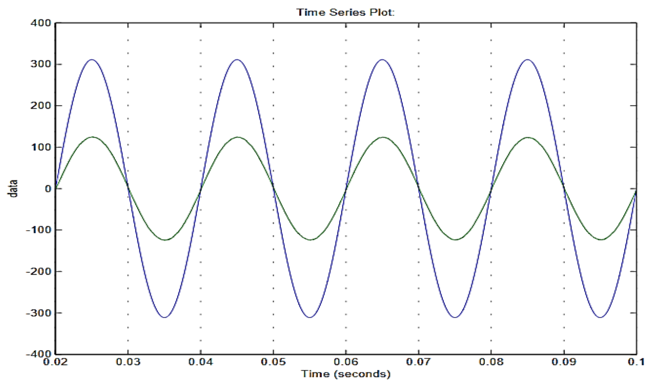


Fig. 12. Input p. f. with PI Hysteresis current control.

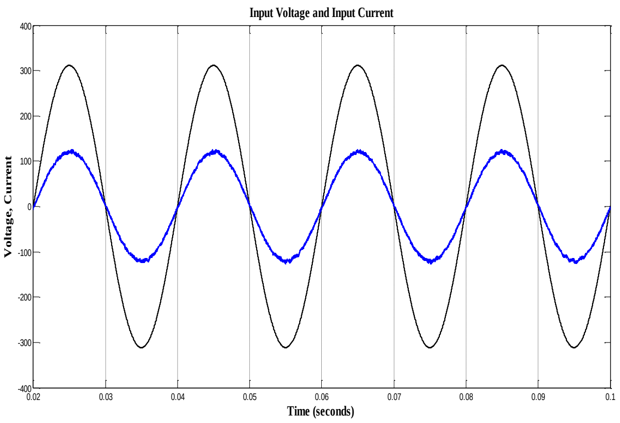


Fig. 13. Input p. f. with Fuzzy Hysteresis Current Control.

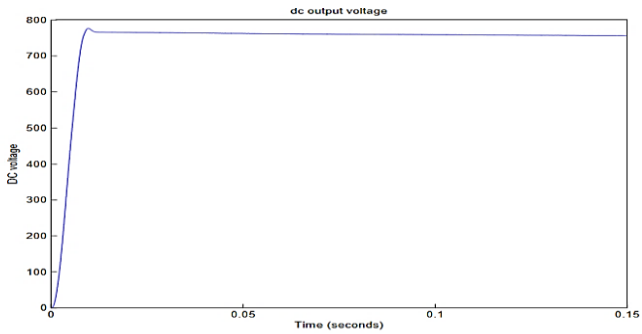


Fig. 14. dc output voltage with PI Hysteresis Current Control.

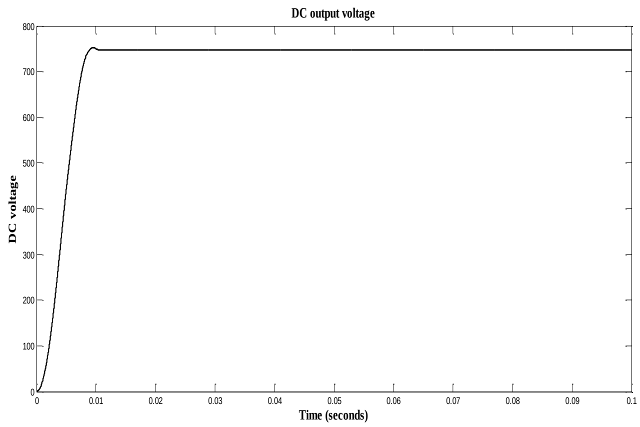


Fig. 15. dc output voltage with Fuzzy Hysteresis Current Control.

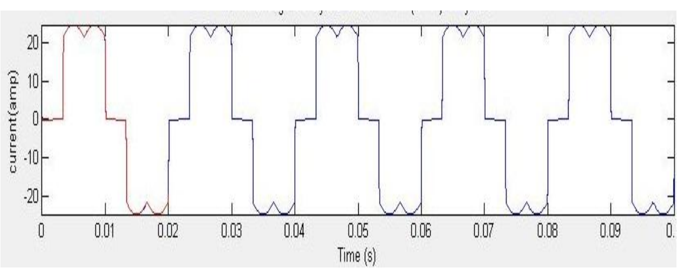


Fig. 16. Input phase A current without control.

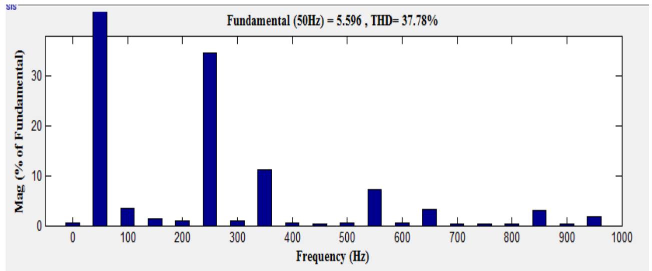


Fig. 17. THD without current control.

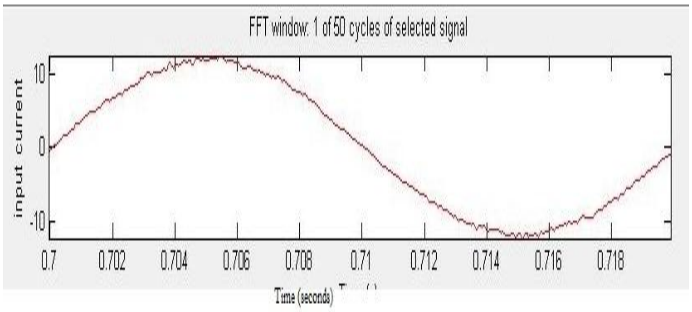


Fig. 18. Input Phase A current with PI Hysteresis Current Control.

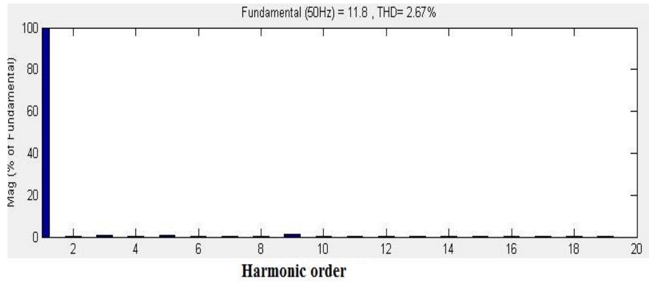


Fig. 19. THD with PI Hysteresis Current Control.

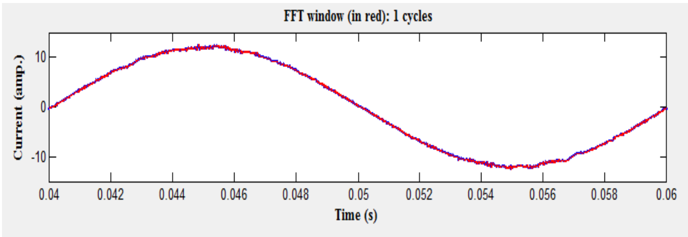


Fig. 20. Input Phase A current with Fuzzy Hysteresis Current Control.

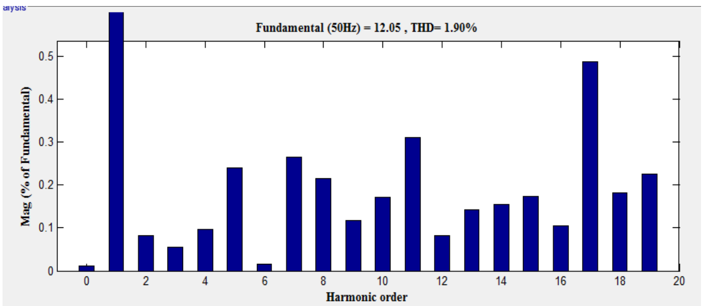


Fig. 21. THD with Fuzzy Hysteresis Current Control.

6 Conclusion

The front end of the unity-power-factor rectifier is proposed by a dc-link voltage control outer loop using PI and fuzzy controller and hysteresis current control in synchronous reference frame as an inner current control loop. The mathematical equation expressing the converter currents and voltages are expressed as like the converter input /output and converter performance is computed. It shows that it offers satisfactory performance to supply voltage regulation and the converter draws current at unity-power-factor with the proposed control strategy. It also exhibits good performance with supply voltage distortion and unbalance. The THD analysis of the controlled I/P phase current is reduced from 37.78% to 2.67% in PI controller and 1.90% in Fuzzy controller. Fuzzy Hysteresis Current Controller is better than PI Hysteresis Current Controller. The controller is expected along the proposed bi-directional switch to be a good retrofit to the converter of the existing medium from less power ac drives.

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