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Photovoltaic Fed Dynamic Voltage Restorer with Voltage Disturbance Mitigation Capability Using ANFIS Controller

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Abstract-The performance of present complex power system suffers with sudden current and voltage variations. The present model uses renewable source for Z - Source Inverter fed Dynamic Voltage Restorer (PV-ZSI-DVR). The proposed DVR topology dynamically compensates voltage interruptions, swell and sag to maintain the required level of voltage to the load. Here conventional DVR topology performance has been extended by incorporating the Hybrid Control technique ANFIS .The model presents the utilization of solar power for DVR operation in compensating the different voltage fluctuations. The performance of PV-ZSI- DVR with different control strategies have been compared in MATLAB/SIMULINK environment.

Keywords:FACTS, DVR, ZSI,FUZZY Controller, Neural Networks, Renewable Sources

1. Introduction

The modern world Complex Power System, consists of large number of loads supplied by more number of generating units, suffers with optimality and quality power supply to the consumers. The main concerned of load centre is to have reliable and quality power supply. Even though there are advances in power sector, which provides reliable supply but suffers to deliver quality power .Generally distribution side abnormalities are due to non linear loads, motor starting, load variations, faults, and load switching [1]. The ultimate reason for high quality power demand by the industries is to have successful working characteristics of their machines [2]. Failure to provide Quality power may cause shutdown of industries which in turn leads to financial loss [3, 4].

In distribution network, the most frequent abnormalities are voltage sag and swells [5].The sudden decrease or increase of voltage with duration of few cycles can be defined as voltage sag and swell respectively. The standard IEEE description of voltage swell and sag are given by IEEE 519-1992 and IEEE 1159-1995[6] which are described in the Table 1.

The proposed PV-ZSI-DVR is a versatile cost effective model capable of eliminating the voltage abnormalities .The proposed model of PV-ZSI-DVR shown in Fig .1 provides the following features.

- Voltage Sag elimination.
- Voltage Swell elimination.
- Supply from Solar energy unit during voltage fluctuations.
- Harmonic reduction in Load Voltage

In this paper, Section 2 illustrates the PV-ZSI-DVR model; Section 3 describes different proposed control strategies.Section 4 extensively presents the simulated outcomes of proposed model.

Table 1. Voltage Sag and Swell Definition.

Voltage Disturbance	Durationin cycles	Voltage in pu
Voltage Sag	0.5 – 30	0.1 – 0.9
Voltage Swell	0.5 – 30	1.1 – 1.8

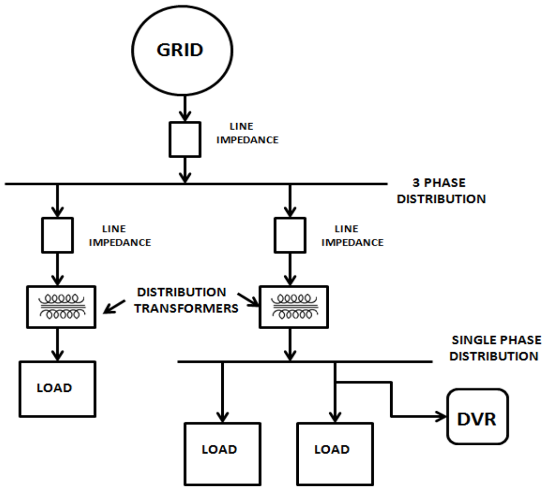

Fig. 1 Block Diagram of DVR connected to Single Phase Distribution System.

2. ZSI based PV fed DVR

Fig. 2 shows detailed structure of the proposed PV-ZSI-DVR model .This model presents a single phase distribution system which will be easily improved to a three phase distribution system. The proposed model is designed with the combination of renewable source unit, lattice impedance network, voltage source inverter (VSI), voltage injection transformer and LC filter.

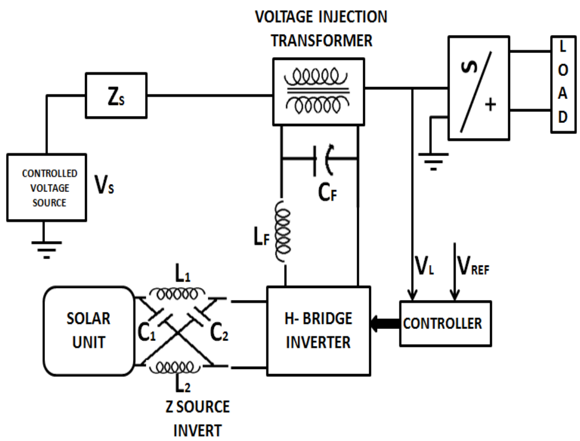

Fig. 2 Proposed PV-ZSI-DVR Model

2.1. Solar Unit

The Renewable Source unit provides the required real power during the compensation of voltage sag [7]. Generally super capacitors, fly wheels, lead acid batteries are used as batteries for supplying the required amount of power. Here the model proposes to utilize the available renewable source in effective manner. The required amount of energy demand depends on voltage abnormality, load MVA requirement and control strategy applied.

Different MPPT algorithms were implemented to track the maximum solar energy. Mostly used techniques are Perturbation & Observation (P&O) and Incremental conductance [8]. The widely used method is P&O method because of simple feedback and fewer parameters .The Solar Unit is the combination of PV cell, Maximum Power Point Tracking (MPPT) unit and DC-DC converter [9-11]. The model of solar cell is shown in Figure 4.The power produced by the solar unit is given by Eq.(1).

$$P_P = V_P * I_P \tag{1}$$

The terminal current and voltage of solar cell are given by,

$$I_p = I_{sc} - I_{sat} \exp\left[\frac{q}{AkT}\left(V_p + I_p R_{se}\right) - 1\right] - \frac{V_p + I_{sc}R_{se}}{R_{sh}} \tag{2}$$

$$\mathrm{V_p} = \frac{\mathrm{AkT}}{\mathrm{q}} \ln\{\frac{\mathrm{I_{sc}}}{\mathrm{I_p}} + 1\} \tag{3}$$

Here R_{se} is series resistance, R_{sh} is shumt resistance, k is Boltzmann constant and Diode Ideality factor is A.

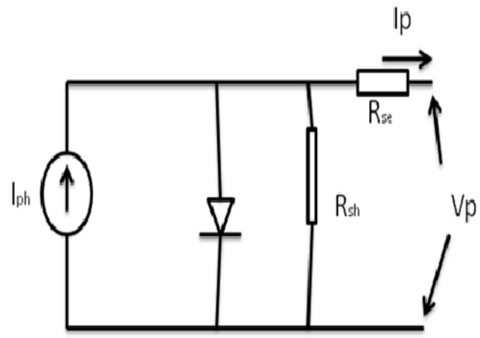

Fig. 3 Solar Cell unit equivalent Circuit.

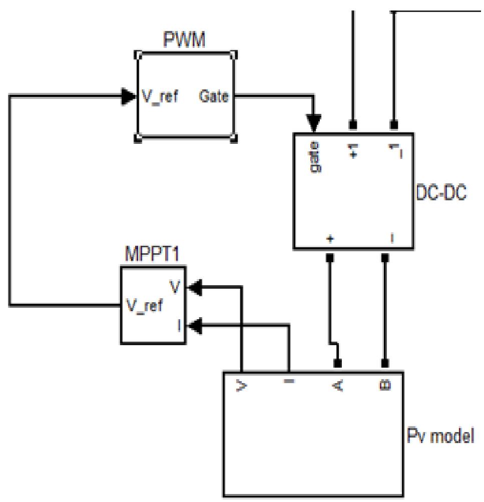

Fig. 4.Solar Unit

The MPPT based Solar cell Unit output is fed to the DC-DC converter in order to maintain constant voltage at DC link of the inverter

2.2. Z Source Inverter

Z Source Inverter (ZSI) consists of lattice structured impedance network fed at DC link side .Unlike the traditional Current and Voltage Source inverters; ZSI has both Buck and Boost characteristics. They increases reliability as they immune to EMI noise .It acts as 2nd order filter which requires less values of inductance and capacitance .It also provides constant DC voltage to the inverter[12-13]. Multiple Pulse Width modulation Technique is utilized to control the ZSI operation .ZSI has five switching modes, which are given Table 2.

Table 2. Switching modes of Single Phase ZSI

S4	S3	S2	S1	Mode	Remarks
1	0	0	1	Active Mode	DC source voltage is applied to load
0	1	1	0		
0	1	0	1	Zero Mode	The inverter output voltage is shorted through S_1S_3 or S_2S_4
1	0	1	0		
0 or 1	0 or 1	1	1	Shoot Through Mode	Two switches on one leg will be turned on

$$C_1 = C_2 = C \tag{4}$$

$$L_1 = L_2 = L \tag{5}$$

At this condition

$$I_{L1} = I_{L2} = I_L \tag{6}$$

$$V_{C1} = V_{C2} = V_C \tag{7}$$

The input voltage to the inverter is given by,

$$V_i = \beta V_{dc} \tag{8}$$

Where β is the boosting factor and V_{dc} is the dc source voltage.

Here the boosting factor is given by

$$\beta = {1}\Big/{1-2(\frac{To}{T})} \tag{9}$$

Where switching period is T and shoot through mode application period is T_0.

2.3. LC Filter

Passive LC Filter designed with a Capacitor and an Inductor. It can be connected at inverter side or hive voltage winding side of injection transformer. The switching harmonic components in injecting voltage are filter out by LC Filter [14]. Preferably LC Filter is placed at inverter side .This causes reduction in higher order harmonics and voltage stress on injection transformer.

2.4. Voltage Injection Transformer

In general step up transformers are utilized to boosting the inverter output to the required levels of voltage i.e it step up the low voltage applied by the inverter and injects into the line .The DVR maximum compensation limit depends on rating of the Voltage injection transformer.

3. DVR Control Strategies

The DVR purpose is to maintain voltage quality by modifying the voltage magnitude, shape and phase. DVR eliminates voltage disturbances by voltage restoration, which involves injection of required amount of energy into the line [15]. In Eq.(10), Vs is supply voltage VL is load voltage and Vin is the injected voltage which are as shown in Fig. 5.

$$V_{in} = V_L - V_S \tag{10}$$

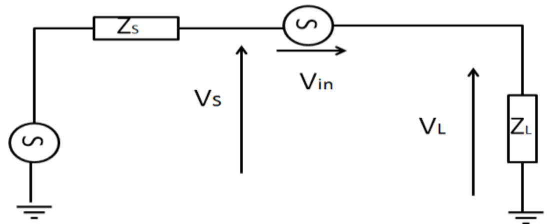

Fig. 5 Voltage compensation.

The proposed DVR uses the in phase compensation technique. Here load voltage is assumed to be in phase with pre sag voltage. In this proposed model only voltage magnitude is compensated. The controller receives the load voltage and reference voltage. Based on the difference in two voltages controller generates the pulses to the inverter using PWM technique. Now inverter injects the corresponding amount of energy into the line through the voltage injection transformer. The amount of voltage injected depends on boosting factor given in Eq.(9)

Following are the different control strategies used for DVR.

3.1 PI Controller

The traditional PI controller regulates the difference between reference and actual values .The function of proportional controller responds quickly where as integral controller is slower but removes the offset between reference and actual value.

3.2 ANFIS Controller

In literature, the hybrid controlling techniques which uses combination of control logics [16] had proven improved performance than traditional controllers. Another more efficient combination is Neuro-Fuzzy controller, which had proven its robust controlling quality in different areas [17-18].The adaptability of Neural Networks and decision making of Fuzzy Logic combinable deals with the imprecision and uncertain data.

ANFIS is a MLFF (Multi Layer Feed Forward) network in which every node performs a specific operation on excited signal [19]. To analyze the working of ANFIS structure nodes are represented with two different symbols as shown in Figure 6. The rectangle node represents adaptive node whose parameters are going to be updated. The circle nodes represent fixed nodes. To get a required input output mapping, adaptive parameters are updated with training data and gradient descent learning rule is used. The network exciting elements are error and change in error and response is active component signal (I_L) Load current.

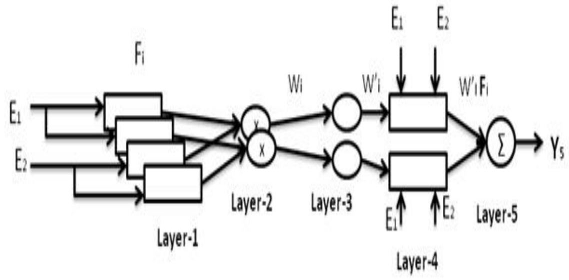

Fig. 6 General ANFIS Structure

The first layer output is given by

$$Y_1 = \mu f(E_1) \qquad (11)$$

Here f is a linguistic function.

The second layer nodes are fixed nodes which performs the multiplication of inputs given by

$$Y_2 = \mu_{fi}(E_1)\mu_{gi}(E_2) \qquad (12)$$

Where E_1 and E_2 are error and change in error input variables.

The third layer consists of fixed nodes. Each node performs the ratio of i^{th} firing strength to the sum of all the firing strengths, given by

$$Y_3 = W_i' = \frac{W_i}{W_1 + W_2} \quad \text{Where i =1, 2} \qquad (13)$$

The fourth layer consists the adaptive nodes whose function is given by

$$Y_4 = W_i'(p_i E_i + Q_i E_2 + R_i) \quad \text{Where i = 1, 2} \qquad (14)$$

The fifth layer has a single fixed node which computes the sum of all the inputs to produce final output given by

$$Y_5 = \sum(Y_{4i}) \text{Where i =1, 2} \qquad (15)$$

This overall output is equivalent to Fuzzy System used in [20]. Fig. 7a&7b shows the ANFIS structure and rules used for the proposed model. The ANFIS learning algorithm has two direction learning process. In forward direction it uses Least Square Error learning. In backward direction it uses back propagation learning. Fig. 7c shows the input and output membership functions. Here three fuzzy linguistic values are chosen. Such as Low,Medium and High for two inputs and single output variable.

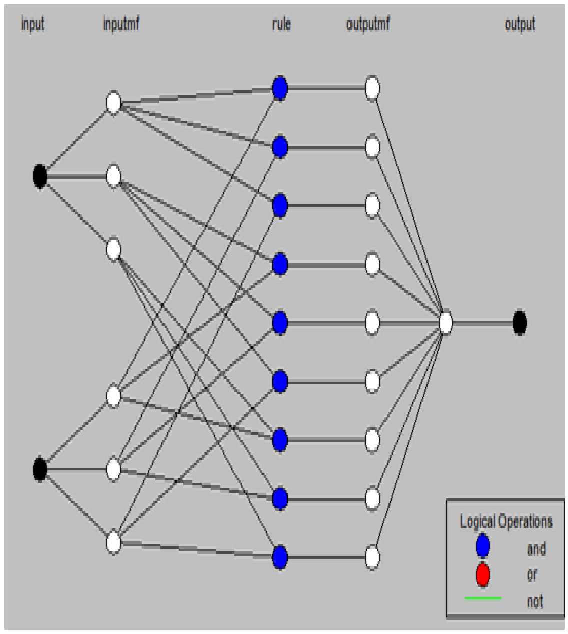

Fig. 7a ANFIS Structure

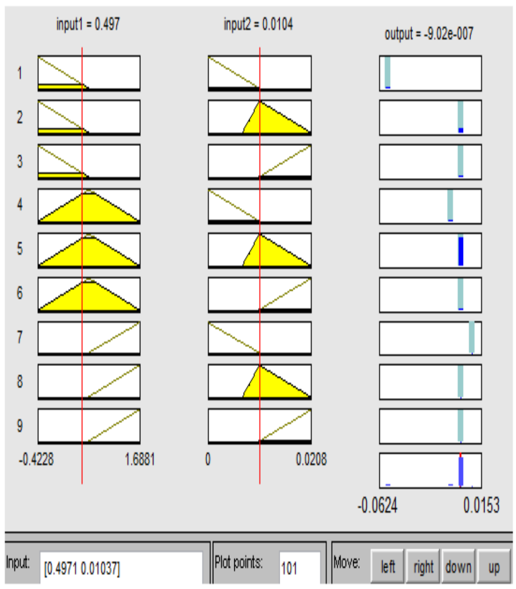

Fig. 7b ANFIS Rules

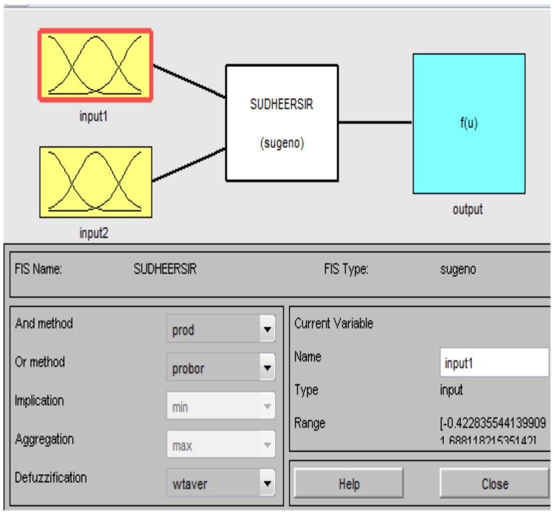

Fig. 7cANFIS Membership Functions.

4. Simulation Results

The proposed PV-ZSI-DVR model is simulated in MATLAB/SIMULINK. The Simulink model of the proposed system and Solar Cell are shown in Fig. 8a & 8b. The parameters used in the proposed PV-ZSI-DVR model are presented in the Table 3. The proposed model has been simulated for two different control strategies. Two controllers performance have been simulated and their results are compared. Fig. 9. presents the traditional PI controlled PV-ZSI-DVR operation. Similarly Fig. 10. Shows the simulated results of ANFIS control strategy.

Case1: Here PI controller is used to inject the required voltage in the line using PV-ZSI-DVR. In Figure 9 25% of voltage swell is created between 0.25 to 0.6 sec and 25% of voltage sag is created between 0.8 to 1.25sec. The abnormalities in the voltage are compensated.

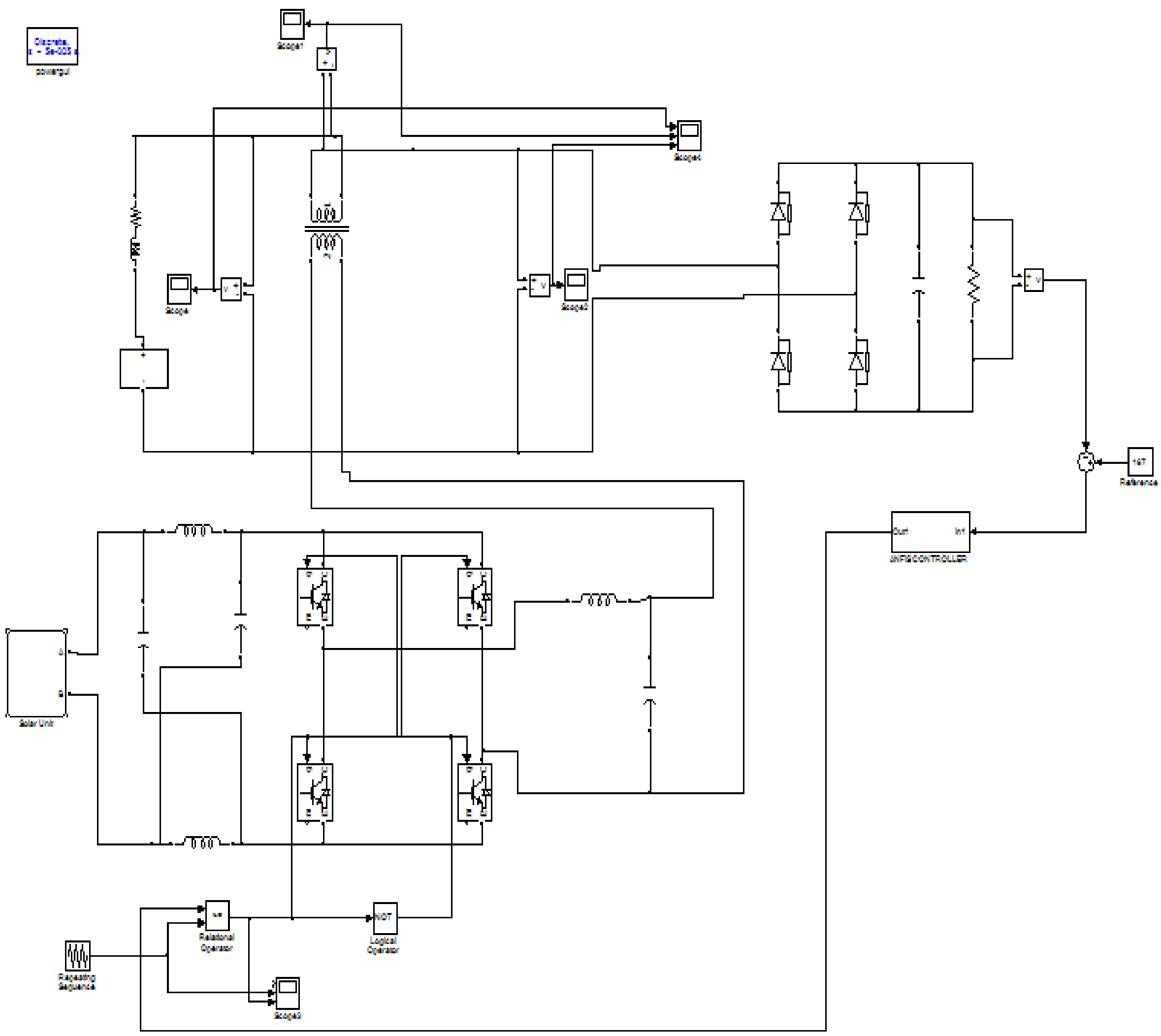

Fig 8a. Simulink Model of Proposed Dynamic Voltage Restorer for Voltage Disturbance Mitigation

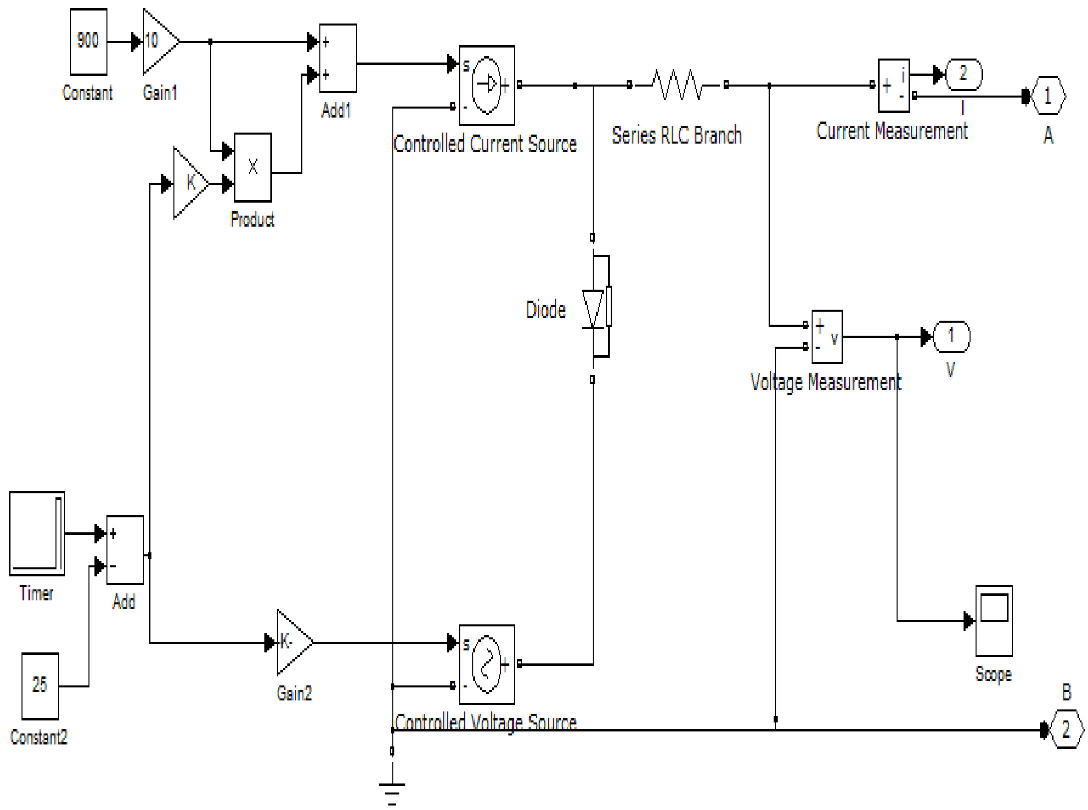

Fig. 8b PV Model

Table 3. System Parameters

S.No	Parameters	Ratings
1	Source voltage	1-phase 200v,50HZ
2	Source impedance	R_S = 0.1ohm,L_S = 0.001mH
3	LC Filter	L = 2mH , C = 0.1μF
4	Z network	L = 1mH , C = 1μF
5	Voltage Injection Transformer	100/240V,50 Hz
6	Dc link	V_{dc} = 100V
7	Solar Unit	35V.6A

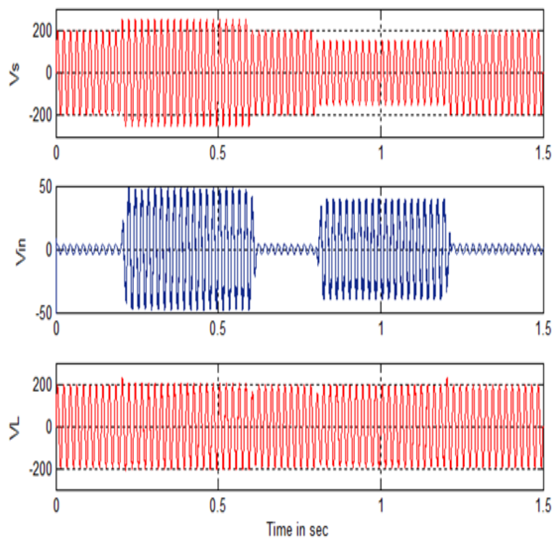

Fig.9 Source, Injected & Load Voltages of PV ZSI-DVR with PI Controller

Fig. 9 describes load voltage % THD using PI controller and Figure 11 shows the real and reactive powers injected from solar unit through the ZSI-DVR.

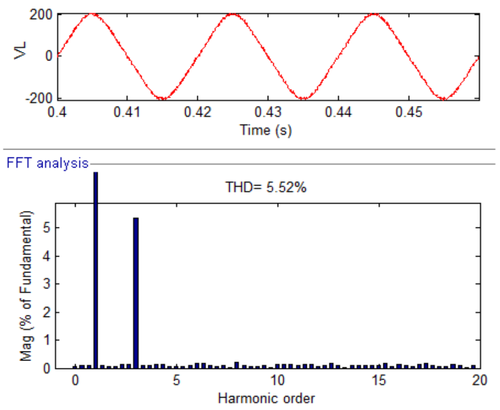

Fig. 10 %THD of Load Voltage is 5.52%

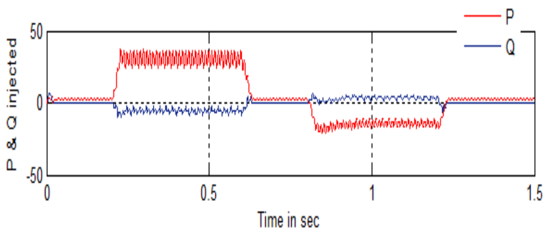

Fig. 11 Real and Reactive power injected by PV-ZSI-DVR

Case-2: Here ANFIS controller is used to inject the required voltage in the line using PV-ZSI-DVR. In Fig.12, The voltage interruption is created between 0.6 to 0.72 sec. 25% of voltage swell is created between 0.35 to 0.5sec and 25% of sag in voltage is created between 0.1 to 0.25 sec. All the three abnormalities in the voltage are compensated.

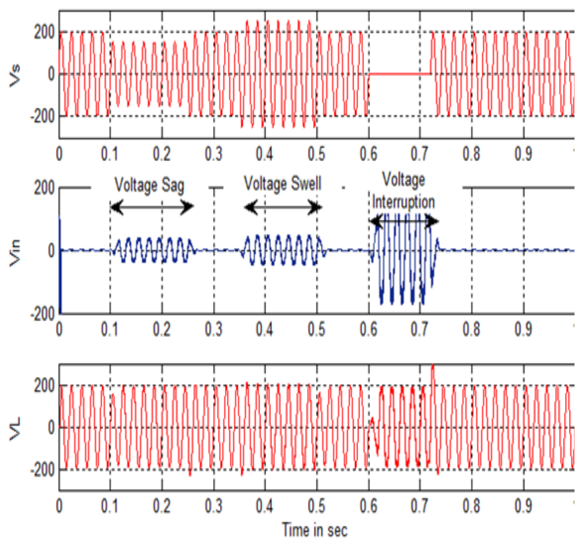

Fig. 12 Source, Injected & Load Voltages of ZSI-DVR model with ANFIS controller

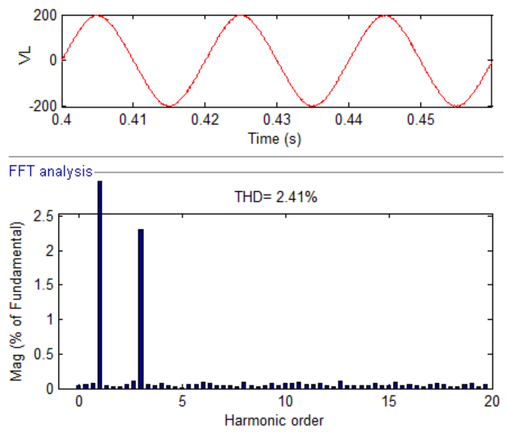

Fig.13%THD of Load Voltage is 2.41%

Fig. 13 describes the %THD of load voltage using ANFIS controller .ANFIS controller reduces the harmonics in the load to 2.41% compared to PI control strategy which is presented in Table 3.

Table 3. Comparison of % THD of V_L for Various control strategies

S.No	Type of Controller	Load volt (VL) %THD
1	PI	5.52
2	ANFIS	2.41

From the simulated results, we can analyze that both the controllers are effectively compensating the abnormalities in voltage. From Table 3, the ANFIS controlled PV-ZSI-DVR effectively reduces the Harmonics in the load voltage.

5. Conclusion

The proposed PV-ZSI-DVR model effectively compensates the voltage interruption, sag and swell. The compensated sag and swell in voltage are within the IEEE standards *IEEE 519-1992 and IEEE 1159-1995.* The comparison of different control strategies proves ANFIS is the best method. The proposed model proves that it is cost effective model as it reduces the cost of inductors, due to usage of lower values of Inductance and Capacitance. It also uses simple hybrid control strategies to compensate voltage abnormalities and harmonics in the source and load voltages. The simulation results compares % THD of V_L for different controller's i.e PV-ZSI-DVR with PI, ANFIS control schemes.

Presented Model in the paper successfully fulfils the following objectives.

- 25% of sag and 25% of swell in voltage were compensated
- Voltage interruption is eliminated
- Harmonics in load voltage were compensated to a THD of 2.21%

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