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Role of PI/Fuzzy Logic Controlled Transformerless Shunt Hybrid Power Filter using 6-Switch 2-Leg Inverter to Ease Harmonics in Distribution System

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Abstract

Background/Objective: The intention of this paper is to propose a Transformerless Shunt Hybrid Power Filter (TSHPF) using 6-Switch 2-Leg Inverter (SSTL) to enhance the power quality in distribution systems. **Methods/Statistical Analysis:** The TSHPF comprises of SSTL inverter and passive filter coupled to Point of Common Coupling (PCC). Here SSTL inverter acts as Shunt Active Filter (SAF). The DC bus voltage in SSTL inverter is retained by using PI/Fuzzy controller. To generate switching pulses in inverter linear control method is used. Here a TSHPF incorporated with fuzzy controller is developed and comparative analysis is made w.r.t conventional PI controller. **Findings:** The proposed system is simulated in MATLAB/SIMULINK for both control strategies. Simulation results shows that compared to PI, by including fuzzy controller the total harmonic distortion is reduced from 8.64% to 3.40%. **Improvement:** The PI controller is not feasible because explicit mathematical model is needed. Hence, fuzzy controller based TSHPF is much efficient for enhancing the power quality.

Keywords: Harmonic Currents, Hybrid Power Filter (HPF), Non-Linear Loads, Power Quality, Total Harmonic Distortion (THD)

1. Introduction

At present almost all household and industrial appliances are equipped with electronics. These electronics are causing nonlinearity on the power system network thereby affecting its healthiness and sensitivity. Hence, IEEE519 standards[1] are recommended to restrict the current harmonics[2].

Passive filters have been employed to pacify distortions due to current harmonics. It comprises of R, L and C components. Usage of passive filters is restricted in low frequency systems due to cost effectiveness and bulk in size.

Active filters[3–5] have been introduced to wipe out the problems of the passive filters. It comprises of R and C components. The practice of active filter is uneconomical due to huge initial investment and high power losses.

On economical reasons to stamp out the problems caused by both passive and active filters, hybrid power filters[6] were introduced in the present power applications. It comprises of both passive and active components. Usage of HPFs is still restricted due to several passive components and transformers causing its weight and size.

To overcome these problems Transformerless Shunt Hybrid Power Filter[7–10] was introduced in this paper. The TSHPF comprises of SSTL inverter and passive filter coupled to Point of Common Coupling. Voltage rating of APF is considerably reduced by introducing SHAF design. Several control methods have been practiced so far, in time and frequency domain. Methods introduced under frequency domain is Fast Fourier Transformation (FFT); under time domain are: 1) Instantaneous reactive power or P-Q theory, 2) Synchronous reference frame or D-Q theory and 3) Sliding mode control. Among them

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P-Q and D-Q theories are wide spread due to reduced computational burden. To generate switching pulses in inverter linear control method is used.

To regulate DC bus voltage and harmonics, conventional PI controllers are used. Presently, evolution of fuzzy logic controller has created enormous interest in various applications over PI controllers. The benefits of fuzzy over conventional controllers are explicit mathematical model is not required; can manage nonlinearity and more feasible than conventional controllers.

The paper is divided as follows:

- Section-2: Briefly introduces implemented TSHPF using SSTL inverter.
- Section-3: Mathematical modeling of hybrid power filter is analyzed.
- Section-4: Deals with overall control strategy of active filter with PI controller as a compensating device. The designing, operation, rule formation of fuzzy controller is explained.
- Section-5: Experimental verification of the system in MATLAB/SIMULINK and its results are discussed.

2. Proposed System Design

Figure 1 shows the fundamental circuit topology for TSHPF using SSTL for suppression of harmonics. The SHPF consists of SSTL inverter acting as an active power filter which is in series connection with passive filter. This passive filter is adjusted to prevailing harmonic content for harmonic removal. APF circuit mainly composes of

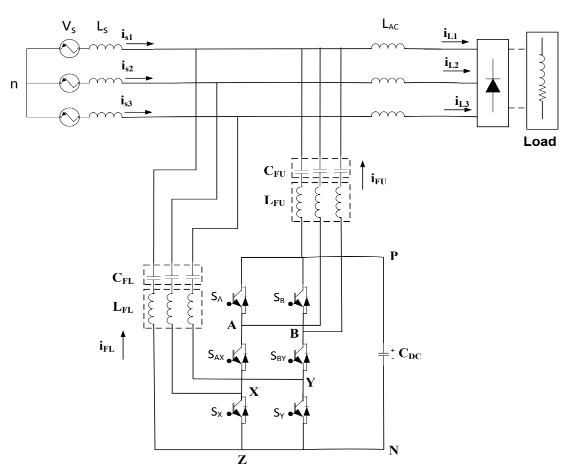

Figure 1. Configuration of proposed Transformerless HPF.

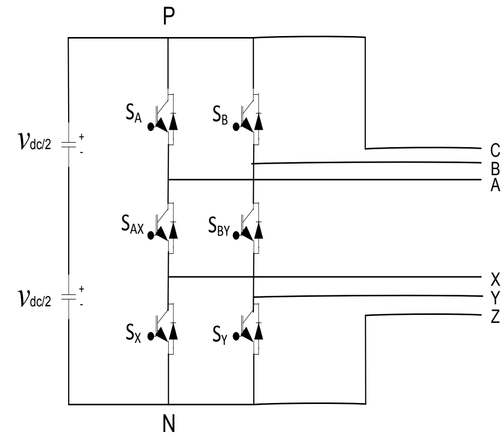

Figure 2. SSTL inverter configuration.

SSTL inverter with a DC bus capacitor. This APF retains a very low fundamental current and voltages of grid; hence the rated capacity of APF is being drastically reduced. Due to these advantages, the combined topology is very effective for compensating the current harmonics in power system network.

2.1 6-Switch 2-Leg Inverter

Figure 2 shows SSTL inverter evolved from a 9-switch inverter. 9-switch inverter is obtained by joining 3-semi conductor switches per phase which leads to a total of 9-switches in all 3-phases. Elimination of a phase among the three viz. removal of three semiconductor switches in the third phase leads to a SSTL inverter. These six switches are powered by a common DC bus capacitor. The SSTL inverter looks like two 3-ø inverters with passive filters in series thereby two sets of 3-ø outputs can be obtained. The two inverter units are treated as upper and lower inverters. ABC represents the output of upper inverter unit with passive filter adjusted to 7th harmonic and is capable for elimination of harmonic pair of 5th and 7th. Similarly XYZ represents the output of lower inverter unit with LC passive filter regulated to 13th harmonic and is capable for elimination of 11th and 13th order harmonic. Both inverters in SSTL inverter topology are powered by a common DC side capacitor. To generate output from both upper and lower inverter units a minimum value of voltage across DC link is sufficient. Hence, HPF formed by series combination of SSTL inverter with LC passive filter would ensure low voltage requirement compare to conventional APFs.

3. Hybrid Power Filter Modeling

3.1 Active Filter

Voltage across DC side capacitor (V_{dc}):

The voltage across DC side capacitor for SSTL inverter can be calculated from the following equation:

$$V_{dc} = \frac{V_{dc,ref}}{\sqrt{2}} \tag{1}$$

Capacitor (DC side) (C_{dc}):

The significance of capacitor (DC side) is:

- Under steady state condition, DC voltage is maintained with small ripples.
- During transient state, the source and load real power variations can be met, by acting as energy storage component.

Basic thing responsible for fluctuations in voltage of DC bus capacitor is total harmonic load current which is to be compensated. Fluctuations in the voltage are to be avoided to enhance compensating phenomenon. Hence in order to achieve this, DC bus capacitor should be properly sized. Based on energy balance principle, the size of DC bus capacitor is determined. The following equation can be derived based on the above stated concept:

$$\frac{1}{2} C_{dc} \left| (\Delta V_{dc}^2 - V_{dc,ref}^2) \right| = \frac{1}{2} * \sqrt{2} V_S * \Delta I_L * \frac{T}{2} \tag{2}$$

Where, ΔV_{dc} is the minimum/maximum DC bus voltage.

$V_{dc,ref}^2$ is DC side reference voltage.

V_s is Source voltage (RMS value).

ΔI_L is peak RMS value of harmonic load currents.

T is time period of Source voltage.

Based on the Equation shown below we can analyze the size of DC-bus capacitor:

$$C_f \geq \frac{(\sqrt{2} V_s * \Delta I_L * \frac{T}{2})}{\left| (\Delta V_{dc}^2 - V_{dc,ref}^2) \right|} \tag{3}$$

3.2 Passive Filter

The working principle of passive filter is to seize discriminatory harmonic currents. Hence to eliminate the particular harmonic currents LC filter is adjusted to selective harmonic filtering frequency. HPF proposed in this paper is basically a SSTL inverter with two units of control and a series connection of passive filter regulated to 7th, 13th harmonics. The 7th harmonic is 2nd dominant harmonic component which is mainly liable for elimination of harmonic pair of 5th and 7th. The reason for tuning to 7th harmonic frequency because it is small in size and inexpensive when compared to 5th harmonic frequency. Similarly the 13th harmonic filter is liable for removal of harmonic pair of 11th and 13th.

Hence the characteristic impedance of passive filter is determined by Equation (4):

$$Z = \sqrt{\frac{L}{C}} \tag{4}$$

To enhance good filtering characteristics the impedance of passive filter ought to be lesser than the following harmonic frequencies i.e 5th, 7th, 11th and 13th. This means both capacitor and inductor values required for designing the passive filter must be vice versa i.e. high capacitor value and low inductor value. Based on the conditions mentioned above, in this paper the values of capacitors and inductors for 7th and 13th harmonic order are chosen as 30.7µF, 61.2µF, 5mH, 0.8mH respectively.

4. Control Strategy of Active Filter

The proportional controller is mainly responsible to control the harmonic component of source current. Hence in order to calculate its real time value, a fast algorithm is required. The greater response time of frequency domain algorithms made them inoperative. So, time domain algorithms are used; among them frequently accepted are instantaneous power theory and synchronous rotating reference frame method. The compensating command signals are acquired from d-q theory after performing transformation from 3-ø currents into 2-ø currents in stationary reference frame. The main difference of d-q theory and p-q theory is phase synchronization. The absence of phase synchronization in d-q theory made it more practi-

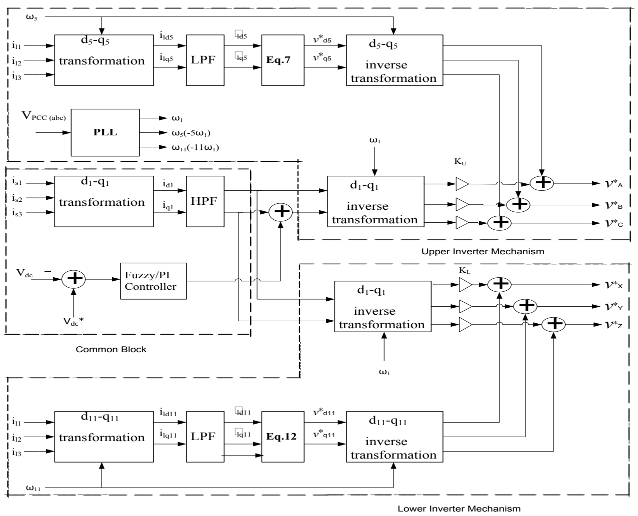

Figure 3. Control strategy of active power filter.

cal than p-q theory thereby avoiding problems associated with zero detection.

In this paper the controlling of filter is performed through synchronous rotating reference frame method[11] and PLL loop. The presence of phase lock loop eliminates the zero detection problems.

4.1 Upper Inverter

4.1.1 Feedback Mechanism

Figure 3 represents upper inverter unit feedback mechanism. The transformation from abc to d-q converters three phase current source currents i_{s1}, i_{s2}, i_{s3} into two phase currents i_{d1} and i_{q1}.

$\tilde{i}_{d1}$, $\tilde{i}_{q1}$ are extracted from i_{d1} and i_{q1} after passing through first order HPFs coordinated with PCC voltage vector. Thus the basic step of separation of harmonic from fundamental components of grid currents is achieved. Then d-q to abc transformation is performed to change the two phase harmonic source currents into three phase which are amplified by the gain k_U as shown below:

$$V^*_{ABC_{ff}} = K_U i_{S_{123h}} \tag{5}$$

The obtained signals are connected to the reference voltages generated from feed-back unit ensuring reference voltages V^*_A, V^*_B and V^*_C from upper inverter unit which are given to gate control circuit of 3-phase inverter.

4.1.2 Controlling DC-Bus Voltage:

In upper inverter, the voltage of DC bus can be retained at desirable value using fuzzy/PI controller and output is connected to $\tilde{i}_{q1}$ in feed-back loop.

4.1.3 Feed Forward Mechanism:

Dominant 5th order harmonic content existing in upper inverter is compensated using feed forward mechanism, by tuning the LC passive filter to 7th harmonic.

The LC filter impedance on d-q frame at 5th harmonic frequency is given by:

$$z_{F_{dq5}}(s) = R_{F_U} + (s + j\omega_5)L_{F_U} + 1/((s + j\omega_5)C_{F_U}) \tag{6}$$

The steady state impedance of LC filter obtained by substituting s = 0, then:

$$z_{F_{dq5}}(0) = R_{F_U} + j\omega_5 L_{F_U} + 1/(j\omega_5 C_{F_U}) \tag{7}$$

Then, the voltage reference given by feed forward mechanism is represented by the following equation which is product of 5th harmonic impedance and load current d-q frame:

$$V^*_{dq_5} = Z_{F_{dq_5}} * \bar{i}_{L_{dq5}} \tag{8}$$

$$\Rightarrow V^*_{dq_5} = \{R_{F_U} + j(\omega_5 L_{F_U} - 1/(j\omega_5 C_{F_U})\} \bar{i}_{Ldq_5} \tag{9}$$

Figure 3 represents the feed forward control of upper inverter unit. The transformation from abc to d-q converters 3- load currents i_{l1}, i_{l2} and i_{l3} into 2- currents i_{ld5}, i_{lq5}. The DC quantities of i_{ld5} and i_{lq5} are extracted after passing through first order LPFs, there by the 5th harmonic components are separated from load current components.

The d-q to abc transformation produces voltage references in feed forward mechanism which are further coupled to feedback voltage references.

4.2 Lower Inverter

4.2.1 Feedback Mechanism

Performances of lower and upper inverters (represented in Figure 3) are same except the voltage across DC-link which is with held by upper inverter. As K_L is different

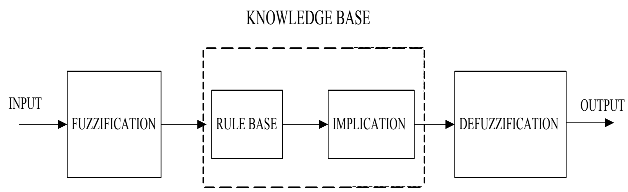

Figure 4. Schematic structure of fuzzy logic controller.

from K_U the voltage references of bottom unit is as follows:

$$V^*_{XYZ_{fb}} = K_L\, i_{S_{123h}} \tag{10}$$

4.2.2 Feedforward Mechanism

The purpose of feed forward mechanism in lower inverter is to overcome the 11th harmonic content. Top unit procedure is adopted here and hence the 11th harmonic feed forward voltage reference and impedance are as follows:

$$V^*_{dq_{11}} = Z_{F_{dq_{11}}} * \bar{i}_{Ldq_{11}} \tag{11}$$

$$Z_{F_{dq_{11}}}(0) = R_{F_L} + j\omega_5 L_{F_L} + 1/(j\omega_5 C_{F_L}) \tag{12}$$

$$\Rightarrow V^*_{dq_{11}} = \{R_{F_L} + j(\omega_{11}L_{F_L} - 1/(j\omega_{11}C_{F_L})\}\, \bar{i}_{Ldq_{11}} \tag{13}$$

4.3 Fuzzy Logic Controller

Fuzzy logic controllers have been used in place of conventional PI controllers due to the adverse effects of PI controllers. The advantages of fuzzy controller over PI are very robust, doesn't require mathematical modeling of the system, simpler, reduced settling time and steady state error and quick operation. Hence for many applications it is renowned, as it reduces human control logic.

The fuzzy logic controller inner structure consists of the following stages:

- Fuzzification.
- Knowledge base.
- Interference mechanism.
- Defuzzification.

The superior dynamic response can be attained under peripheral disturbances by designing a knowledge base which is a collection of data and a rule base. The input and output membership functions specified in data base gives data regarding exact fuzzification procedure. Figure 5 illustrate the triangular membership functions for input variable error 'e' ($V^*_{dc} - V_{dc}$), change in error 'ce' (de/dt) and output 'du'.

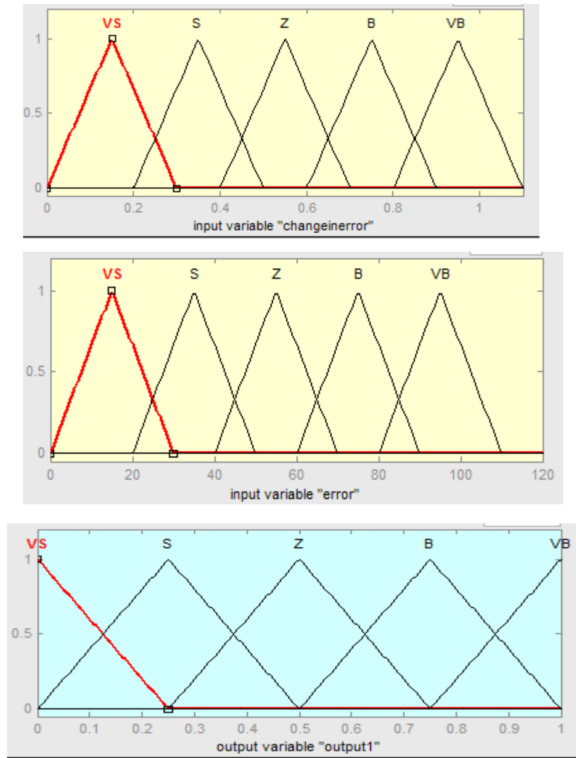

Figure 5. Input/output variables.

5 membership functions such as VS, S, Z, B and VB are chosen as input and output variables. The fuzzified output can be obtained from inference mechanism through collection of linguistic rules represented in Table 1.

The final stage is defuzzification is performed using centroid method where the conversion of fuzzy linguistic terms to crisp value is obtained.

5. Simulation Diagram and Results

The simulation diagram for proposed Transformerless Hybrid Power Filter is shown in Figure 6 below:

MATLAB environment is used to examine the complete system. Table 2 specifies the parameters of the system. The passive filters are tuned at 7th and 13th harmonic order respectively. The grid voltage amplitude is taken as 220V and dc-side voltage reference is 120V. Simulation results without filter with PI and fuzzy based controllers are projected in the following diagrams: 7, 8 and 9 respectively.

Table 1. Fuzzy decision table.

Error→ Change in error ↓	**VS**	**S**	**Z**	**B**	**VB**
VS	VS	VS	VS	B	B
S	VS	S	Z	B	Z
Z	VS	Z	Z	B	VB
B	S	S	S	B	B
VB	VS	VB	VB	B	VB

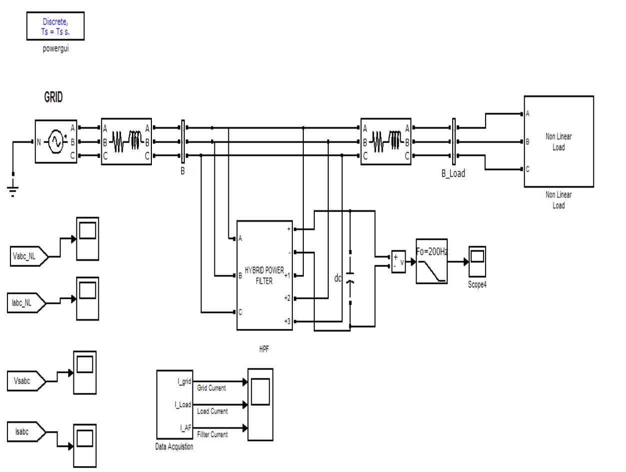

Figure 6. MATLAB model for TSHPF using SSTL inverter.

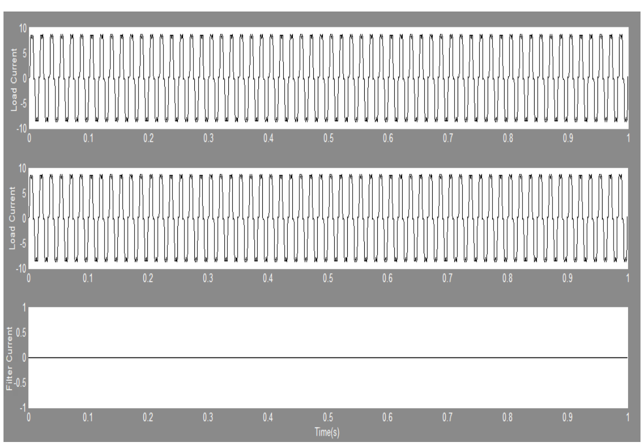

Figure 7. Simulation results without filter.

The results obtained from Figures 7, 8 and 9 demonstrate the usage of fuzzy controller incorporated in TSHPF using SSTL inverter, the supply current turn out to be almost sinusoidal from the distortion wave.

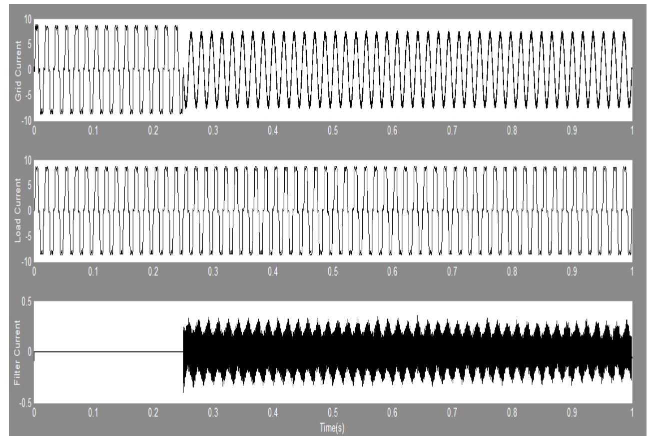

Figure 8. Simulation results with PI controller.

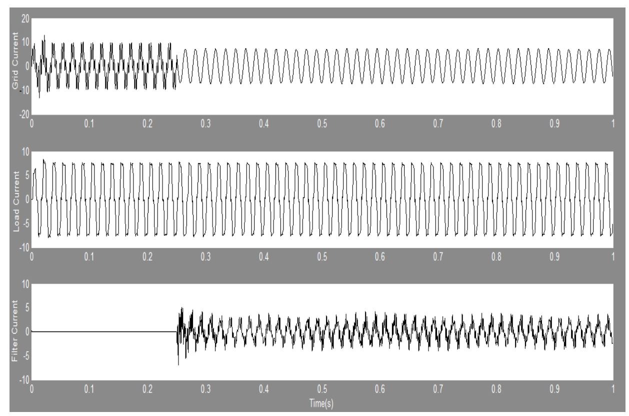

Figure 9. Simulation results with FUZZy logic controller.

Table 2. System parameters

PARAMETER	SYMBOL	VALUE
Seventh order harmonic tuned Upper capacitor	C_{FU}	30.7 μF
Thirteenth order harmonic tuned Upper inductor	L_{FU}	5 mH
Seventh order harmonic tuned Lower capacitor	C_{FL}	61.2 μF
Thirteenth order harmonic tuned Upper inductor	L_{FL}	0.8 mH

Table 3. Comparison of %THDs

TYPE OF CONTROLLER	% THD VALUES
Without filter	23.15
Transformerless HPF with PI controller	8.64
Transformerless HPF with Fuzzy controller	3.40

Following Table 3 specifies the comparison of THDs for grid current with various controllers.

From the Table 3 it can be seen using the PI controller based Transformerless HPF, the grid current total harmonic distortion reduced to 8.64% from 23.15%. When the fuzzy controller is incorporated in the Transformerless HPF, the grid current total harmonic distortion is reduced to 3.40% from 23.15% which is in the allowable range as per the IEEE standards. Hence it can be observed that the proposed fuzzy based controller exhibits much better performance than the conventional PI controller.

6. Conclusion

Power quality depends on the satisfactory operation of the load with minimum maintenance, maximum care by avoiding malfunctioning of remaining loads equipped to the system. To eradicate the limitations of active and passive filters, hybrid power filters have been preferred as best option for nonlinear load compensation. In the proposed scheme, Transformerless Hybrid Power Filter is preferred for the distribution system. Absolute assessment between PI and fuzzy based Transformerless Hybrid power has been performed in this paper by which we can conclude that the fuzzy logic based Transformerless Hybrid Filter leads to improved performance of the controller with near sinusoidal source current. Thus proposed fuzzy control technique is found extremely adequate to stabilize dc link voltage since it does not require complex mathematical modeling and hence it is more robust compared to PI controller.

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