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Fuzzy Logic Controller Using dq Based Detection and Strategy for Compensating Voltage Sag

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Abstract: **Improving the power quality in the distributed network is one of the major drawback in the present era. Major percentage of power quality problem occurred due to voltage sags. Voltage sag decreases the rms voltage, reduces power production, decreases output voltage and reduces reliability of the electrical and electronics equipment. To overcome this problem, there are several devices such as Distribution Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR) Unified Power Quality Conditioner (UPQC) are used. The proposed compensation method uses DVR, which is the most efficient and cost effective device and it has the fast dynamic response against disturbance in power distribution networks. The role of DVR depends on the efficiency of the control technique involved in switching circuit of the inverter. The proposed control scheme uses PI and Fuzzy Logic controller for compensating the voltage sag and both the controllers are compared to differentiate the performance based upon the THD analysis. Microgrid is used as the energy storage device for given to the supply for three phase inverter. The performance of both the controller are validated with simulation result using Matlab/Simulink.**

Index Terms- **Dynamic Voltage Restorer (DVR), PI and Fuzzy Logic Controller, Voltage sag.**

I.INTRODUCTION

In Industrial applications power quality leads to major problem due to introduction of the sophisticated devices such as Computers, Programmable Logic Controllers (PLC's), variable speed drives. Particularly, industrial automation takes a wider role in power quality problem such as voltage sags, swells, interruptions, flicker and harmonic distortions. According to IEEE standard voltage sag is defined as decrease in rms voltage between 0.1 pu to 0.9 pu at the power frequency for duration from 0.5 cycles to 1 minuite. Generally voltage sags are caused by abrupt increase in loads, short circuit or faults, motors starting and increase in source impedance.

Based on the time duration of disturbances, sag is divided into three categories are, momentary, instantaneous and temporary sag. Time varies from 0.5 cycles to 30 cycles called the Instantaneous sag, If it is varies from 30cycles to 3 seconds Called momentary sag. Suppose the variation occurs between 3 seconds to 1 minute called temporary sag. There are several custom power devices are used for voltage sag compensation such as DSTATCOM, DVR, UPQC. Also the other devices like constant voltage transformer, Ferroresonant transformer, Magnetic synthesizers, Uninterrupted Power Supply (UPS), super conducting Magnetic Energy storage devices can also provide the solution for the mitigation of voltage sag [1]. DVR is more efficient and cost effective custom power device and it is connected in series with the load. Various the Distributed static compensator connected in parallel with the sensitive load or distribution feeder. The next chapter explains the brief discussion about Dynamic Voltage Restorer.

II. DYNAMIC VOLTAGE RESTORER

The primary function of the DVR is to inject the compensation voltage to the sensitive load [2]. DVR can provide the better results when compared with the other compensation device. The DVR responses quickly within the fraction of seconds when it is installed between supply and the critical load side [3]. After the installation of the DVR it ready

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to perform against voltage sag. DVR can operated by two modes are injection mode and standby mode. During the injection mode the DVR provide the injecting voltage to the sensitive load. During the standby mode of operation, the DVR takes no action for the compensation because of the system normal condition [4]. DVR consist the major components of Voltage Injection Transformer or Boost transformer, Energy storage device, Voltage source Inverter and Filter.

A.Voltage Injection Transformer:

The transformer connects DVR to the distribution network through high voltage windings and it couples the Voltage source converter to the supply voltage line for the compensation.

B. Voltage Source Inverter:

VSI can generate the sinusoidal voltage at any magnitude, frequency and phase angle. The three phase inverter taken the supply from the energy storage device and it consist of the power electronic switches. IGBT/MOSFET switches can preferred for better results.

C. Filter:

The converted AC voltage containing harmonics due to the switching action of the IGBT inverter. The harmonic filter can eliminate these high frequency switching harmonic content present in the inverter output.

D. Dc Energy Storage Device:

During the compensation of DVR, DC storage provides the real power requirement to the system. Various technology was implemented for the storage with fast dynamic response. Using the battery as energy storage device having the limited suitability for the Dynamic Voltage Restorer applications.

E. Control System:

Various control method can be used for the control of DVR. The controller maintains the necessary voltage provide for producing the compensating voltage.

III.DESIGN OF THE SYSTEM

A. Block Diagram:

Voltage sag is normally produced due to sudden increase in load or using programmable voltage source. In proposed method, voltage sag is produced due to the connection of load 2 for certain period. Overall block diagram is shown in figure.1.

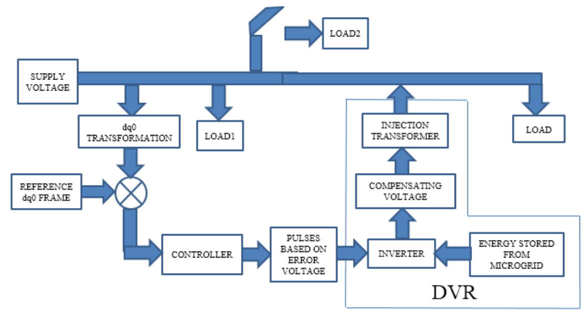

Figure. 1. Block Diagram

Load 1 is connected to the system all the time. Load 2 will be connected when switch is closed. During that instant sag is produced. Supply voltage is converted into dq0 frame using park transformation and it is compared with the reference dq0 (Vd=1;Vq=0;V0=0) frame to obtain error voltage. The controller produces the accurate gate pulses based upon the input. SPWM technique is used to generate pulses to the switches of three phase inverter. Inverter compensates the voltage sag based upon the error voltage. Microgrid compensates for the error voltage. Finally this compensating voltage is injected to the line through the injection transformer. The sensitive load connected is maintained with constant voltage even during the occurance of sag.

B.Design of Phase Locked Loop(PLL):

PLL shown in figure 2 is the most common method is used for synchronizes the frequency as well as the phase angle.

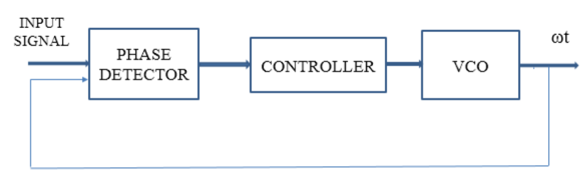

Figure. 2. PLL Design

There are several methods is used for designing the PLL [5]. PLL consist of Phase detector, controller and Voltage controlled oscillator. The Oscillator generates the periodic signal. Phase detector compares the phase of that signal with the input periodic signal and it adjust the oscillator to keep the phases are matched using the feedback loop with tuning the controller [6].

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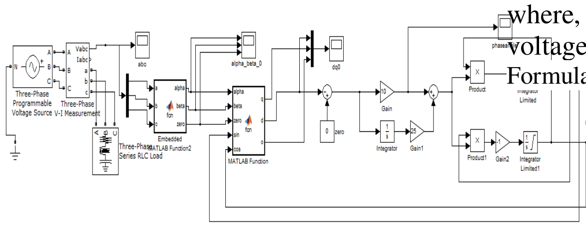

Figure. 3. Simulink model of PLL

PLL design is shown in the figure 3 as simulink model. The output of the controller generate the phase angle. The sin and cos angle produces for the transformation using the voltage controlled oscillator based upon the phase angle, which act as the feedbackloop of the dq0 transformation process. In the figure 4 the PLL output which shows phases of frequency get locked at the 314 rad/sec(50Hz).

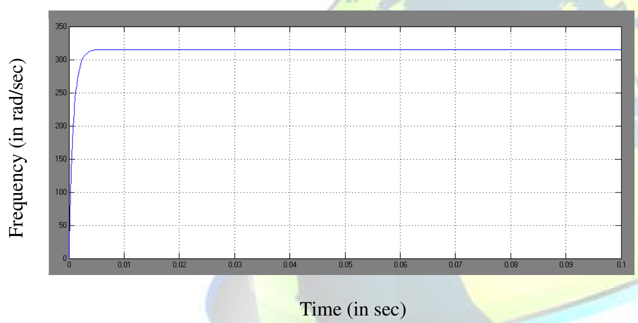

Figure. 4. Simulink result of PLL

C.dq0Transformation:

Direct quadrature zero(dq0) transformation is used for the projection of three phase quatities into a rotating DC two axis reference frame(Parks transformation). Before converting the rotating two axis frame, it is necessary to convert as the stationary reference frame called clarke'stransformation. Formulae for transformation as given below,
For converting abc to αβ0,

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

where, Va,Vb,Vc are the three phases of the supply voltage.
Formula for transforming αβ0-dq0,

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} \cos\delta_p & -\sin\delta_p \\ \sin\delta_p & \cos\delta_p \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (2)$$

where, Vd=Direct axis and Vq=Quadrature axis. Using the the above formula abc-dq0 transformation is performed.

Dq0 frame of the supply voltage after the connection of load 2 is as given below in the figure 5,

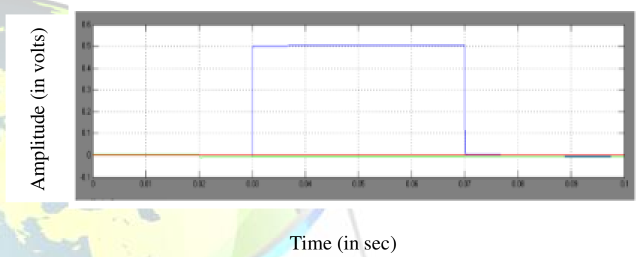

Figure. 5. Simulink result of Error Voltage

In this figure the depth of the sag is increased at the particular period 0.03 to 0.07 due to the connection of second non sensitive load.

IV.CONTROLLER DESIGN

The design and accuracy of the appropriate controller decided the performance of the gate pulse is given to input of the controller. In the proposed method both PI and Fuzzy logic controller is designed for producing the accurate error voltage for the gate pulses generation for the switches of three phase inverter.

A.PI Controller Design:

PI controller is designed based upon proportional and integral term. Variables of the designed controller are obtained by varying the values of controller Kp and Ki. The block diagram of PI controller is shown in figure 6.

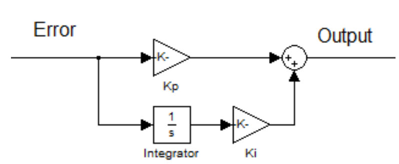

Figure. 6. PI Controller Design

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Here, Kp-Proportional constant

$$P_{out} = K_p e(\text{t}) \quad (3)$$

Ki-Integral constant $I_{out} = K_i \int_0^t e(\tau)d\tau \quad (4)$

The proportional term produces the output value which is proportional to the current error value given to the input of the controller. It can be adjusted by multiplying the error by constant value of Kp. If the Kp value is high, the output become unstable also Kp value is too small which responses slowly during the disturbance occurred on the system. The proportional term should be tuned within the particular limit [7]. Ki value is tuned based on the magnitude and duration of error signal. Finally the accumulation output is multiplied Ki value and added with the controller to achieve the appropriate output shown in the figure 11.

B.Design of Fuzzy Logic Controller:

Comparing with the other controller design, the fuzzy logic controller design is very robust technique to implement easily [8] and it has the options of using the multiple input and output and also it can be easily modified the input and output by simply changing the rules are framed using the membership functions [9]. The contruction of fuzzy logic controller having the following process Fuzzification, Fuzzy Inference mechnism and Defuzzification process. The fuzzification is the process conversion of crisp input values to the fuzzy logic values. Fuzzy inference is the decission making process, the ouput is produced based upon framing the rules using the membreship function. In the defuzzification process, the fuzzy sets in linguistic term transformed into the real control signal. Before going to the controller input, the error and the change of the error should be calculated which are the two inputs of the controller. The error rate is defined by the rate of change of error. The error and chage in error as following in the equations,

Error=V_{ref} - V_{supply}

Change in error=error(n)-error(n-1)

After the formation of errors the membership functions are defined for fuzzifiction process. In the membrship function formation each set of data are devided into ranges. The input linguistic variables such as Low negative (LN), Medium negative (MN), Small negative (SN), Small(S), Small positive (SP), Medium positive (MP), Low positive (LP) are defined by the membership functions. Membership function plot of the error is as shown in the figure 7. Similarly the derivative error(change in error) plot of membership function as shown in the figure 8,in which same linguistic variables are used for the plotting only the data ranges are varied depending upon the error input to the controller. Based upon this input data ranges the rules are framed in the fuzzy inference process.

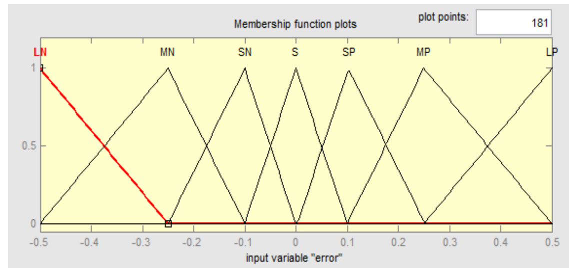

Figure. 7. Plot of Error in FIS Editor

The first and last linguistic variables are framed by using the trapezoidal membership function, and remaining variables are framed by the triangular membership function for both error and derivative error. Similarly the output variables are realized such as Negative big (NB), Negative medium (NM), Negative small (NZ), Zero (Z), Positive small (PS), Positive medium (PM),Positive Big (PB) and its corresponding membership functions plot as shown in the figure 9.

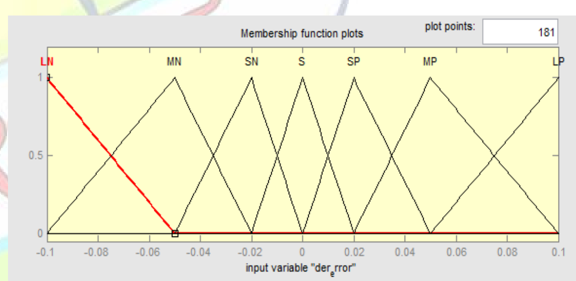

Figure. 8. Plot of Change in Error in FIS Editor

The Mamdani inference system is realized for framing the rules because of its simplicity to framing the rules by using the “and” function. The simple if-then rules are framed by as follows,

‘If the value of error(e) is MP and error rate(Δe) value is MN then output is Z’

Based upon this formation of 49 rules are framed depending upon the combination of 7x7 error and derivative error inputs. The fuzzy decision table as given in the following table 1,

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TABLE 1.Fuzzy Decision Table

e/Δe	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	ZS	NM	NM	NB	NB	NB

By evaluating all the rules based upon the fuzzy sets and its logic operations, the output is produced as control signals is termed as defuzzification process. FLC produced the accurate error value as shown in the figure 11 which shows at the particular sag affected portion the amplitude of the waveform crosses its subtracted value of the dq0 frame and reference dq0 frame.

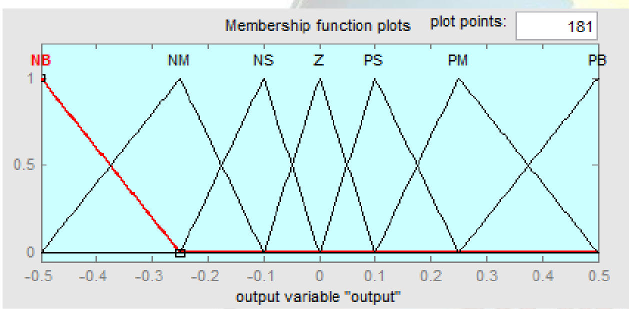

Figure. 9. Plot of output in FIS Editor

V.COMPENSATION

A.Inverter and Filter Designing:

The output of the controller is used to generate gating pulses. Using the sine PWM technique, the gate pulses are generated for giving the switching pulses of the three phase inverter. By comparing a sinusoidal reference signal with a triangular carrier wave of high frequency the gating signals are generated. The same gating signals can be generated using unidirectional triangular carrier-wave. The output of the controller produces the error voltage which is known as the reference sine wave signal. This reference signal compared with the carrier wave to obtaining the pulses for the inverter. By varying the modulation index, the RMS output voltage can be varied [10]. Using the SPWM technique the gate pulses are generated as shown in the figure 10. Only the occurrence of sag portion the pulses are produced which gives the proper switching pulses to the inverter.

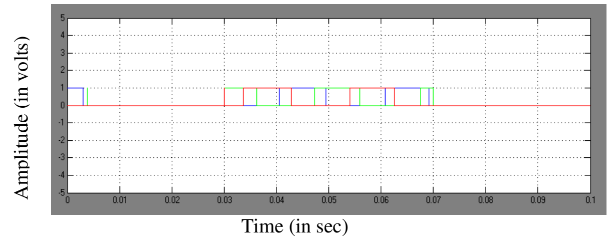

Figure. 10. Gating pulse to the Inverter

The IGBT switches are used for three phase inverter and the appropriate designing of the inductor and capacitor value improves the performance of the filter which reduces the harmonic content present in the inverter output to obtaining the pure sine waveform. The output of the filter is known as the compensating voltage is injected to the line through the injection transformer.

VI.SIMULATION RESULTS

A.PI CONTROLLER:

For the voltage sag compensation both PI and Fuzzy Logic Controller(FLC) are designed to obtain the accurate results. First the PI controller simulation is designed,the proper results making by the proper tuning of proportional and Integral constants (Kp and Ki). The constants Kp and Ki values are 0.1 and 0.2 respectively. The voltage sag compensation simulation using PI controler as shown in the figure 10.

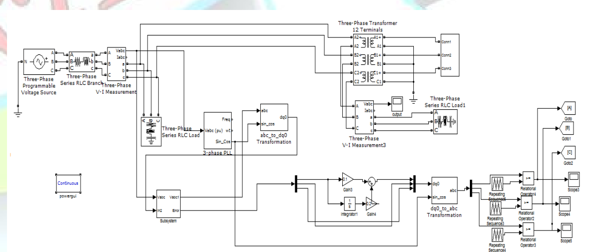

Figure. 10. Simulink model for Sag Compensation Using PI Controller

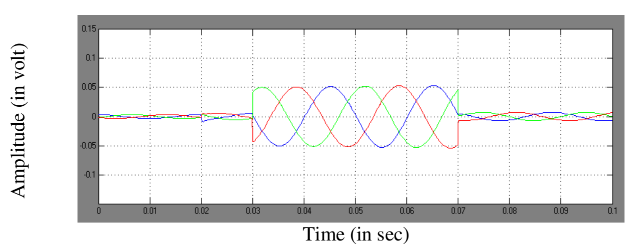

Figure. 11. Output of PI Controller

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Vol. 3, Special Issue 2, March 2016

The output shown in the figure 14, which shows the compensation is done at the paticular sag affected period of 0.03 to 0.07.and it's corresponding THD analysis also shown in the figure 15.

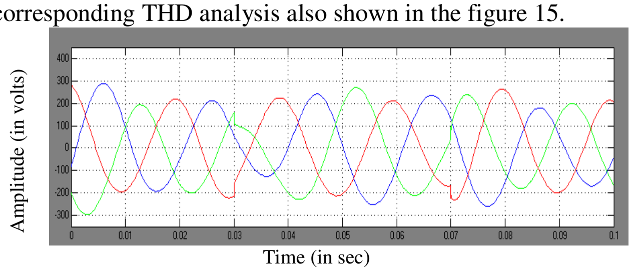

Figure. 12. Sag Compensation Using PI Controller

THD analysis shows the eliminating of third and fifth harmonics totally and its corresponding value is 3.86%.

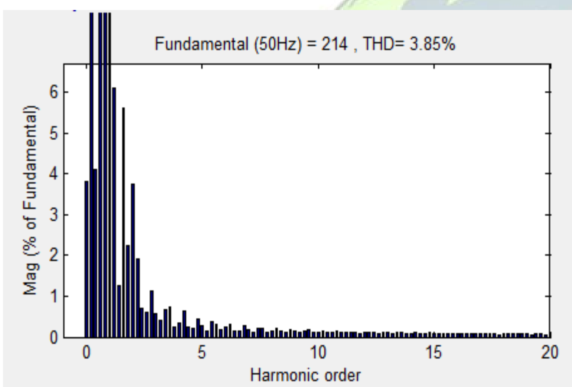

Figure. 13. THD Analysis Using PI Controller

The THD analysis differentiate the performance of both the controller design. Similarly the design using Fuzzy logic controller (FLC) as shown in the figure 16 and it output showed in the figure 17.

B.FUZZY CONTROLLER:

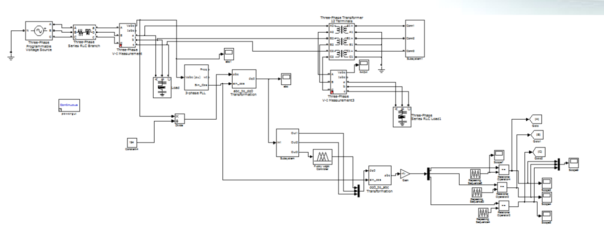

Figure. 14. Simulink model for Sag Compensation Using FLC

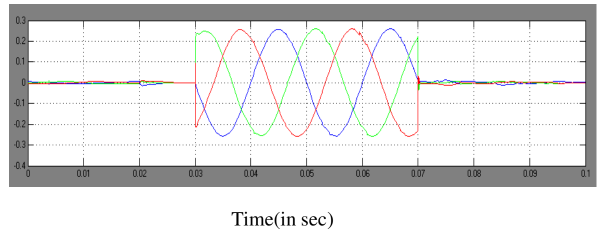

Figure. 15. Output of Fuzzy Logic Controller

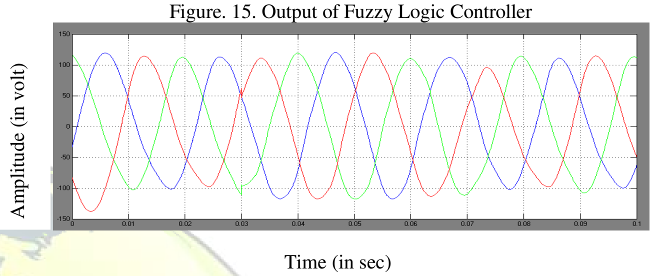

Figure. 16. Sag Compensation Using Fuzzy Logic Controller

The THD analysis for using the Fuzzy controlled simulation having the THD value is 2.66% and its value is lower than the value of using of PI controller.

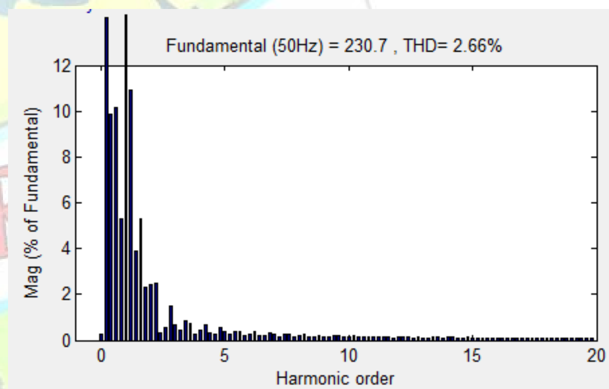

Figure. 17. THD Analysis Using Fuzzy Logic Controller

VII.CONCLUSION

DVR is effective custom power device used for the voltage sag compensation. The appropriate controller decided the performance of the compensation.

The THD analysis shown in the table 2 differentiates the performance based analysis of the controller designing. THD values shows that FLC perform better than PI controller.

TABLE 2.Comparision between PI and FLC

Amplitude (in volt)

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VOLTAGE	THD USING FLC	THD USING PI
Phase A	2.66	3.85
Phase B	0.89	2.84
Phase C	2.43	2.81

Proposed work uses a PI controller and Fuzzy Logic Controller, which responses quickly which results in a good dynamic performance. Comparing with the PI controller, FLC has the option of using multiple input, output sources and give the better result**.** It can be easily modify by simply changing the rules of membership functions.

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