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Fuzzy Inference System Based Power Factor Correction of Three Phase Diode Rectifier Using Field Programable Gate Array

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ABSTRACT

This study describes a novel method in improving the input current total harmonic distortion as well as power factor of a three-phase diode rectifier circuit. In this method, three bidirectional switches comprising MOSFET and four diodes are used across the three-phase supply and load. In a three-phase rectifier only two diodes conduct at any given time. As a result, the current in the third phase is zero. But in this method, the bidirectional switch corresponding to the third phase is turned ON. The closing of bidirectional switches provides an alternate path for the input current to flow. Once the input voltage crosses zero-voltage axes, the corresponding switch will be triggered. The fuzzy logic based control method is used to generate the triggering pulse for the bidirectional switches. The conduction angle of bidirectional switch is adjusted to make the output power constant and at the rated value for converter operation above and below its rated power. The performances of DC motor drive as well as Induction motor drive are evaluated with this method. The analysis, simulation and experimental results of three phase rectifier are also presented in this study.

Keywords: Bidirectional Switch, MOSFET, Three Phase Diode Rectifier, DC Drives and AC Drives

1. INTRODUCTION

Harmonic current pollution generated by nonlinear loads is a serious problem in power systems. Numerous harmonic standards have been put forward on this issue, for example, IEEE and IEC standards (Halpin, 2005). Since three-phase diode rectifiers are widely used in industry, such as adjustable speed drives and dc power supplies (Thasananutariya and Chatratana, 2009; Chen and Luo, 2001; Grbovic *et al*., 2001), the harmonics generated by the diode rectifier in the line current is a main concern in power electronics. To eliminate the harmonic current generated by this type of harmonic source, the shunt Active Power Filter (APF) or series APF has been an effective solution (Corasaniti *et al*., 2009; Singh and Solanki, 2009; Lavopa *et al*., 2009; Rahmani *et al*., 2010; Vodyakho and Mi, 2009; Salmeron and Litran, 2010; Bhattacharya and Chakraborty, 2011). However, the rating of APF is normally small because of its partial power processing property. Hence, it generally features with low cost and small volume. Shunt APF's are usually paralleled at the ac side. Therefore, both the voltage and the current processed by APF are with alternating values.

A four-quadrant inverter is commonly used in the power stage of the ac side APF and an ac side APF always needs complicated harmonic current detection and control. On the other hand, the three-phase Power Factor Correction (PFC), which is a full power processing solution, has been extensively studied (Gensior *et al*., 2009; Bierhoff and Fuchs, 2009; Heldwein and Kolar, 2009; Carlton *et al*., 1998; Dalessandro *et al*., 2008; Chivite-Zabalza *et al*., 2009; Roux *et al*., 2009; Salmon, 1996). The most popular topology of the three-phase PFC is a six-switch bridge. This type of PFC has the feature of bidirectional power

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flowing capability. In some specific applications, unidirectional PFC topologies such as the Vienna converter (Dalessandro *et al*., 2008; Chivite-Zabalza *et al*., 2009) and the series connected dual boost converter (Salmon, 1996; Qiao and Smedley, 2002) are considered. Both bidirectional and unidirectional three-phase PFCs are required to process all the load power. Thus, most of them suffer from higher silicon cost as compared with the APF solutions which require only partial power processing. Multipulse rectifiers, which employ low frequency phase shift transformer to synthesize reasonable line current waveform, are also reported for the reduction of the silicon cost (Chivite-Zabalza *et al*., 2009; Roux *et al*., 2009). Due to the application of low frequency transformer, the volume is a critical limitation. A performance of P-I, I-P, Fuzzy and Neuro-Fuzzy Controllers (Khuntia *et al*., 2010) for Speed Control of DC Motor was compared and it is observed that fuzzy logic based controllers give better responses than the traditional P-I as well as I-P controller for the speed control of dc motor drives. The DC Link Active Power Filter (Du *et al*., 2012), composed of two series-connected bidirectional boost converters is implemented in three phase diode rectifier, intends to eliminate the input current harmonics. The control structure is complicated.

In this study, we propose a simple buck converter at the output stage of three phase diode rectifier with bi directional switches. The buck converter regulates the voltage at the output stage for speed control applications. The fuzzy logic based control method is developed to improving the conduction period of the bi directional switches. The new technique is simulated with DC drive application by PI controller as well as Fuzzy controller and the results are compared.

1.1. Analysis of Proposed Diode Rectifier with Buck Regulator

The circuit diagram of proposed diode rectifier with buck regulator is shown in **Fig. 1**. For the circuit analysis, six topological stages are presented in **Fig. 2** a to f, corresponding to the 0 to 180 half period. Two main situations can be identified:

In the stage I, III and V, there are only two conducting diodes. As a result, on a conventional three-phase rectifier, the current on the third phase remains null during that interval. In the circuit, the switch associated with the third phase is gated on during that interval. For instance, during the 0 to 30 stage, the bidirectional switch is gated on, so the input current evolves from zero to a maximum value.

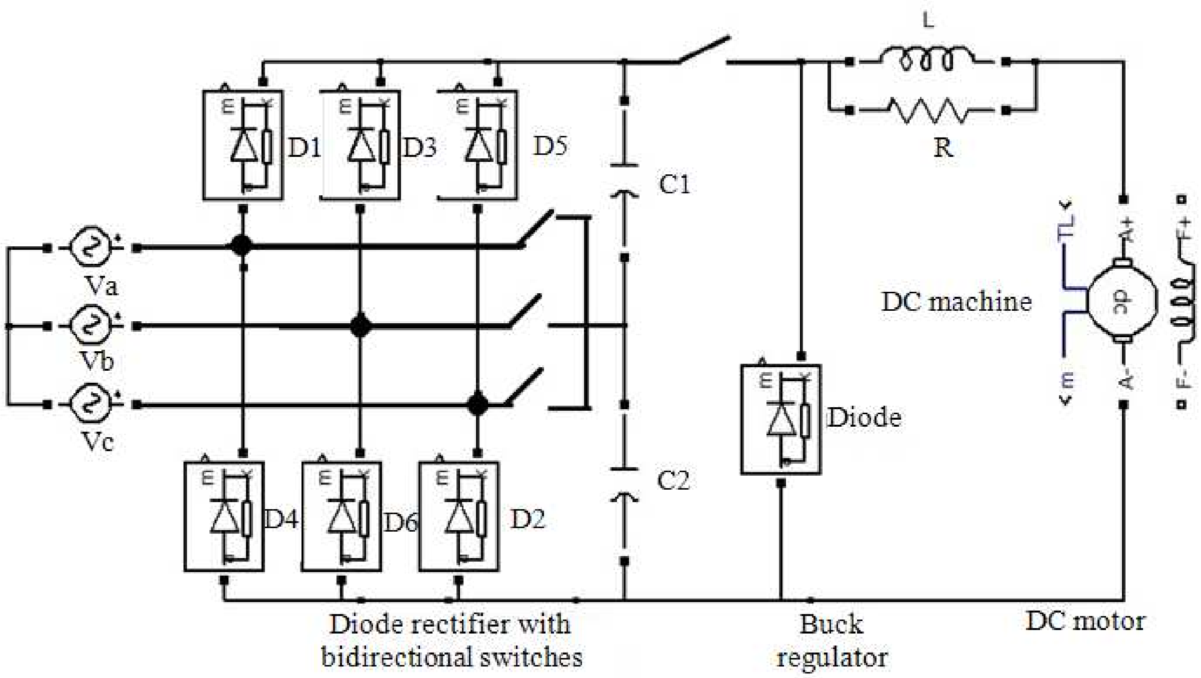

Fig. 1. Proposed diode rectifier with buck regulator

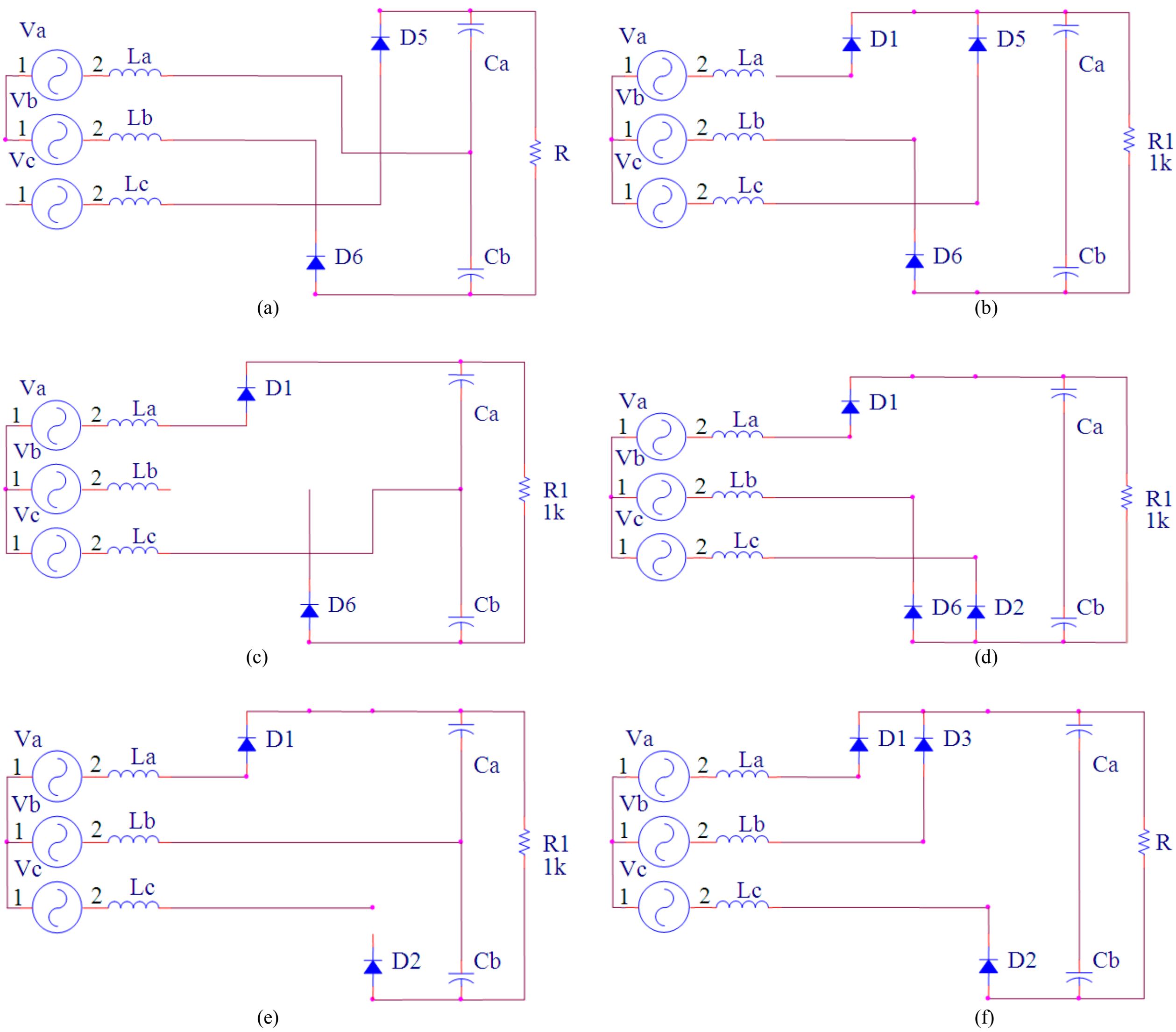

Fig. 2. Six topological stages of three phase diode rectifier

In the stage II, IV and VI, there are three conducting diodes, one associated with each phase. The three switches are off, so the converter behaves like a conventional rectifier with input inductors.

1.2. Bidirectional Switches

When gate circuit is open and Vdd is present, no current flow from drain to source. When gate terminal is made positive with respect to source, current flows from drain to source.

The construction of bi-directional switch using four diodes and MOSFET is shown in **Fig. 3**.

During positive half cycle of the input voltage, diodes D1 and D2 are forward biased. When gate signal is applied with respect to source, current flow from drain to source. So the input current is supplied to the load through D1, MOSFET and D2.

During negative half cycle of the input voltage, diodes D3 and D4 are forward biased. When gate signal is applied with respect to source, current flow from drain to source. So the input current is supplied to the load through D3, MOSFET and D4.

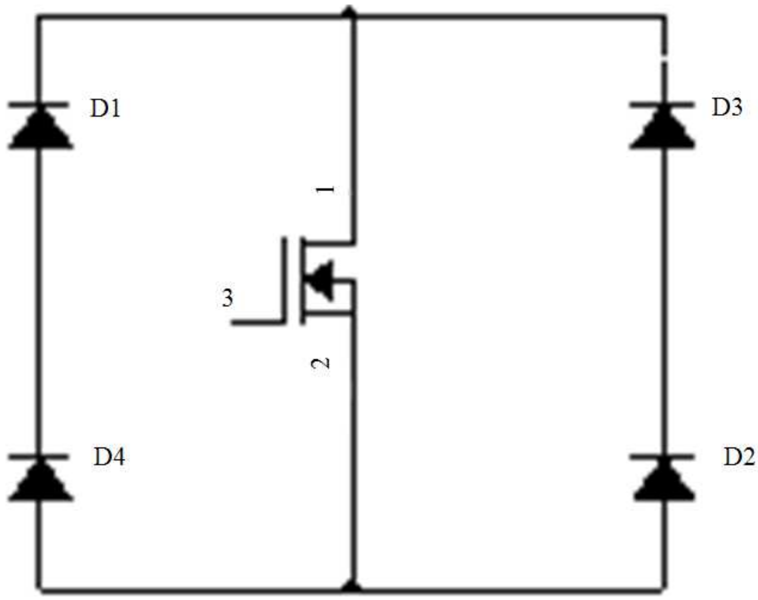

Fig. 3. Bi-directional switch

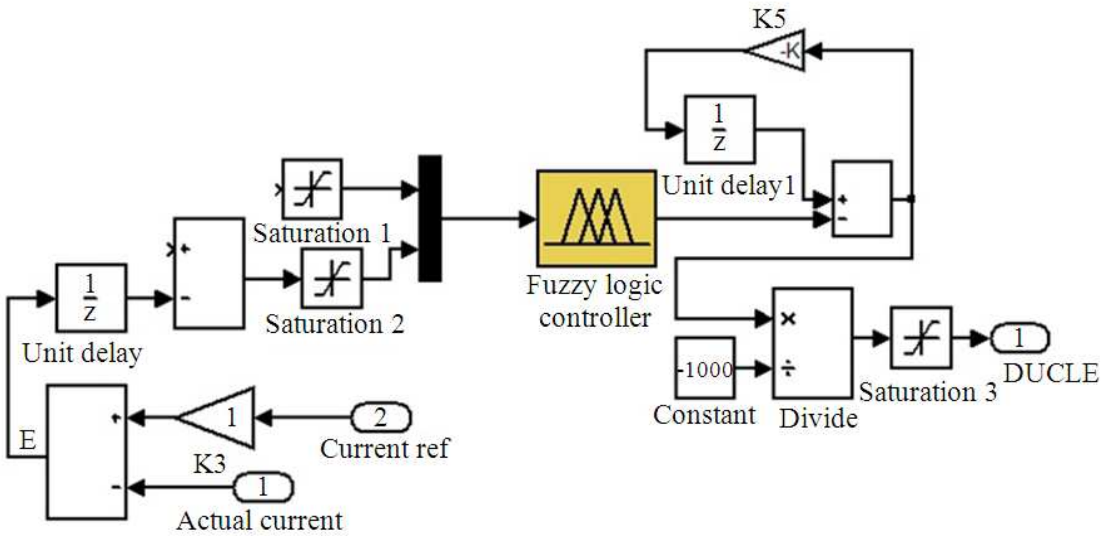

Fig. 4. Fuzzy controller

1.3. Fuzzy Controller

The objective is to design fuzzy logic controller that will improve the input current Total Harmonic Distortion (THD) as well as power factor at the input stage by controlling the conduction period of the bidirectional switches.

The FL controller will use both the output current and output current error of the circuit as input and obtain a control signal as its output. The controls signal will then increase or decrease the conduction period of bi-directional switches that will either achieve the desired power factor at the input stage.

1.4. Fuzzy Rule Base Process

By converting the input values to the appropriate linguistic variable, the Fuzzy Inference System (FIS) is executed to obtain a conclusion from the rule base.

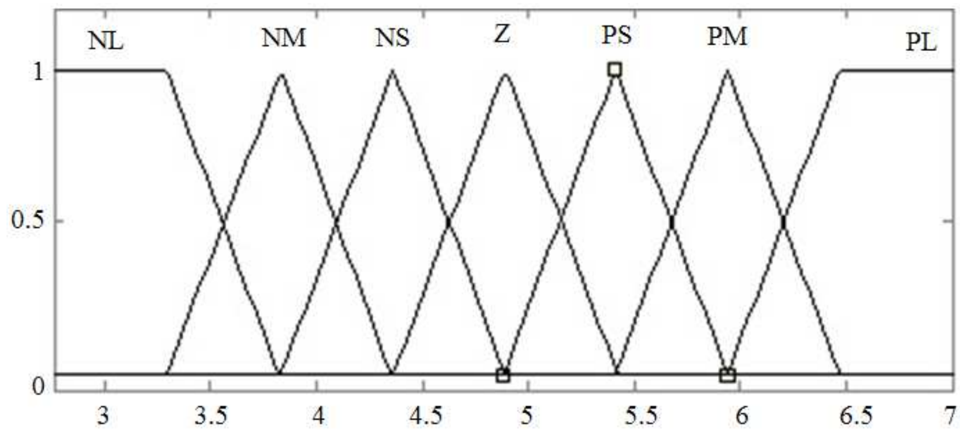

Fig. 5. Fuzzy membership functions of output current I

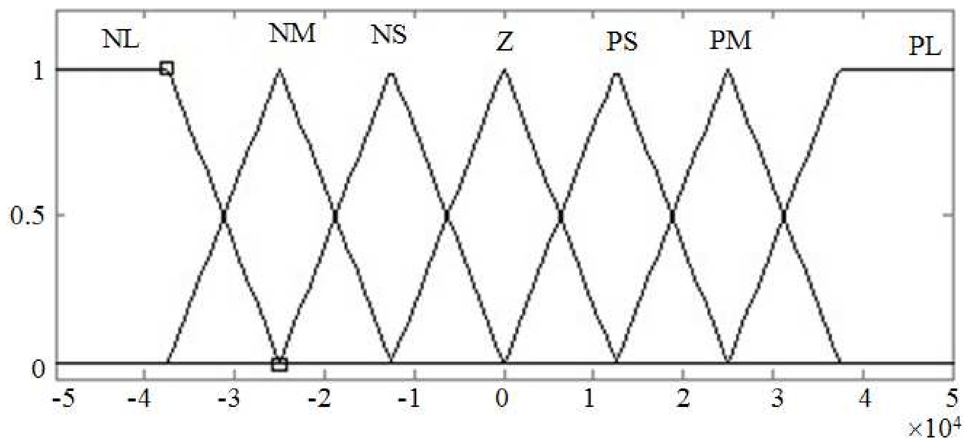

Fig. 6. Fuzzy membership functions of output current error e

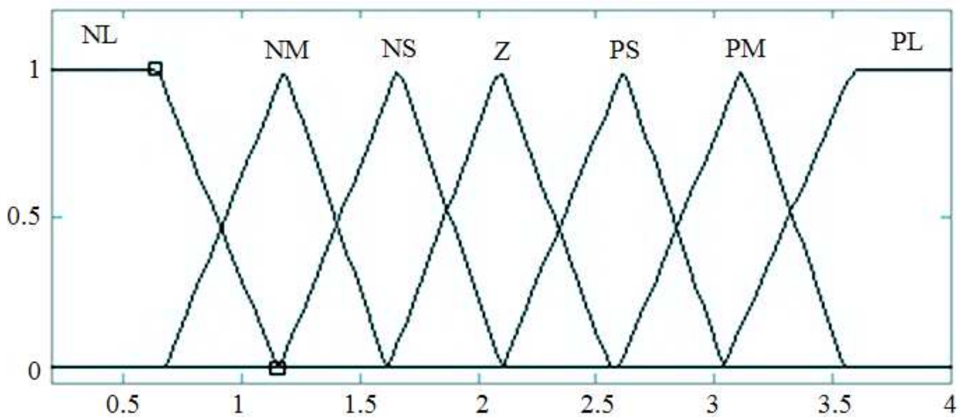

Fig. 7. Fuzzy membership functions of control signal CS

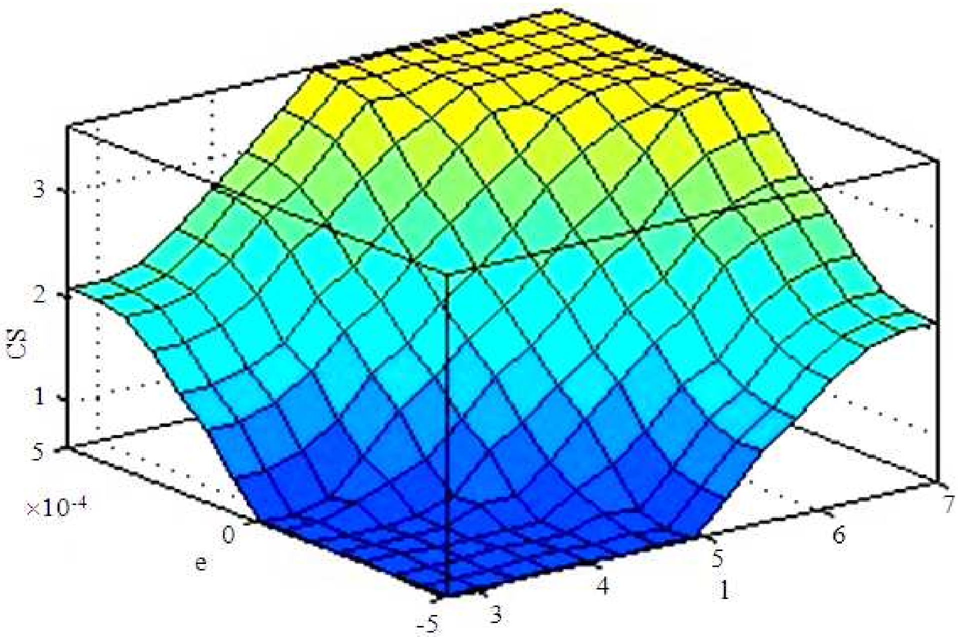

Fig. 8. Surface diagram

Table 1. Linguistics matrix of fuzzy rules

	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

Table 2. Fuzzy controller actions for correction in conduction of bidirectional switches

Adjustment	Output Current I	Error e	Δα
Negative large	3.82	-0.000250	0.555
Negative medium	4.36	-0.000125	1.17
Negative small	4.88	0.000000	2.09
Zero	5.41	0.000125	3.09
Positive small	5.94	0.000250	3.65
Positive medium	6.47	0.000375	3.65
Positive large	8.81	0.001080	3.64

1.5. Fuzzy Variables

Output Current, error (e) in current and Output Control Signal (CS) are detection as Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Large (PL), Positive Medium (PM) and Positive Small (PS)

The linguistics matrix of fuzzy rules for the FL Controller is shown in **Table 1**.

1.6. Defuzzification

In the defuzzification step, the TSK weighted average formula is employed to produce a single output value Control Signal (CS) that represent the combined effects of all the fuzzy outputs.

1.7. Practical Design Example

In the simple block diagram of the Fuzzy Logic control system shown in **Fig. 4**, the reference current is compared with a output current of diode rectifier and the difference between the reference current and output current is equal to the error (e). The output current and error are both uses as inputs to the FL controller. The FL controller uses the TSK technique to obtain control signal as its output. The control signal is then fed to the bidirectional switches to modify the conduction period and then input current.

1.8. FL Controller Design

The FL controller uses seven membership functions for the output current and seven membership functions for the output current error. Fuzzy membership functions of output current and error are shown in **Fig. 5 and 6** respectively. A fuzzy membership function of control signal is also shown in **Fig. 7**. The three dimensional FL control surface, of the forty nine membership function rules, shows (**Fig. 8**) a picture of the characteristics of the controller.

The membership functions could be tuned, to give the set point and this will be reflected by a change in the control surface output. The surface plot represents the fuzzy rule base output value that is added to the defuzzification constant to produce the field current (output). The controller surface shape is steepest where the combined value of both inputs is further away from zero. Alternatively, the controller surface shape is flattest about the set point:

- Coefficient of Output Current I: 2.76 to 7
- Coefficient of e: -0.0005 to 0.0005

The Fuzzy controller actions for correction in conduction of bidirectional switches are shown in **Table 2**.

1.9. Simulation Results

1.9.1. Closed Loop Simulation of three Phase Diode Rectifier with Bidirectional Switch

The closed loop simulation diagram of three phase diode rectifier with bi directional switch is shown in **Fig. 9**.

The input current waveform and THD of three phase diode rectifier with bi directional switch is shown in **Fig. 10**. The THD value of input current is 24.94%.

The load test on DC motor with closed loop control was performed and reading was tabulated in the **Table 3**. In this closed control, input current value is further increased when compared with open loop control and therefore input power is also increases gradually. So the performance of the DC motor is improved.

Table 3. Load test on three phase DC Motor with closed loop control

Torque N-m	I amps	V Volts	Speed RPM	Input power watts	Output power watts	EFFICI %
1	2.4	223	1730	535.2	181.07	33.83
2	3.1	221	1711	685.1	358.17	52.28
3	4.1	217	1697	889.7	532.86	59.89
4	5.0	214	1685	1070.0	705.45	65.93
5	6.2	212	1674	1314.4	876.06	66.65
6	7.4	210	1664	1554.0	1044.90	67.25
7	8.5	208	1655	1768.0	1212.50	68.58
8	9.4	206	1647	1936.4	1379.00	71.22
9	9.9	204	1642	2019.6	1546.70	76.59
10	10.2	203	1638	2070.6	1714.40	82.80

Table 4. Load test on three phase DC Motor with fuzzy logic loop control

Torque N-m	I amps	V Volts	Speed RPM	Input power watts	Output power watts	EFFICI%
1	2.6	218	1756	566.8	183.79	32.43
2	3.2	214	1749	684.8	366.12	53.46
3	4.2	212	1737	890.4	545.42	61.26
4	5.1	210	1726	1071.0	722.62	67.47
5	6.3	209	1719	1316.7	899.61	68.32
6	7.5	207	1707	1552.5	1072.00	69.05
7	8.6	206	1692	1771.6	1239.67	69.97
8	9.5	205	1684	1947.5	1410.07	72.40
9	10.1	203	1672	2050.3	1575.02	76.82
10	10.4	201	1669	2090.4	1746.89	83.57

Table 5. Load test using dc-link inverter with bidirectional switches

V volt	I amps	N rpm	Pi Watts	S1 ~ S2	T N-m	Po Watts	PF
440	1.0	1474	320	0.0	0.0	0	0.419
440	1.5	1450	800	5.5	5.23	794	0.699
440	2.0	1140	1200	7.2	6.85	1032	0.787
435	2.5	1410	1620	9.0	8.56	1263	0.860
435	3.0	1400	1940	10.8	10.27	1505	0.858
435	3.5	1380	2350	12.4	11.79	1704	0.891
430	4	1375	2720	13.9	13.22	1903	0.913
430	4.5	1370	3060	14.9	14.17	2033	0.913

Table 6. Load test using dc-link inverter with bidirectional switches

V volt	I amps	N rpm	Pi Watts	S1 ~ S2	T N-m	Po Watts	PF
440	1	1474	320	0.0	0.000	0	0.419
440	1.5	1450	800	5.6	5.323	798	0.699
440	2	1443	1249	7.3	6.990	1048	0.819
435	2.5	1408	1671	9.2	8.952	1289	0.887
435	3	1400	2019	10.9	10.98	1545	0.893
435	3.5	1378	2440	12.8	11.99	1742	0.925
430	4	1372	2810	14.5	13.88	1922	0.943
430	4.5	1369	3192	15.3	14.58	2045	0.952

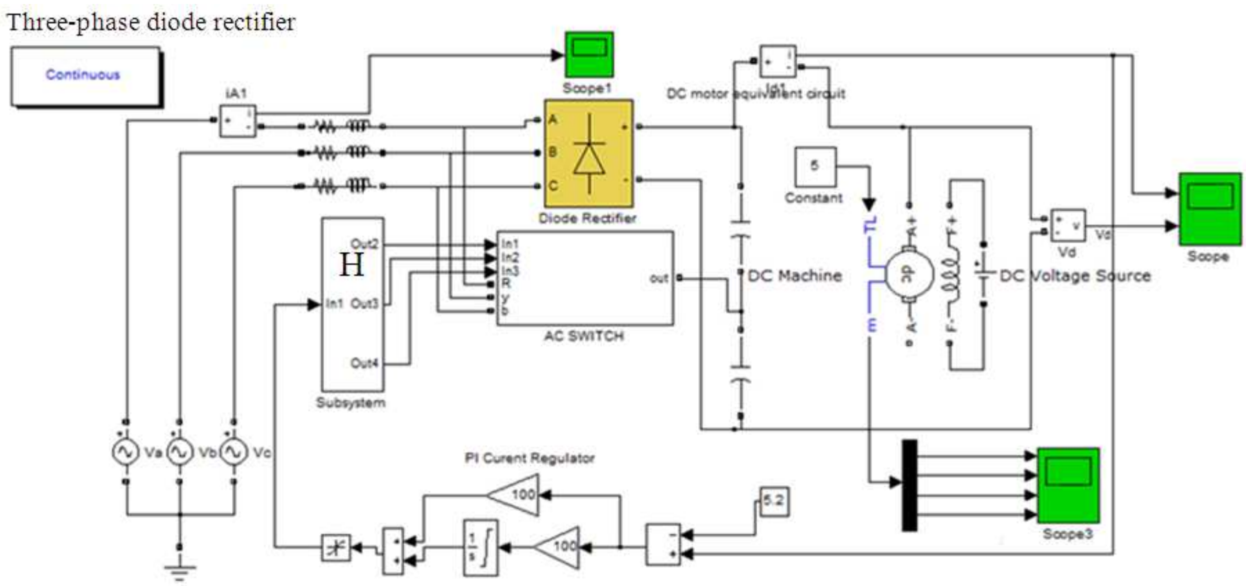

Fig. 9. Closed loop control of three phase diode rectifier with directional switch

1.10. Implementation of Fuzzy logic Controller

The fuzzy logic controller based simulation diagram of three phase diode rectifier with bi directional switch is shown in **Fig. 11**.

The input current waveform and THD of three phase diode rectifier with bi directional switch is shown in **Fig. 12**. The THD value of input current is improved with 24.20% when compared with closed loop system of 24.94%.

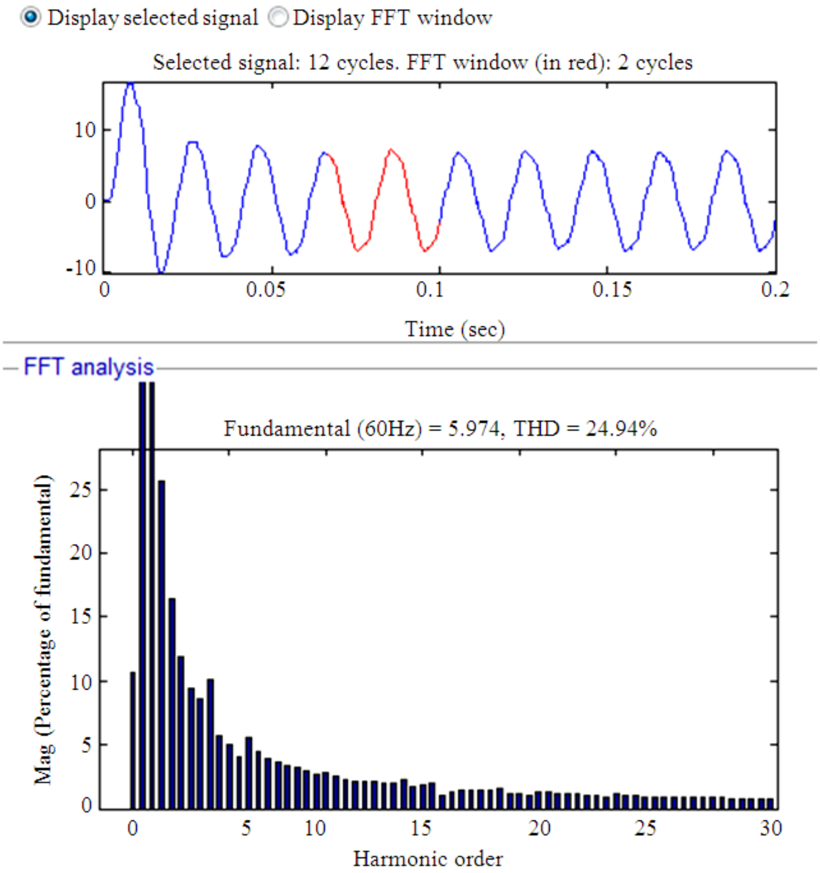

Fig. 10. The input current waveform and THD of three phase diode rectifier with bi directional switch for closed loop control

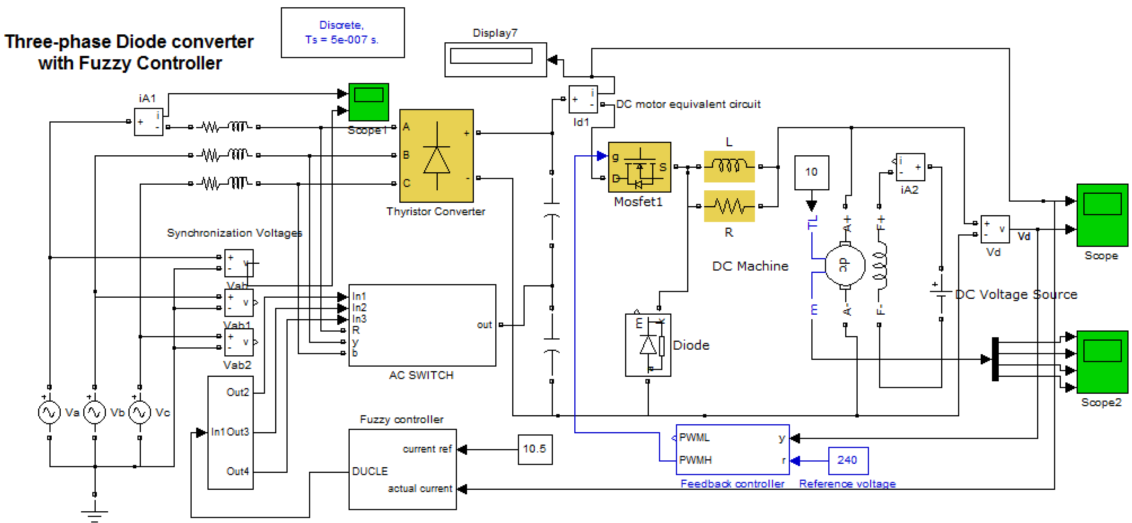

Fig. 11. Simulation diagram of three phase diode rectifier with Fuzzy logic controller

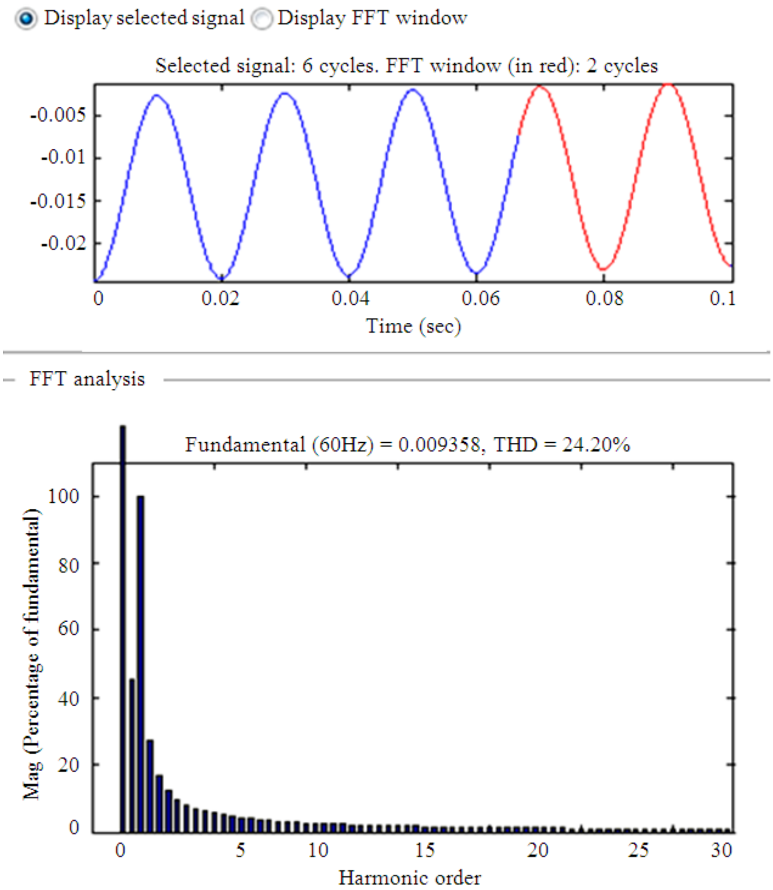

Fig. 12. The input current waveform and THD of three phase diode rectifier with bi directional switch for fuzzy logic control

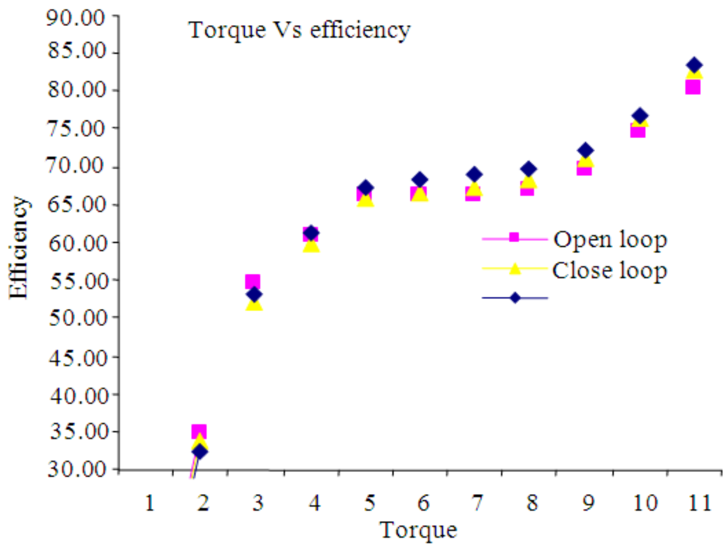

Fig. 13. Variation of efficiency with torque

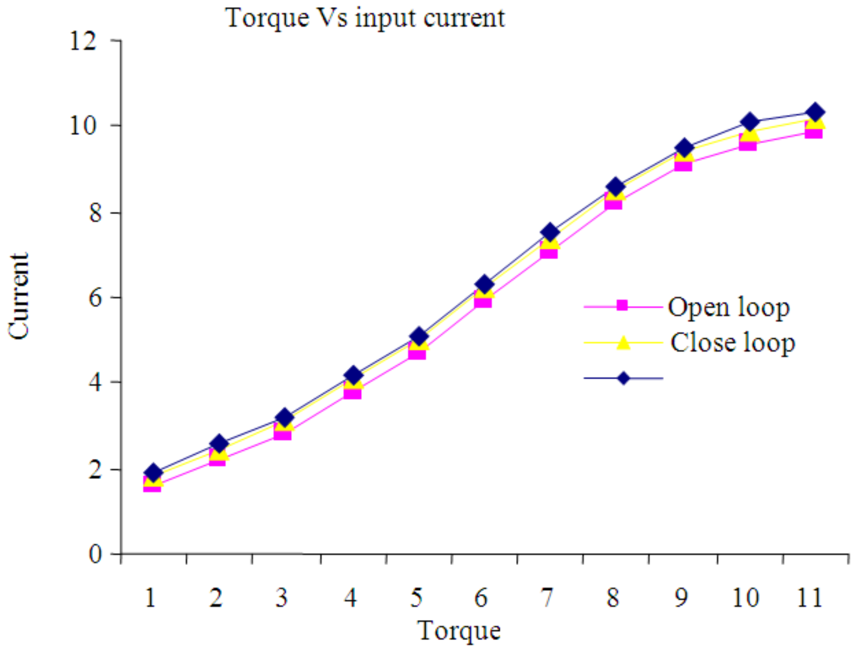

Fig. 14. Variation of torque with input current

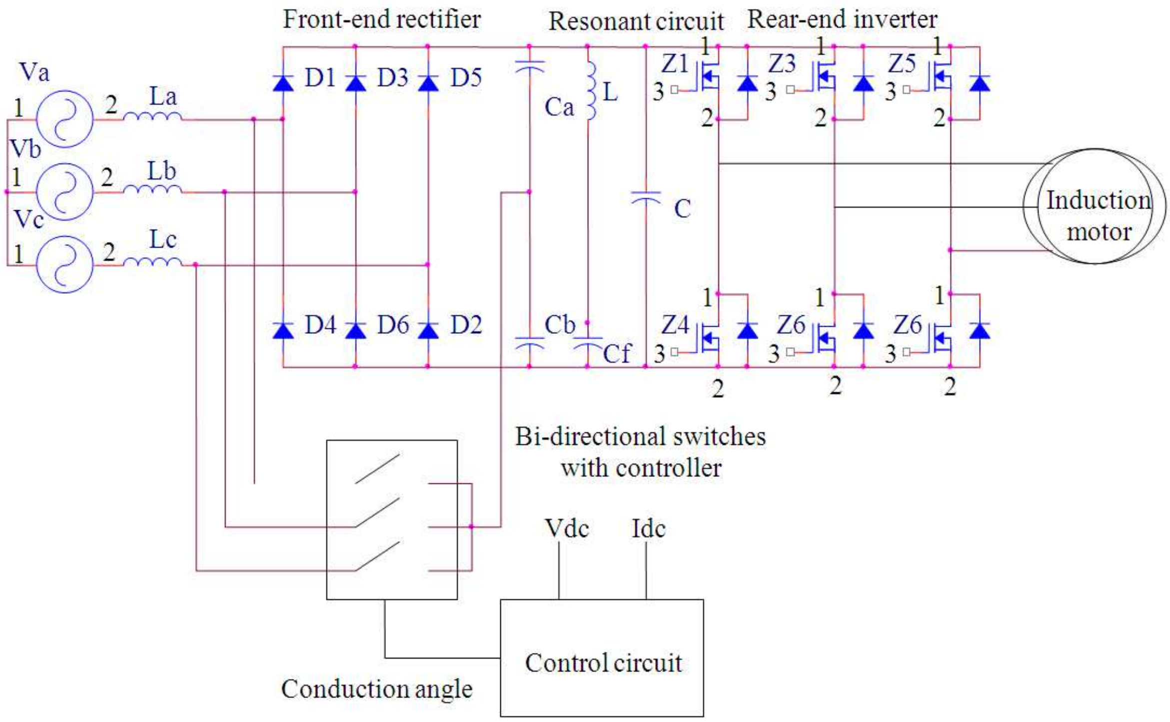

Fig. 15. Experimental setup of diode rectifier with resonant inverter

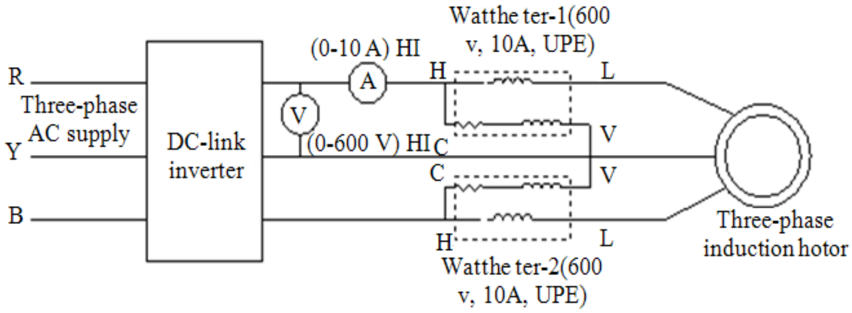

Fig. 16. Load test using dc-link inverter

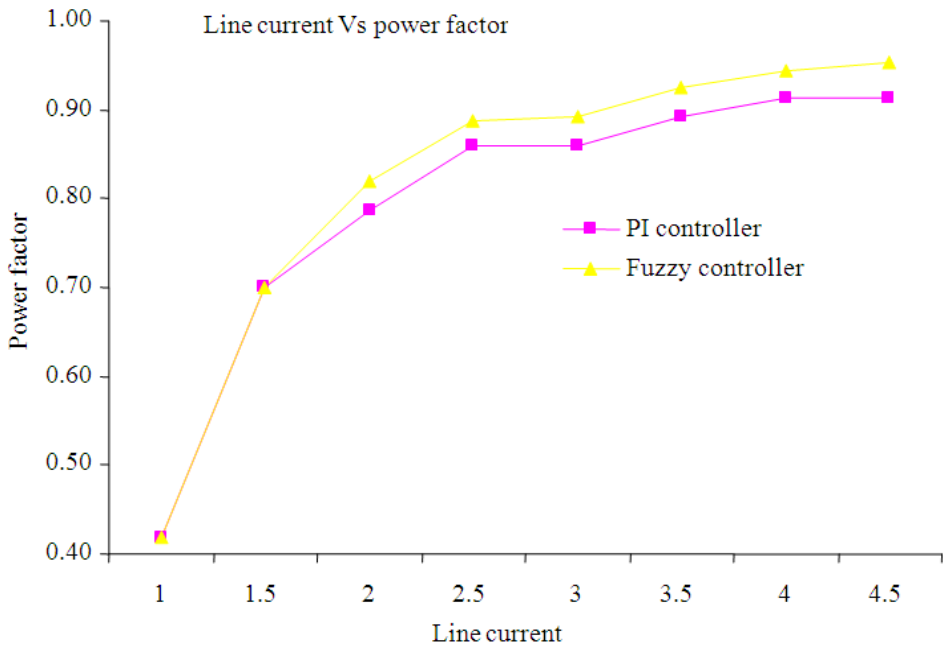

Fig. 17. Input Power factor with variation in line current

So the input current waveform is also improved with sinusoidal form.

The load test on DC motor with fuzzy logic control was performed and reading was tabulated in the **Table 4**. In this fuzzy logic control, input current value is further increased when compared with closed loop control and therefore input power is also increases gradually. So the performance of the DC motor is improved.

The relationship between torque and efficiency for open loop, closed loop control and fuzzy logic control is shown in **Fig. 13**. The efficiency of the DC motor is improved in the fuzzy logic control.

The relationship between torque and input current for open loop, closed loop control and fuzzy logic control is shown in **Fig. 14**. The input current of the DC motor is improved in the fuzzy logic control.

1.11. Experimental Results

The fuzzy logic controller based scheme with resonant inverter at the output stage is demonstrated using FPGA with three phase induction motor as shown in **Fig. 15**.

For the purpose of experimental analysis, three-phase induction motor with the following specifications is chosen:

Power = 3 HP
Current = 4.8 A
Voltage = 440 V
RPM = 1440

Power factor is calculated by conducting the load test on three-phase induction motor. Load test on three-phase induction motor is conducted with dc-link inverter. For analyzing the improvement in the power factor, the same load test is repeated by fuzzy logic controller based scheme.

1.12. Load Test Using DC-Link Inverter

The circuit diagram for conducting load test on three-phase induction motor is shown in **Fig. 16**.

Connections are given as per circuit diagram. The load is increased steps by steps and ammeter, voltmeter and wattmeter readings are noted and tabulated in the **Table 5**.

The input power, output power, torques and power factor are calculated by the following formulas:

1) Input power $P_i = W_1 + W_2$
W_1, W_2 – Wattmeter readings
2) Output power $P_o = \frac{2\pi N t}{60}$ watts
3) Torque $T = (S_1 \sim S_2).g.r$ N-m
S_1, S_2 – Spring balance readings in Kg
g – Acceleration due to gravity in m/sec 2-9.81
r – Radius of the brake drum in m
4) Power factor $\cos\phi = \frac{W_1 + W_2}{\sqrt{3}.V_L.I_L}$
V_L – Line voltage in volts
I_L – Line current in amps
Radius of the brake drum = 0.097 m
Multiplication factor = 600×10 /4 = 1500

1.13. Load Test Using Fuzzy logic Controller Based DC-Link Inverter

Connections are given as per circuit diagram. The load is increased steps by steps and ammeter, voltmeter and wattmeter readings are noted and tabulated in the **Table 6**.

The relationship between input power factor and line current for Load test using dc-link inverter and fuzzy controller based scheme is shown in **Fig. 17**.

The power factor of the front-end rectifier is calculated using the equation mentioned with PI controller and Fuzzy Controller. The input power factor of DC link inverter using PI controller is 0.913. Similarly, the input power factor of DC link inverter using PI controller is 0.9524. So the power factor is improved by 5%.

2. CONCLUSION

The simulation results are obtained for three phase rectifier with open loop and closed loop control show that sinusoidal input supply current waveform presents at the input stage. Experimental results obtained from three phase DC motor for both open loop and closed loop control shows that improved power factor presents at the input stage. A power factor and input current THD improvement for a DC motor load has been verified open loop and closed loop control. Due to the low-frequency operation of the front bi-directional MOSFET switches, the gating circuit is simple and more reliable. The low-frequency operation provides low switching losses. The MOSFET based bi-directional switches conducts only a small fraction of the total cycle, yielding a negligible switch KVA rating. With these excellent rectifier power factor capabilities, the converter will be an excellent energy saver in a clean power environment.

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