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Comparison the Performance of the Dynamic Voltage Restorer Based on PI, Fuzzy Logic, and Fuzzy Neural Controller

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Abstract: The Dynamic Voltage Restorer (DVR) is one of the most efficient and effective custom power devices in protecting the sensitive equipment against voltage sag and voltage harmonics due to; lower cost, smaller size and dynamic response. The inverter is the core of the DVR and it directly affects the performance of the DVR, incorrect injection or delay in the process would be dangerous to sensitive loads. The major functions of the DVR controller are, detection of voltage disturbances events in the system, calculation of the compensating voltage and generation the reference signal for the PWM to trigger the voltage source inverter. PI controller and fuzzy logic controller has been compared with the proposed fuzzy neural optimized fuzzy logic controller in correcting the sag problems and mitigating the harmonics distortion with linear and non-linear loads. Fuzzy Neural optimized Fuzzy Logic controller is the most efficient in improving the performance of the Dynamic Voltage Restorer in compensating any kind of voltage variations and reducing the voltage Total Harmonic Distortion (THD) by enhancing an injection capability of the DVR which is highly influenced by a control algorithm employed. The system is simulated in MATLAB and results confirm the validity and feasibility.

Keywords: Dynamic Voltage Restorer, Fuzzy Logic Controller, Fuzzy Neural Optimized Fuzzy Logic Controller, Sag Correction and Harmonics Mitigation

1. Introduction

Power quality measures the fitness of electric power transmitted from the utilities to the industrial, commercial, and domestic consumers [1]. Recently a large attention has been focused on the power quality domain in power system network due to increase in the number of sensitive equipment, disturbances introduced by the renewable energy sources and nonlinear loads. Voltage distortion caused by harmonics and voltage sags are considered to be the most severe disturbances affecting power quality in a power system, as these affect both the utilities and the consumers. Voltage sag is a sudden decrease in the r.m.s voltage that its value becomes between 10% and 90% from a nominal value, and keeps from 0.5 cycle to several seconds. Sag with duration of less than 0.5 cycle are regarded as transient. Voltage sag is either symmetrical or unsymmetrical, three phase fault produces symmetrical sag while double line to ground fault and single line to ground fault produce unsymmetrical sag. Harmonics are spectral components with frequencies equal to multiplies of the base frequency the main contribution of the harmonics voltage distortion is the nonlinear loads. Harmonics have a number of undesirable effects on the distribution system and power system equipment such as motors and transformers, it causes overloading, overheating and additional losses [2]. To protect equipment from power problems several types of power improvement devices have been developed, but the efficient and effective devices are custom power devices which are able to provide customized solutions to power quality variations. The notion of custom power devices is using power electronic controllers in the power systems to supply high quality power and reliable that is needed for the sensitive equipment. The custom power devices can be classified into two categories: Network Reconfiguring type and Compensating type [3]. Network Reconfiguring type protects the sensitive loads by; *Avoid

interruption, voltage sag, and voltage swell by connecting healthy feeder, *disconnects the fault circuits, *limits fault current by quickly inserting a series inductance in the fault path. The compensating type is used for load balancing, active filtering, power factor correction, and voltage regulation. Compensating type are Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC), and Distributed Static Compensator (DSTATCOM). Dynamic Voltage Restorer (DVR) is a Series device, it is efficient and effective to compensate large voltage variation by voltage injection, it is used for mitigating the power disturbances [4]. Distributed Static Compensator (DSTATCOM) is a Shunt device, it is efficient to compensate a small voltage variation by current injection which is very difficult to achieve because the supply impedance is low and the injected current has to be high to increase the load voltage, DSTATCOM is larger in size and costs more compared with the DVR [5]. Unified Power Quality Conditioner (UPQC) is a combination of the series (DVR) and the shunt (DSTATCOM) connected together by a common DC link capacitor, combining the series/shunt controllers improve the performance but with higher costs [6]. Hence, the Dynamic Voltage Restorer is considered as a power efficient device compared to other custom power devices. The first DVR in the world was installed in the USA in the year 1996, it was engineered by Electrical Power Research Institute, this DVR was installed at the medium voltage level of 12kV and rated for 2MVA. Artificial intelligent controller which have an adaptive characteristics such as fuzzy neural optimized fuzzy logic controller prove that it is effective and powerful in eliminating the power quality problems. The performance of the DVR based on PI controller, fuzzy logic controller and fuzzy neural optimized fuzzy Logic controller in correcting the voltage sag and mitigating the harmonics distortion with linear and non-linear loads are presented in this search.

2. The Control System of the DVR

Control strategy of DVR plays an important role in its performance. The incorrect injection or the delay in the process would be dangerous to the sensitive loads [7]. The major functions of the DVR controller are, detection of voltage disturbances events in the system, calculation of the compensating voltage and generation the reference signal for the PWM to trigger the voltage source inverter. The controller of the DVR in this search consists of several functional blocks as shown in Figure 3
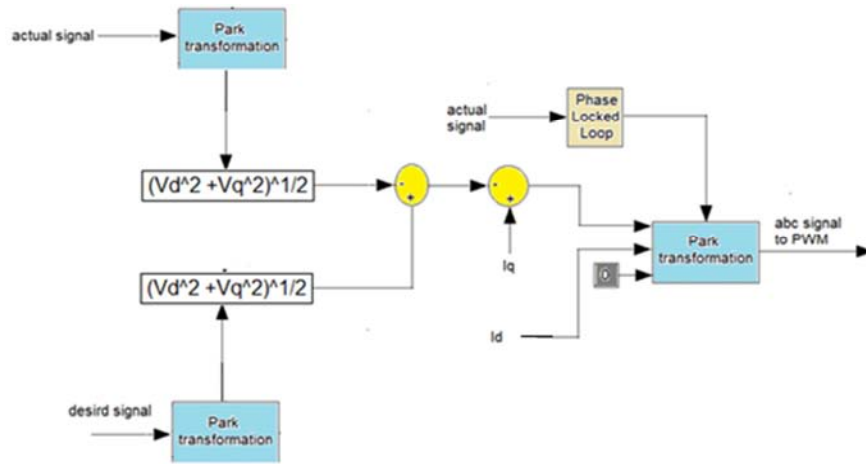

Figure 1. The control system of the DVR.

These functional blocks are:

i. The Phase Locked Loop (PLL) which is shown in Figure 4. It is synchronized to the fundamental of the transformer primary voltages
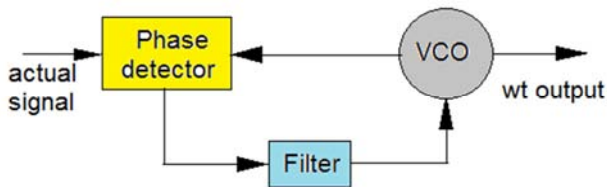

Figure 2. The Phase Locked Loop.

ii. Park transformation transforms the three AC quantities (V_a, V_b, V_c) to two DC quantities (V_d, V_q) to simplify the calculations, control and analysis [8].

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

iii. Two measurement systems, V_{meas} and I_{meas} blockes.

$$V_{meas} = \sqrt{V_d^2 + V_q^2}$$

$$I_{meas} = \sqrt{I_d^2 + I_q^2}$$

iv. Inner loop for regulating the current. This loop consists of one controller which controls the q-axis current. The

controller output is V_q voltage. The V_d and V_q voltages are converted into phase voltages V_a, V_b, V_c which are used to synthesize the PWM voltages. The I_q reference comes from the outer voltage regulation loop

v. An outer voltage regulation loop consists of one controller to regulate the voltage

3. Dynamic Voltage Restorer Based on PI Controller

It is one of the earliest techniques that is used in industrial sector because of its robust performance and easy implementation [9]. Figure 5 shows the block diagram of PI controller
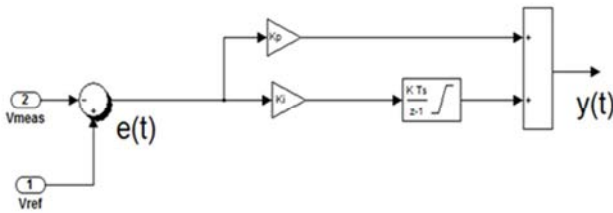

Figure 3. *The block diagram of the PI controller.*

The general equation of the PI controller is given by

$$Y(t) = Kp * e(t) + Ki \int_0^t e(t)dt$$

The performance of the PI controller depends on the values of K_p and K_i. K_p to improve the rise time and K_i to eliminate the steady – state error [10].

From the equation above the relation between input e (t) and output y (t) is linear, so it is called linear controller. In this work the K_p and the K_i for the first controller is 40 and 1540 respectivity while for the second controller K_p is 25 and K_i is 2600.

4. Dynamic Voltage Restorer Based on Fuzzy Logic Controller

The using of FL controller will reduce the tracking error and transient overshoot of PWM [11]. The performance of the FL controller depends on the knowledge and expertise of the designer. FL controller is preferred over the PI controller because of the accurate mathematical formulations model is not required and its robustness to system variation during operation [12]. FL controller is one of the most successful operations of fuzzy set theory. It uses the linguistic variables rather than numerical variables. FL provides a simple way based on vague, ambiguous, noisy, imprecise, or missing input information. This controller based on the capability to understand the system behavior and it relies on quality control rules. In this paper FL controller is used for controlling the voltage injection of the DVR

5. The Input and Output Membership Function and the Set of the Linguistic Rules for the Fuzzy Logic Controllers

The input and output membership function for the first controller is shown in figures 4, 5, 6. Table 1 shows the 20 linguistic rules for the first controller
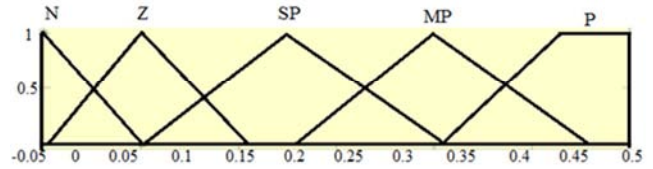

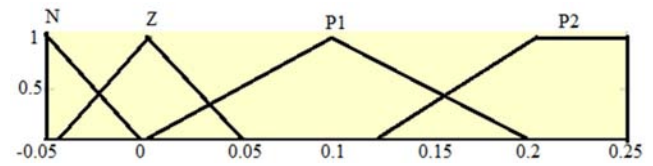**Figure 4.** *The input membership function of error for the first controller.*

Figure 5. *The input membership function of the change of error for the first controller.*
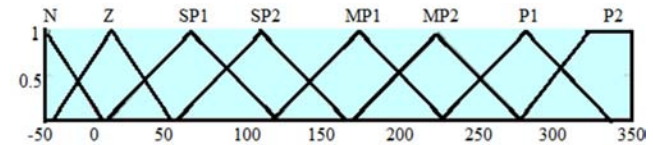

Figure 6. *The output membership function for the first controller.*

Table 1. *The rules set for the first controller.*

Δe / e	N	Z	P1	P2
N	N	N	N	N
Z	Z	Z	Z	Z
SP	SP1	SP1	SP2	SP2
MP	MP1	MP1	MP2	MP2
P	P1	P1	P2	P2

The input and output membership function for the second controller are shown in figures 7, 8 and the rules set which is 9 rules for the second controller is demonstrated in table 2.
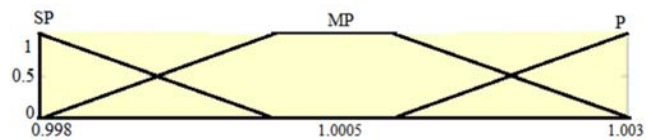

Figure 7. *The input membership function of the error and change of error for the second controller.*
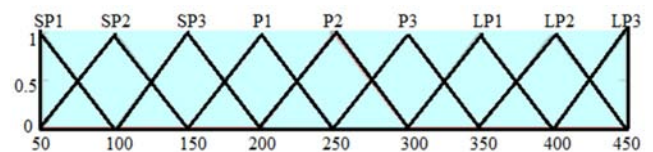

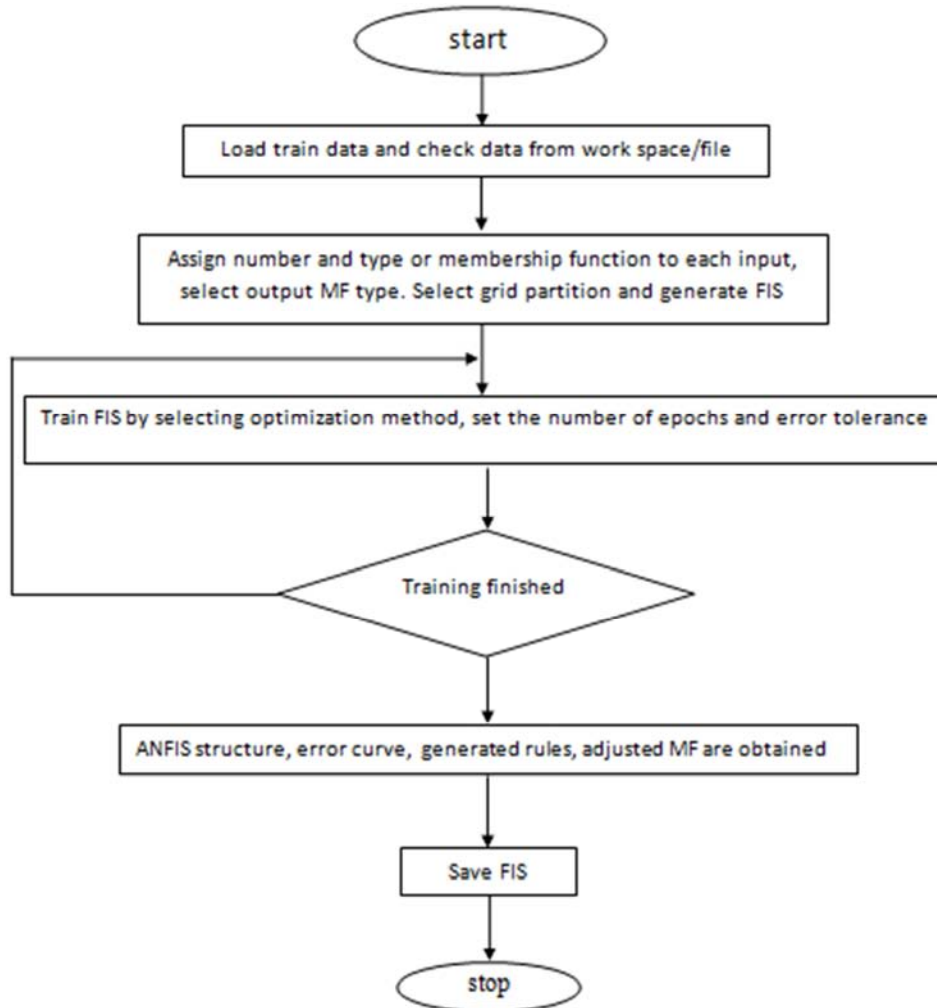**Figure 8.** *The output membership function for the second controller.*

Table 2. *The rules set for the second controller.*

Δe e	SP	MP	P
SP	SP1	SP2	SP3
MP	MP1	MP2	MP3
P	LP1	LP2	LP3

6. Fuzzy Neural Based Dynamic Volage Restorer

In general, there are no standard method for transforming human knowledge to the rules base of the fuzzy inference system. The selection of the type, size and parameters of the membership functions has been achieved by trial and error, therefore there is a real need to an effective method of tuning the input and output membership functions and reducing the rules to the minimum rules. Fuzzy Neural Optimized Fuzzy Logic Controller (ANFIS) is a combined between the fuzzy qualitative approach and the adaptive learning abilities of the

neural network [13], where this system can be trained without a significant amount of expert knowledge that usually required for the standard FL. Jang in 1993 introduced Adaptive Neuro Fuzzy Inference System and mentioned that the (ANFIS) architecture can be utilized to model non-linear functions in control systems [14]. ANFIS uses the Sugeno-type fuzzy inference system. ANFIS requires for training a set of input and output data, it can choose the parameters of the fuzzy inference system adaptively from the training data. It produces a set of membership functions to map the input data to output. The implementation of the ANFIS uses for tuning input and output the back propagation method and it uses for learning the hybrid algorithm [15]. This sugeno fuzzy model has two inputs and one output and the ANFIS used here contains 9 rules with 3 membership functions for error and change of error for each controller. 10000 training data are used for the training of ANFIS and 1000 checking data are used for verifying the identified ANFIS. Figure 9 demonstrated the flow chart of the ANFIS algorithm and figure 10 shows the structure of the ANFIS.

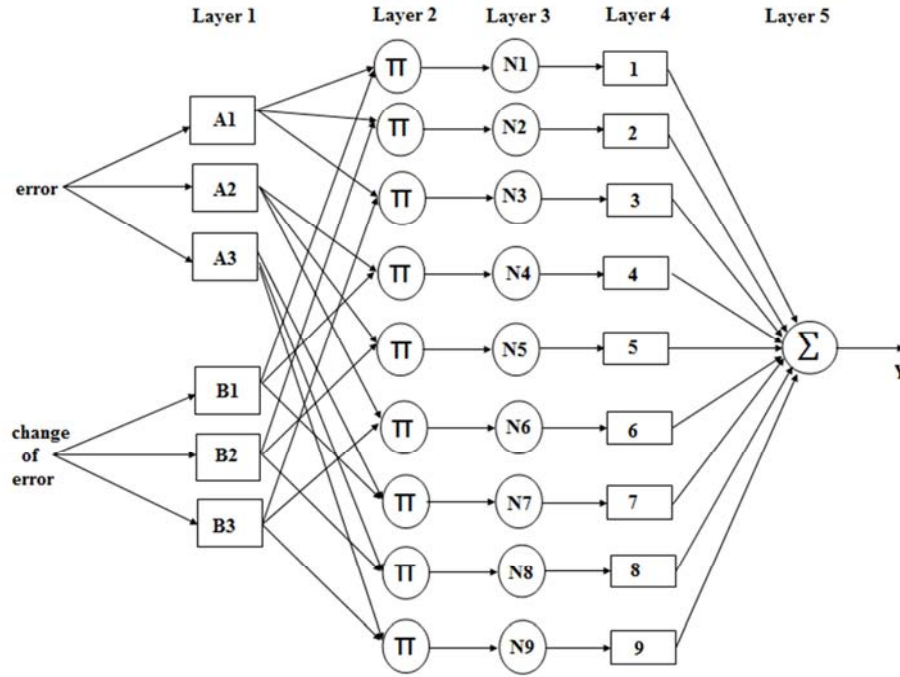**Figure 9.** *The flow chart of the ANFIS [12].*

Figure 10. *The structure of the ANFIS.*

It is depicted from figure 10 that the ANFIS has five layers. The basic principle of these layers are as following [16]:

Layer 1: It calls the fuzzification layer and it has six nodes each node is adaptive to an output. If the membership functions in this layer is a triangle function, then the output from each node in this layer is obtained from the equations of the triangle function

$$A(x) = \begin{cases} \alpha\left(\frac{x-a}{c-a}\right) \ if \ a \leq x \leq c \\ \alpha\left(\frac{x-b}{c-b}\right) \ if \ c \leq x \leq b \\ 0 \ otherwise \end{cases}$$

Where the a, b, c is the parameter of the triangle function and α is the cut set. The parameters a, b, c in this layer is known as premise parameter. This layer calculates the grade of membership for each input ($\mu_{Ai}(x)$)

Layer 2: It determines the firing strength for each rule. It has nine nodes (equal to the number of rules). This layer is multiplying the incoming signals from the previous layer. The results is forward to the next layer.

Output from second layer for each node is:

$$O^2i = Wi = \mu_{Ai}(x) * \mu_{Bi}(y)$$

Layer 3: It calculates the normalized firing strength for each rule and the output from each node in this layer is equal to the ratio between the firing strength of this node and the summation of all nodes's firing strength

Output from each node in third layer is:

$$O^3i = Wni = \frac{Wi}{\sum_{j=1}^{j=9} Wj}$$

Layer 4: It determines the output for each rule. Each node in this layer is an adaptive to an output. The output from each node in this layer is obtained by multiplying between the incoming signal from third layer and the set of parameters.

Output from each node in the forth layer is: $O^4i = Wni*fi = Wni*(p_ix + s_iy + t_i)$ where (p, s and t) are the parameters for each node and it is called the consequent parameter.

Layer 5: This layer determines the output o/p by summing the all incoming signals from the forth layer

$$O/P = \sum_{i=1}^{i=9} Wni * fi$$

7. The Parameters of the Electrical Power System with Linear and Nonlinear Loads

The parameters of the electrical power system with linear and nonlinear loads are demonstrated in table 3.

Table 3. *The parameters of the electrical power system with linear and non-linear loads.*

The parameters of the electrical power system	The values of the parameters
The voltage source	11kV$_{r.m.s}$, 50Hz
The transformer of the linear load	11000/400 V$_{r.m.s}$, 1MVA
The transformer of the nonlinear load	11000/400 V$_{r.m.s}$, 350KVA
The DC source	17500v
The active filter	100μF, 300mH
The injection transformer	5000/11000V$_{r.m.s}$, 3MVA
The electrical linear load	1MW, 50Hz, 400v
The electrical non-linear load	350KW, 50Hz, 400v
The fault resistance	0.001 ohm
The ground resistance	0.001 ohm
Double tuned filter	Tuned at 5th and 7th harmonics, Q=1.25MVAR

8. Modeling and Simulation

The control system of the DVR based on Fuzzy Neural

Controller uses the Sugeno-type fuzzy inference system is shown in Figure 11.

Figure 11. Modeling and simulation of The control system of the Fuzzy Neural based DVR.

The function of the DVR based on PI controller, Fuzzy Logic controller and Fuzzy Neural controller has been invistigated with linear and nonlinear loads

1-With linear loads

Figure 12 demonstrates the electrical power system with

linear loads. DVR is connected at the second feeder to restore the load voltage to its nominal value. The efficiency and capability of the PI controller, fuzzy logic controller, and fuzzy neural controller have been demonstrated by the simulation results.

Figure 12. Modeling and Simulation the power system with DVR with linear loads.

50% sag is simulated for a period of 0.15s from 0.8s to 0.95s as depicted in figure 13. PI controller and Fuzzy Neural controller perform a better error compensation compared

with the compensation by the Fuzzy Logic controller which contains high harmonics as shown in figures 14, 15 and determined in table 4.

Figure 13. *The load voltage without DVR.*

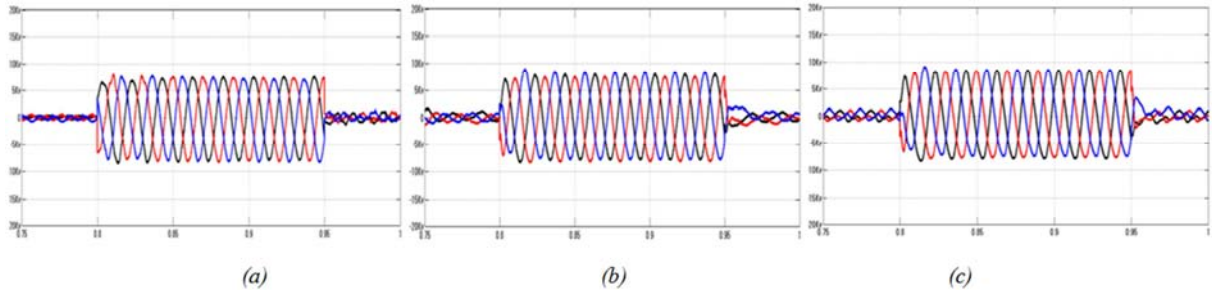|		
(a)	*(b)*	*(c)*

Figure 14. *(a) the voltage injection with the PI controller (b) the voltage injection with the Fuzzy Logic controller (c) the voltage injection with the Fuzzy Neural controller.*
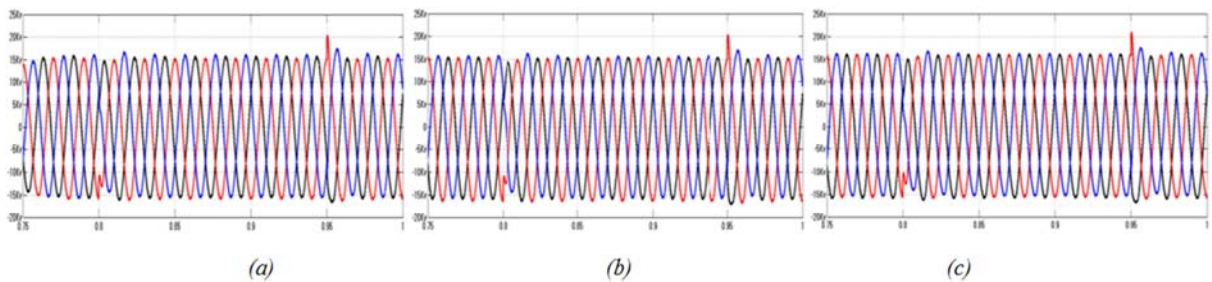

(a)	*(b)*	*(c)*

Figure 15. *(a) the load voltage with the PI controller (b) the load voltage with the fuzzy logic controller (c) the load voltage with fuzzy neural controller.*

2- With non-linear loads

The function of the DVR based on PI controller, fuzzy logic controller and fuzzy neural controller also will be shown with the nonlinear loads under sag condition, low order harmonics and high order harmonics which are simulated at 0.8s and kept till 0.95s. Figure 16 shows the non-linear loads have been connected to the electrical power source and the double tuned filter which has been tuned at the 5th and 7th harmonics is connected to help the DVR in mitigating the THD under non-linear loads.
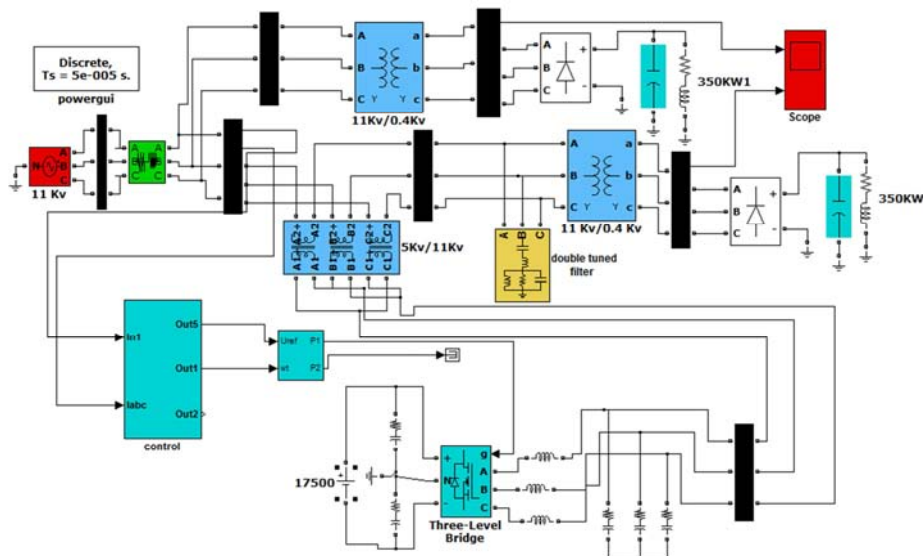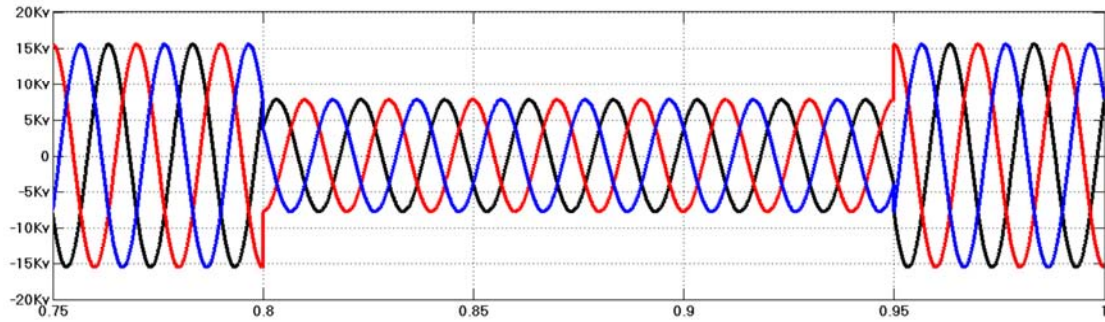

Figure 16. *Modeling and Simulation the power system with the DVR under nonlinear loads.*
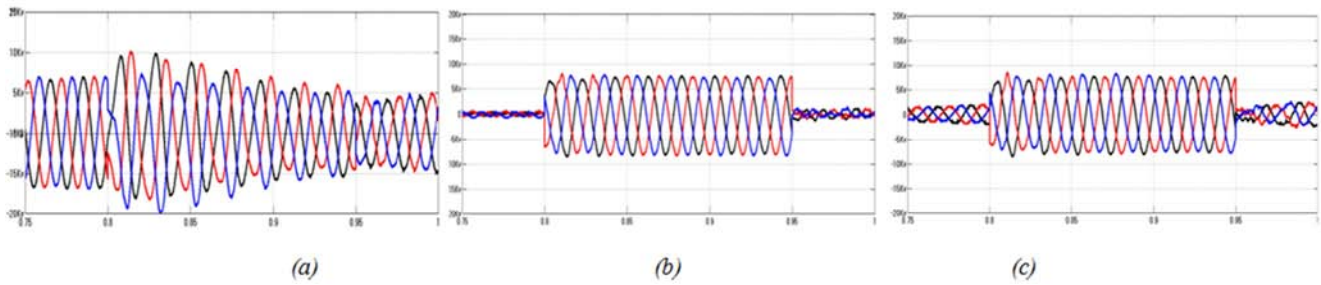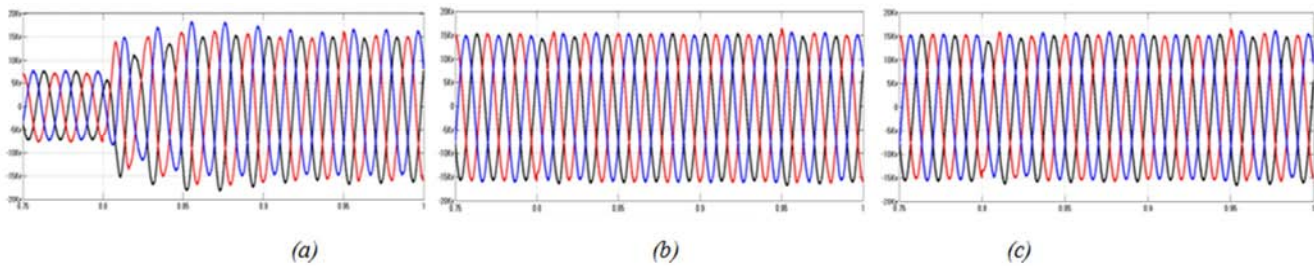
Case-1: 50% Sag

Fuzzy Neural controller performs a good compensation compared with Fuzzy Logic controller which provides a correct compensation but with high harmonics. PI controller cannot inject the required voltage in this case
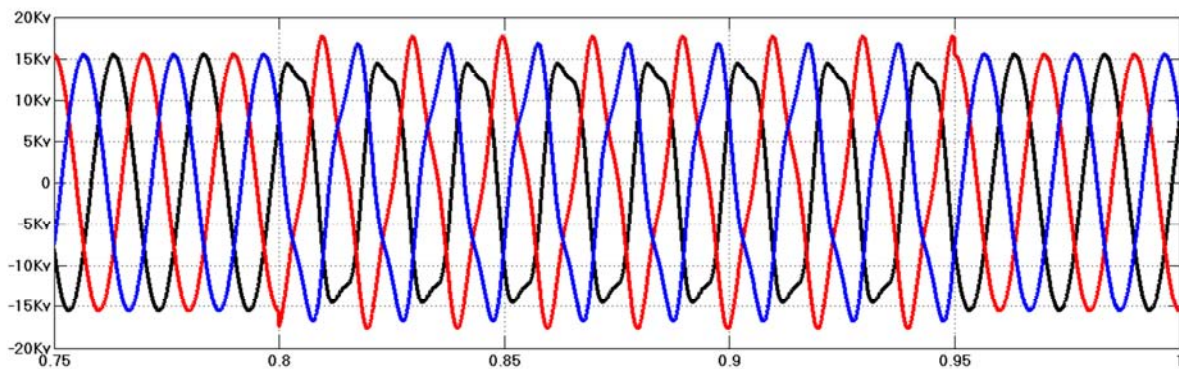

Figure 17. *The load voltage without DVR.*

Figure 18. *(a) the voltage injection with the PI controller (b) the voltage injection with the Fuzzy Logic controller (c) the voltage injection with the Fuzzy Neural controller.*

Figure 19. *(a) the load voltage with the PI controller (b) the load voltage with the fuzzy logic controller (c) the load voltage with fuzzy neural controller.*
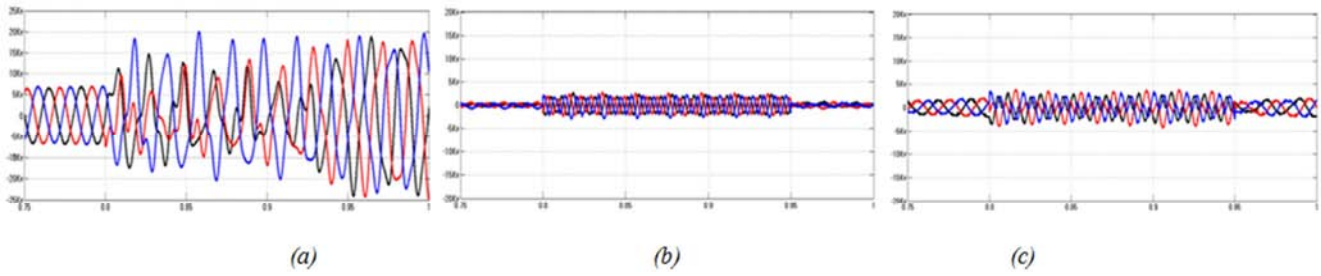
Case-2: Source voltage with 2nd and 3rd harmonics

From the simulation results it was noted that the proper compensation can be achieved with Fuzzy Logic controller and Fuzzy Neural controller. PI controller fails in injecting the required voltage in this category
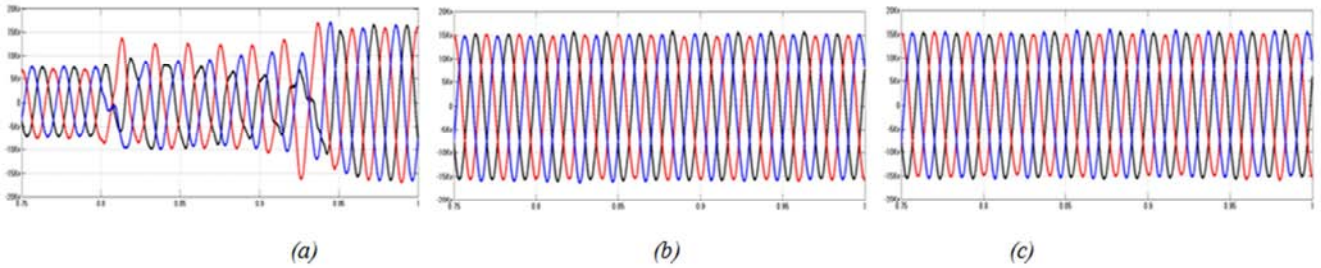

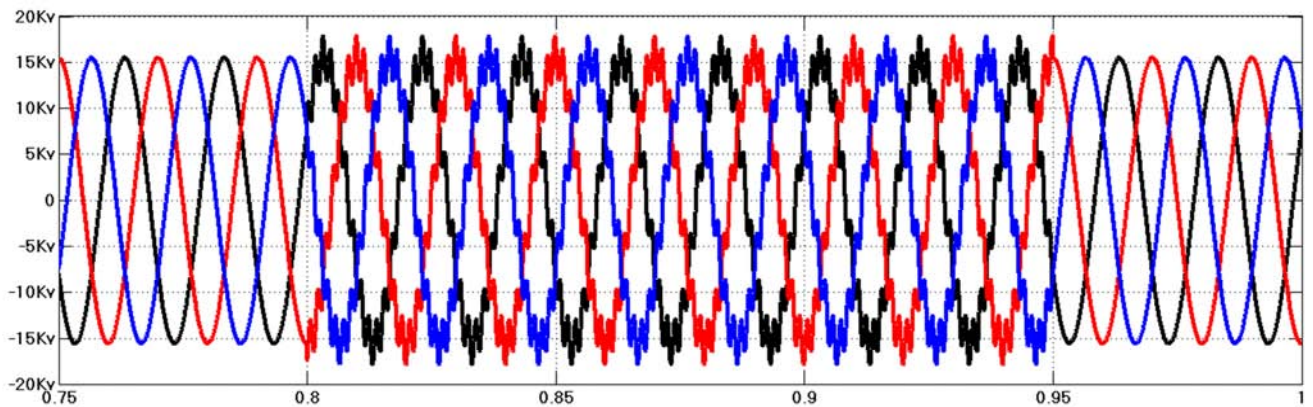**Figure 20.** *The load voltage without DVR.*

Figure 21. (a) the voltage injection with the PI controller (b) the voltage injection with the Fuzzy Logic controller (c) the voltage injection with the Fuzzy Neural controller.

Figure 22. (a) the load voltage with the PI controller (b) the load voltage with the fuzzy logic controller (c) the load voltage with fuzzy neural controller.

Case-3: Source voltage with 3th and 4th harmonics

The simulation results show best optimal compensation obtained for both Fuzzy Logic controller and Fuzzy Neural controller, While PI controller is incapable to inject the appropriate voltage in this category.

Figure 23. The load voltage without DVR.

Figure 24. (a) the voltage injection with the PI controller (b) the voltage injection with the Fuzzy Logic controller (c) the voltage injection with the Fuzzy Neural controller.
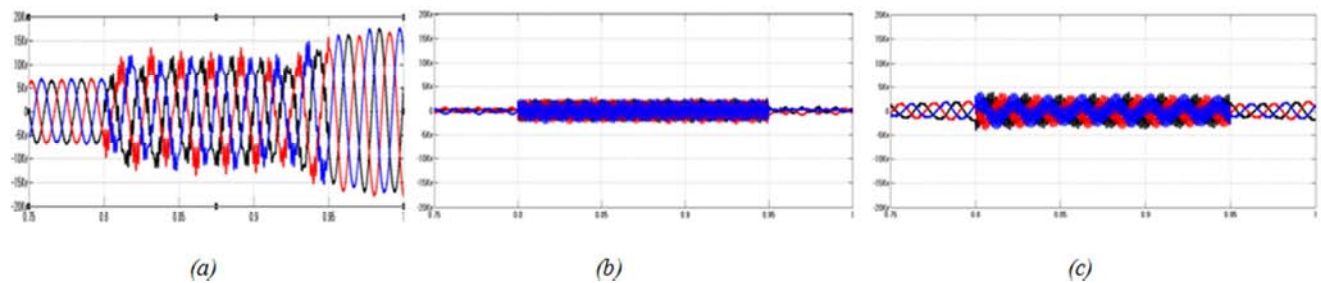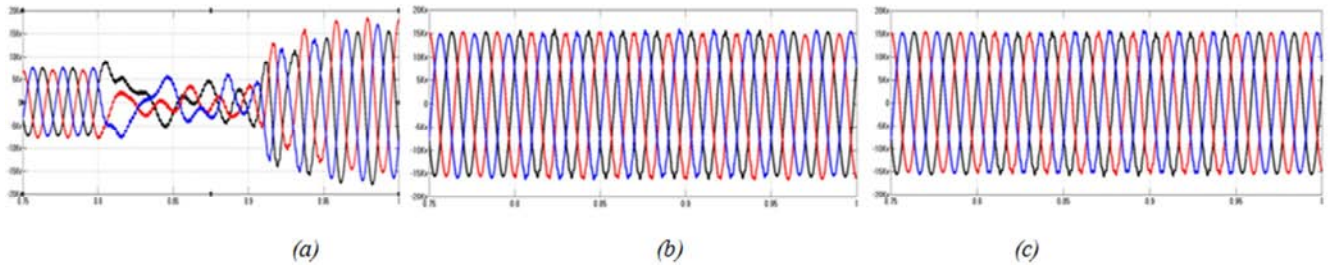
Figure 25. *(a) the load voltage with the PI controller (b) the load voltage with the fuzzy logic controller (c) the load voltage with fuzzy neural controller.*

9. The Total Harmonics Distortion of the Load Voltage with Non-linear Loads

The Total Harmonics Distortion is an important indication used for analyzing the Total Harmonics Distortion. The definition of the THD is given by Hung T. Nguyen et al.[17].

$$\text{THD}_{vp}=\frac{\sqrt{\Sigma_{n=2}^{\infty} v_{pn}^2}}{v_{p1}}\text{x}100$$

Where, p is the phase order and n is the harmonic order
The THD can be calculated as follows:

$$\text{THD}=\frac{\text{THD}_{va}+\text{THD}_{vb}+\text{THD}_{vc}}{3}$$

Table 4 shows the THD of the load voltage with and without the DVR under linear and non-linear loads.

Table 4. *Total harmonic distortion of the load voltage.*

With linear loads	Power quality problems	Load voltage without DVR	Load voltage with DVR based on PI controller	Load voltage with DVR based on Fuzzy Logic controller	Load voltage with DVR based on Fuzzy Neural controller
	50% sag	**2.416%**	**1.356%**	**4.003%**	**1.47%**
With non-linear loads	50% sag	2.586%	3.253%	2.7%	1.636%
	Source voltage with 2nd and 3rd harmonics	10.25%	18.496%	2.666%	1.953%
	Source voltagewith 11th and 13th harmonics	10.25%	9.026%	2.996%	2.036%

10. Conclusion

The custom power devices are used to enhance the power transfer capabilities and stability margins of the transmission line, Dynamic Voltage Restorer can solve voltage disturbances for protecting the sensitive load in distribution system. From the simulation results obtained, it can be concluded that since the PI controller has linear characteristics and simple implementation it shows better harmonics compensation with linear loads compared with other proposed controller while with the non-linear loads it fails in correcting the voltage sag and mitigating the THD to an acceptable value. Fuzzy Logic controller gives a worse value of the THD with linear loads due to its complex construction and nonlinear characteristics, the performance of the Fuzzy Logic controller with nonlinear loads is more best compared with its function under linear loads. Fuzzy Neural controller provides a good compensation with a permissible value of THD with linear and nonlinear loads as it has an adaptive characteristics and simple implementation compared with the Fuzzy Logic controller, it has 12 membership functions and 18 rules for the two controllers in the control system, while the fuzzy logic controller has 29 membership functions and 29 rules for the two controllers. Finally the double tuned filter has been used with non-linear loads to help the DVR in restoring the load voltage to the pre-sag value and mitigating the THD from a high value to less than 3%.

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