



# Hybrid Multilevel Inverter based DVR with PI and FL controller for power quality enhancement

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**Abstract:** This paper presents the dynamic voltage restorer based on 7-level Hybrid Multilevel Inverter. The new multilevel inverter is a combination of the capacitor clamped and the cascaded H-bridge type multilevel inverters. This new topology provides different levels of output voltages and high modularity. In this paper two new control strategies using PI controller and Fuzzy Logic controller are presented. The sags or swells are detected in a transmission line and the voltage is injected from the multilevel inverter through a boost transformer. Use of Fuzzy Logic controller helps in obtaining low THD values at the load side parameters. Simulation results in Matlab show that the performance of the new Hybrid MLI inverter using Fuzzy Logic controller is better than using a PI controller and also these Hybrid MLI inverters have the advantages like absence of the filter compared to the traditional inverters.

## I. INTRODUCTION

Multilevel converters have been continuously developed in the last years due to the necessity of increase in the power level on industry. The main reason for this development is the capability of these topologies to handle voltage in the range of kV and Megawatts with medium voltage semiconductors. Some of the conventional and emerging multilevel voltage source converter applications include flexible AC transmission system (FACTS), custom power and distributed energy system (e.g. photovoltaic, wind, micro turbine) in transmission and distribution systems, respectively [1]-[3].

Power quality is crucial to companies operating in a highly competitive business environment because it affects profitability, which

definitely is a driving force in the industry. Control of most of the loads in the industry is mainly based on semiconductor devices, which causes such loads to be more sensitive against power system disturbances such as voltage sag, voltage swell, current harmonics, interruption and phase shift. Thus, the power quality problems have gained more interest recently [4, 5].

The dynamic voltage restorer (DVR) in a distribution network is a power quality device, which can protect these plants against the bulk of these disturbances that is distribution system voltage sags and swells related to remote system faults. DVR compensates for these voltage excursions provided that the supply grid does not get disconnected entirely through breaker trips [4]. The main considerations for the control system of a DVR include: sag/swell detection and voltage reference generation for transient/steady-state control of the injected voltage. Voltage sag must be detected fast and corrected with a minimum of false operations.

Monitoring of  $V_d$  in a vector controller is the simplest type of sag detection, which will return the state of supply at any instant in time and hence, detect whether or not sag has occurred [6]. To separate the positive and negative sequence components, low pass filters (LPFs) are used after the d-q transformation in the literature. For effective removal, the cut-off frequency of the LPF must be reduced, but has the side effect of reducing the controller response time [7]. Further information about conventional sag detection method is presented in [8].

In [7], a new control method for DVR system is proposed by detecting the negative and positive sequence components using differential controllers and digital filters. In this study, the

control method in [7] is used for sag/swell detection. By using this proposed approach the detection time can be further improved with respect to conventional methods using LPF. Recently, new fuzzy logic (FL) methods have been applied to custom power devices, especially for active power filters [9–11].

The operation of DVR is similar to that of active power filters in that both compensators must respond very fast on the request from abruptly changing reference signals. In the literature, FL control of DVR based on dq synchronous reference frame (SRF) is only examined in [12]. In [12], three-phase supply voltages are transformed into d and q coordinates. The reference values for  $V_d$  and  $V_q$  are compared with these transformed values and then voltage errors are obtained. FL controllers evaluating 81 linguistic rules process these errors in [12]. Resulting outputs are re-transformed into three-phase domain and compared with a carrier signal to generate PWM inverter signals. The DVR in [12] has no sag detection function, which means that the device is always in operation and generates compensating voltage also for small voltage drops within 10% that causes high losses. In [12], the results only for balanced sags are presented.

Among the multilevel inverter topologies the Multicell group presents some advantages due to its modularity and scalability. A neutral-point-clamped pulse width modulation (PWM) inverter composed of main switching devices which operate as switches for PWM and auxiliary switching devices to clamp the output terminal potential to the neutral point potential has been developed. This inverter output contains less harmonic content as compared with that of a conventional type. In [14] a unique topology for Multilevel Multicell Inverters is proposed. This inverter is based on a new cell obtained from the mixture of the two most popular Multicell topologies, Flying Capacitor and Cascaded Multicell inverter. The new cell provides a high number of output levels, high modularity, low number of components and low losses.

In this paper, a new DVR model is proposed using Hybrid multilevel inverter. The basic information about DVR is presented in Section II. In Section III a new Multicell topology is presented, called Mixed Cascade Multicell, which not only

gather advantages of both original cells, but also reduces the amount of switching devices and the losses, because some of the semiconductors can switch at fundamental frequency. A simple modulation strategy based in the PWM Phase-Shifted modulation is also provided to exploit these advantages in the control system presented in Section IV. The experimental results are presented in Section V. Finally the conclusions are drawn in Section VI.

## II. DYNAMIC VOLTAGE RESTORER (DVR)

A Dynamic Voltage Restorer (DVR) is a series connected solid state device that injects voltage into the system in order to regulate the load side voltage. The DVR was first installed in 1996. It is normally installed in a distribution system between the supply and the critical load feeder [15]. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load [15]. There are various circuit topologies and control schemes that can be used to implement a DVR. In addition to voltage sags and swells compensation, DVR can also added other features such as: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations. The general configuration of the DVR consists of an Injection/Booster transformer, a Harmonic filter, a PWM Inverter, and a Control and storage system as shown in Fig. 1.

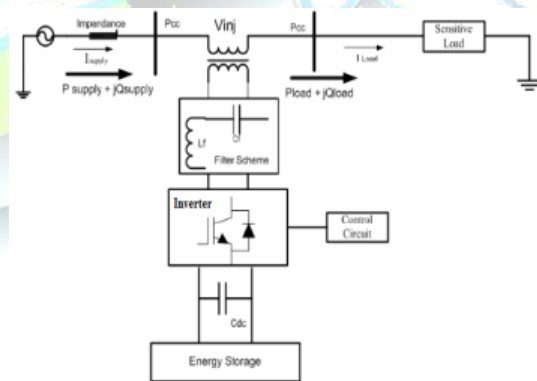


Fig. 1: DVR series connected topology

The DVR will work independent of the type of fault, with the reference acquired from the control strategy used in the system. There are many types of control strategies like PID, fuzzy logic, PLL and many other systems for the voltage disturbance

detection in the transmission line. The strategy used in this paper is PLL based magnitude comparison method. We are supposed to generate the magnitude of the phase voltage in per unit value and compare with a unit magnitude and the resultant signal is given as a reference to the inverter. Normally a inverter is used to convert the DC to AC supply in the compensation of the disturbances. In this paper we are designing a new multilevel inverter to inject the voltages in the system.

### III. HYBRID MULTILEVEL INVERTER

The three-level H-bridge inverter topology used in the CM inverter presents some advantages over two level topologies. Beyond the obvious advantage on the number of output levels, this structure allows to double the peak to peak voltage from  $v_{dc}$  to  $2v_{dc}$ , by applying to the load the voltages:  $+v_{dc}$ , 0 and  $-v_{dc}$ . This topology would be even more powerful if the dc-link voltage could be adjusted according the load requirements, turning in to a variable dc-link voltage  $V_m$ , as shown in Fig. 2.

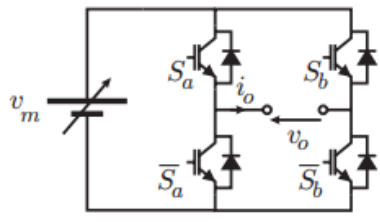


Fig. 2: Cell conceptual approach for CMI

The proposed way to achieve this adjust is by the use of a FC topology on the dc-link of each cell, as shown in Fig. 3, in this way, with a proper modulation of switches  $S_1$  to  $S_i$  (being  $i$  the number of FC sub-cells used), the values for  $v_m$  can be:

$$v_m = \begin{cases} v_{dc} \\ \dots \\ k/v_{dc} \quad , 1 \leq k < i \\ \dots \\ 0 \end{cases}$$

The proposed model is a 7-level inverter which contains 3 cells of capacitor clamped MLI connected in series with a cell of cascaded H-bridge

MLI. The capacitor clamped gives a 4 level output including 0v for a DC voltage and the output is given as input to cascaded H-bridge MLI which gives +ve and -ve output for the input which gives 7-level output for the given DC supply. The proposed Hybrid multilevel inverter (Hybrid MLI) is given the Figure 3. We can observe that the 3 cells of capacitor clamped are connected in series with the H bridge inverter. The levels of output obtained in the Hybrid MLI are  $V$ ,  $2V/3$ ,  $V/3$ , 0,  $-V/3$ ,  $-2V/3$ ,  $-V$  for a DC supply of  $V$  volts.

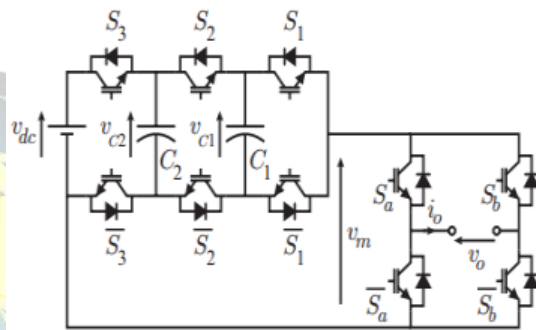


Fig. 3: Hybrid multilevel inverter

The main dc-link voltage source of value  $v_{dc}$  must be an isolated source, as on any CM converter, however due to the high number of levels that one cell can achieve, there are no need of a big number of cells connected in series, so if a multi-secondary input transformer is used, the number of secondary will be less than in a traditional CM inverter.

With a proper modulation, the number of levels that this new topology can reach is:

$$l = n(2i + 1) - 1 \quad (1)$$

Where  $n$  is the number of cells connected in series and ' $i$ ' is the number of FC sub-cells on each cell.

### IV. PROPOSED CONTROL TECHNIQUES

Control unit is the heart of the DVR where its main function is to detect the presence of voltage sags and swells in the system, calculating the required compensating voltage for the DVR and generate the reference voltage for PWM generator to trigger on the PWM inverter. To obtain the reference



signal for PWM generator two control strategies are presented here.

#### A. Using PI Controller:

PI Controller is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between output and desired set-point) and the integral of that value. The control strategy is shown in the Figure 4.

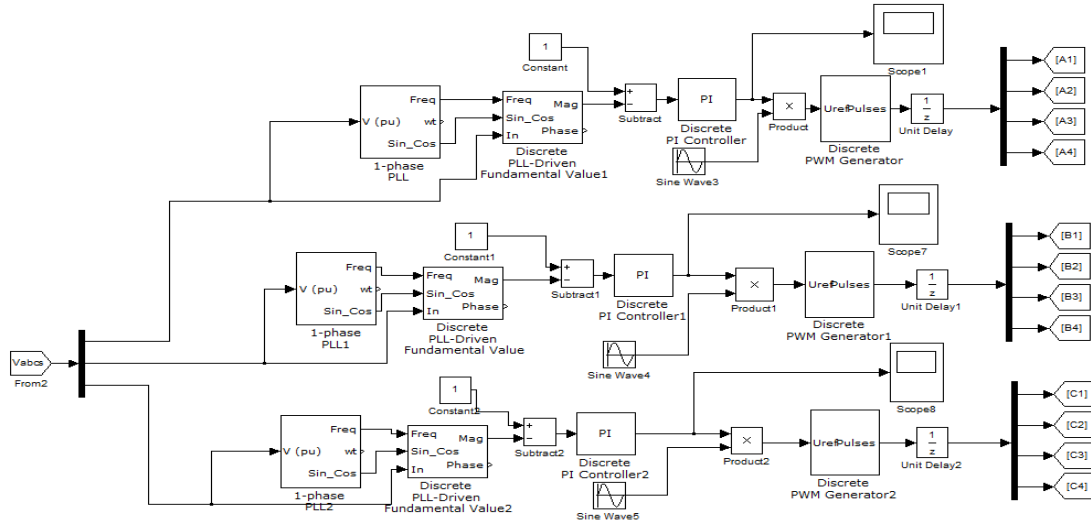


Fig. 5: Control strategy of the proposed DVR model using PI controller.

The phase voltages are taken from the three phase voltage measurement and given to the control block. The signals are processed by sending them to PLL blocks and magnitude comparison and conversion into a sine wave. These are compared with the unit function to give an error signal. The error magnitude is adjusted using a proportional integral (PI) controller. The PI controller provides a reference signal to the PWM system. This signal is given as the reference input for the PWM generation. By using the PWM generator the gating pulses required for turning on the inverter circuit is obtained and fed to the IGBTs in the inverter. This turns on the inverter when there is a fault occurred in the line. The sag or swell is detected and the reference signal is given to the Hybrid MLI and this inverter injects the required voltage to the line through a boost transformer. The voltage from each phase is then compensated using three single phase Hybrid multilevel inverters. The main circuit diagram of the DVR system using the proposed multilevel inverter is shown as in the Fig. 8.

#### B. Using Fuzzy Logic Controller:

Unlike Boolean logic, Fuzzy Logic (FL) allows states (membership values) between 0 and 1. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and big), may be represented by fuzzy sets. The general structure of an FLC is represented in Fig. 5.

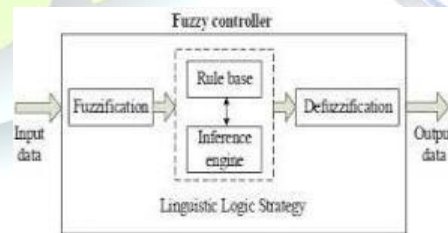


Fig. 5: Basic configuration of FL controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication

using Mamdani's, 'min' operator. v. Defuzzification using the height method.

TABLE I: FUZZY RULES

$e/\Delta e$	LP	MP	SP	S	SN	MN	LN
LP	PB	PB	PB	PM	PM	PS	Z
MP	PB	PB	PM	PM	PS	Z	NS
SP	PB	PM	PM	PS	Z	NS	NM
S	PM	PM	PS	Z	NS	NM	NM
SN	PM	PS	Z	NS	NM	NM	NB
MN	PS	Z	NS	NM	NM	NB	NB
LN	Z	NS	NM	NM	NB	NB	NB

**Fuzzification:** Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership CE(k) E(k) function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor.

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular E(k) input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph}(k) - P_{ph}(k-1)}{V_{ph}(k) - V_{ph}(k-1)} \quad (2)$$

$$CE(k) = E(k) - E(k-1) \quad (3)$$

**Inference Method:** Several composition methods such as Max-Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

**Defuzzification:** As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height“ method is used and the FLC output modifies the

control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output.

The set of FC rules are derived from

$$u = -[\alpha E + (1-\alpha)C] \quad (4)$$

Where  $\alpha$  is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable. A large value of error E indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. The control strategy using Fuzzy logic controller is demonstrated in fig. 6.

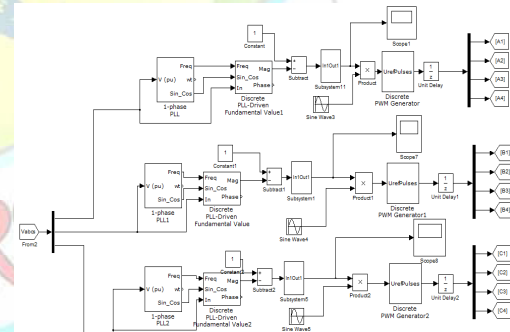


Fig. 6: Control strategy of the proposed DVR model using Fuzzy Logic controller.

The phase voltages are taken from the three phase voltage measurement and given to the control strategy block. The signals are processed by sending them to PLL blocks and magnitude comparison and conversion into a sine wave. These are compared with the unit function to give an error signal. The error magnitude is adjusted using a Fuzzy logic controller. The FL controller provides a reference signal to the PWM system. This signal is given as the reference input for the PWM generation. By using the PWM generator the gating pulses required for turning on the inverter circuit is obtained and fed to the IGBTs in the inverter. This turns on the inverter when there is a fault occurred in the line. The sag or swell is detected and the reference signal is given to

the Hybrid MLI and this inverter injects the required voltage to the line through a boost transformer. The voltage from each phase is then compensated using three single phase Hybrid multilevel inverters. [13] discussed about microwave linear beam tubes including Klystrons , reflex klystrons tubes (TWTs)and it studies microwave cross field tubes such as magnetrons and microwave measurements

The PWM circuit which is used for firing the capacitor clamped MLI is given in the Fig.7. The reference signal of one phase voltage is taken and compared with three carriers using a technique similar to sinusoidal PWM. The resultant pulses are given to the capacitor clamped MLI. These pulses switch the IGBTs giving different levels of voltages in the output.

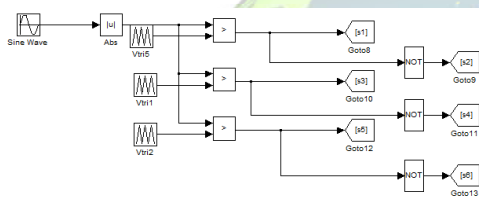


Fig. 7: PWM generation circuit for capacitor clamped MLI.

## V. SIMULATION RESULTS

The proposed DVR model is simulated and tested for all types of sags and swells in the transmission line. For this, a power system model is created with the faults being created at supply side. With the nominal voltage at the supply side being 1 p.u and the load used is of 10KW. A DC source of 5.5KV is used for the supply to inverter. The total output is boosted up using 1:2 transformers and supplied to the line. For the designed system, a LC filter is used with the specifications of inductance L at 10mH and capacitance C at 20uF.

The per unit value of the voltages are taken in the control block and the proportional controller is set for a value  $K=0.9$  for this case. The error signals are generated and this error is given as a reference to the PWM circuit. The proposed DVR circuit is shown in fig. 8.

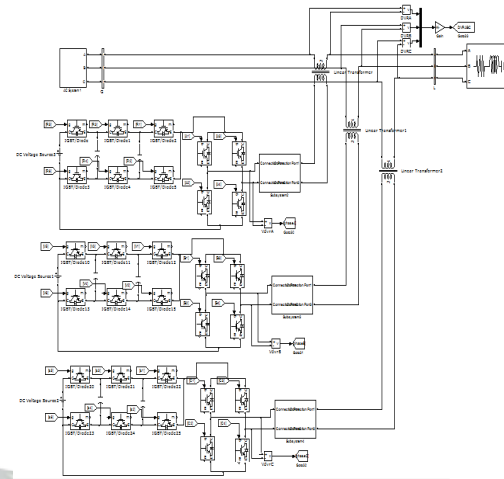
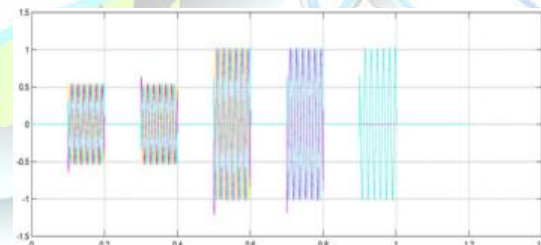


Fig. 8: Proposed DVR circuit

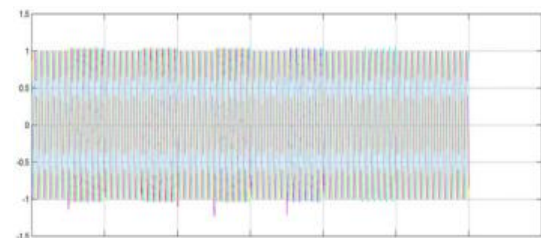
The below figure demonstrates the load voltage, supply voltage and DVR voltage, that is being injected into the circuit to compensate the faults being introduced when using PI controller.



(a)



(b)



(c)

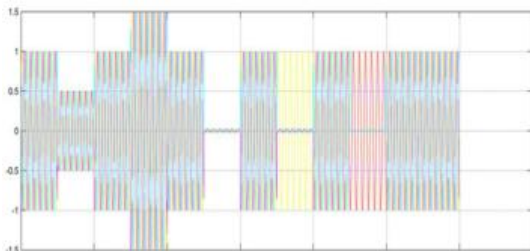
Fig. 9: When using PI controller (a) Supply voltage with different faults. (b) Compensating Voltage. (c) Load Voltage.

The Table II illustrates the time period of faults and also the amount of THD value that is present at different times when there is sag and swells present in the system with PI controller.

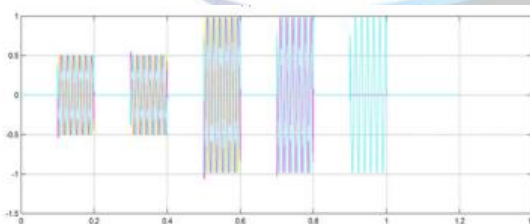
**TABLE II: THD values using PI Controller**

Voltage	Sag in 3-phase	Swell in 3-phase	Interruption	Sag in 2-phase	Sag in single phase
THD for 5 cycles in %	0.82	0.81	1.56	0.19	0.18

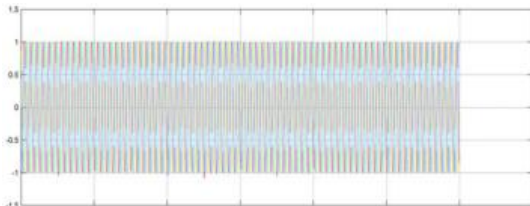
The following figure demonstrates the load voltage, supply voltage and DVR voltage that is being injected into the circuit when using Fuzzy Logic Controller.



(a)



(b)



(c)

Fig. 10: When using Fuzzy Logic controller (a) Supply voltage with different faults. (b) Compensating Voltage. (c) Load Voltage.

The Table III illustrates the time period of faults and also the amount of THD value that is present at different times when there is sag and swells present in the system with Fuzzy Logic Controller.

**TABLE III: THD values using Fuzzy Logic Controller**

Voltage	Sag in 3-phase	Swell in 3-phase	Interruption	Sag in 2-phase	Sag in single phase
THD for 5 cycles in %	0.49	0.54	0.75	0.18	0.19

**TABLE IV: Comparison of THD values using Fuzzy Logic and PI Controller**

THD during various fault conditions in %					
voltage	Sag in 3-phase	Swell in 3-phase	Interruption	Sag in 2-phase	Sag in single phase
PI controller with SPWM(for 5 cycles)	0.82	0.81	1.56	0.19	0.18
Fuzzy controller with SPWM(for 5 cycles)	0.49	0.54	0.75	0.18	0.19

The above tabular columns clearly shows that by using Fuzzy logic controller the THD values are completely lower than PI controller and are in the IEEE standard region. Hence, FLC is superior than PI controller.

## VI. CONCLUSIONS

The outline of a new DVR topology utilizing the Hybrid multilevel inverter (Hybrid MLI) rather than the conventional inverters or the customary multilevel inverters is successfully finished and the results demonstrate that the compensation of the DVR is working productively.





The benefit of utilizing the Hybrid MLI in the DVR is that it has a decreased number of switches when contrasted with the customary multilevel inverters and in the meantime, it diminishes the necessity of the size of capacitor as we can get the close sinusoidal voltages not at all like the conventional inverters which deliver the rectangular voltage outputs with harmonics. A comparative analysis of the two control strategies proposed in the above paper shows that the use of Fuzzy Logic controller produced low THD values rather than using a PI controller. Also the compensated voltages are well in the region of the required THD level in the fuzzy logic controller strategy. This ensures that there is a continuous supply of power to load even though there are different types of faults in the system supply.

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