Research Article

Implementation Of ANFIS-Based Dynamic Voltage Restorer To Improve The Voltage Profile Of a PV-integrated Grid

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Abstract: Fluctuations in system voltage can disrupt the system possessions both at the utility and customer end. Such a problem is most prominent at a point where a renewable source is attached to feed the grid. Photovoltaic (PV) power is one of the proposing renewable resources in the twenty-one century. However, its output depends on sunlight which varies throughout the day. This varying output of grid-connected PV systems causes harmonics and variation in system voltage. This work proposes a model of Dynamic Voltage Restorer (DVR) to overcome the issues mentioned above. DVR is a three-phase voltage source inverter (VSI) fed by a DC source. Adaptive neuro-fuzzy inference system(ANFIS) controller along with synchronous reference frame theory (SRF) is used to control the switching of voltage source inverter. According to SRF theory, three-phase a–b–c stationary frames are changed into 0–d-q rotational frames. The 0–d–q rotating frame reference signals are regulated using a PI or ANFIS controller to achieve the necessary reference signals. The measured amplitudes of the reference phase voltages are used directly to calculate the PWM signal generation for the three-phase inverter. MATLAB software is used to implement the proposed model and verify the proposed controller. The DVR is attached to a grid integrated with the PV system. PV system parameters like irradiance and temperature are varied to disturb the voltage. Voltage fluctuations and harmonics generated were mitigated by DVR. The results show that the proposed device can improve the voltage profile of a PV-integrated grid.

Keywords: Dynamic Voltage Restorer DVR, Flexible Alternating Current Transmission System FACTS, Voltage Source Inverter, Adaptive Neuro-Fuzzy Inference ANFIS, Synchronous reference frame theory (SRF), SPWM

1. Introduction

Traditional power generation tended to have centralized generating plants along with transmission and distribution networks consisting of long and overloaded lines [1]. Which resulted in serious low voltage problems at the consumer end. This problem was reduced with the introduction of distributed generation (DG) [2]. Which is a decentralized approach defined as the integration of a power generating system within the distribution system. Any of the generator technology can be used in DG. The most common and environment-friendly generating sources are renewable ones. Among these renewable sources, photovoltaic-based generation is prominent. Because of their low costs and zero pollution, PV-based systems have great potential. Equation (1) shows that the power output of the PV system depends on sunlight intensity which varies throughout the day. This varying output of grid-connected PV systems causes harmonics and variation in system voltage. This voltage variation problem is the main challenge of DG [3]. The use of capacitor banks was one of the traditional methods to overcome voltage profile issues. Traditional methods are not sufficient to overcome the issues mentioned above [19]. This work aims to develop a dynamic voltage restorer (DVR) model to improve the voltage profile at the common coupling point of a PV-connected grid.

$$\boldsymbol{P_{dc,m} = G \times \eta_m \times A_m \times \frac{\gamma_{mp,ref}}{100} \times (T_c - 25)} \tag{1}$$

1.1 Background

Nowadays, power efficiency is one of the most critical issues. The implementation of flexible alternating current transmission systems (FACTS) is particularly significant, whose output is highly sensitive to the efficiency of the power supply. The issue of power quality is a non-standard occurrence of voltage, current, or frequency that results in an inability of the terminal equipment [4-5]. One of the biggest challenges is voltage fluctuation. FACTS devices are used to compensate for this issue [6]. DVR is one of those. Its appeal are reduced costs, smaller dimensions, and a quick response to disturbances [7].

Voltage fluctuation is one of the most common issues in power efficiency. The Voltage fluctuation results from a malfunction of the utility grid, such as a sudden rise in the load current. [8]. It is one of the most common issues in power efficiency, especially in renewable-based power systems. Voltage fluctuation occurs more frequently in industry and leads to serious complications and economic losses [9]. In transmission and distribution systems, there are many approaches to minimize power efficiency issues. Some of the Conventional approaches for voltage fluctuation compensation are capacitor banks and synchronous condensers.

DVR is one of the most efficient instruments among these. It defends the power grid from voltage fluctuation due to sudden load changes, fluctuant power injection, or faults [10-12]. Based on the implementation of sinusoidal pulse width modulation (SPWM) for a three-phase voltage source converter (VSC), the low-voltage DVR is presented. The proposed DVR model is created in MATLAB/Simulink environment. Today, the use of custom power devices (electronics-based) to sustain power efficiency is important because of the more responsive nature of the charges. Several research papers and studies discuss the issue of power improvement by different power devices in the delivery grid. The next paragraph will discuss the recent research articles published about DVR.

1.2 Dynamic Voltage Restorer (DVR)

DVR is a static series compensation device, which protects a sensitive electric load from power quality problems such as voltage sags, swells, unbalance, and distortion.

The DVR output voltages are in phase with system voltages and are connected to the AC system by the coupling transformer reactance [7]. The appropriate step and magnitude modification of the DVR output voltages permits an efficient regulation of voltage exchange between the DVR and the AC system. This design enables the system to consume or create active and reactive power [16].

The DVR system essentially consists of three main parts: a VSC, a coupling reactor collection, and a controller. Mounted in a power system, the basic concept of a DVR is to provide an AC voltage source by a (VSC) attached to a DC condenser (ESD). In general, the AC voltage source appears behind a transformer leakage reaction. The active and reactive power transmission between the power grid and the DVR is due to this reluctance voltage gap. The DVR is attached to the power grid at the Point of Common Coupling (PCC) where the voltage quality issue exists. The appropriate voltages are calculated and fed into the controller for comparison with the reference values. The controller then implements the input control and emits a series of switching signals to drive the power converters main semiconductor switches (Insulated-gate bipolar transistor (IGBTs) used at the delivery level).

Regulation of the AC voltage is accomplished by control of the firing angle. In constant conditions, the DC side capability is held at a set voltage and no true power exchange except for losses. The main goal DVR incorporates is the AC voltage control of the power grid attached to the DVR. There are two voltage regulating units in the traditional control system for these purposes: the AC voltage regulator for the control of the bus voltage and the DC voltage regulator for the control of the condenser voltage. Both regulators are proportional-integral controllers (PIs) in the simplest approach. Separate PI regulators of DC voltage and AC-bus voltage receive reference values for these currents; DVR is a series system capable of injecting voltage. While storing energy is a long-term challenge, actual power compensation is not an ideal case for voltage control [17-18].

Table I
Description of the five layers in ANFIS

1st Layer	It performs the Fuzzification process. Every neuron is a versatile hub in which the value of fuzzy input is stored.
2nd Layer	This layer is a suggestion layer with neurons which is the result of the information sources i.e. the influence of reason boundaries.
3rd Layer	This layer is a shifting layer, the neurons numbers are specified and standardized by the completion of all neurons in this layer's loads
4th Layer	This layer is for defuzzification, where every neuron is additionally a versatile hub and contains the architecture's corresponding parameters.
5th Layer	It consists of a single neuron for output that sums up all the inputs. While using classical ANFIS, it chooses a hybrid learning process in which parameters are updated twice, and two different optimization strategies are used.

1.3 Adaptive Neuro-Fuzzy Inference System (ANFIS)

An Adaptive Neuro-Fuzzy Inference System (ANFIS) combines ANNs with Fuzzy Logic (FL). It can learn quickly and adapt to new situations, modeling complex patterns and understanding nonlinear interactions. The fuzzy system is unsuitable for complex human jobs requiring precision machines and system manipulation. This issue focuses on the use of ANFIS in the developing area of engineering sciences. The fundamental Fuzzy architecture is much strengthened when integrated with experienced techniques and nature-inspired algorithms through parameter calibration and tuning. It is vital for complex technological processes requiring human judgment, especially in the mechanical, electrical, and geological fields [20]. It has five layers.

1.4 Training Fuzzy with Adaptive Neural Network

Neuro-adaptive learning methods may be used to modify fuzzy inference systems similarly to neural networks are trained using Fuzzy Logic.

An input/output training data set from experiments or computer simulations of the model's actual behavior is required before neuro-adaptive procedures may be used to train a fuzzy system [21]. The training data for ANFIS training is generally effective if it accurately represents the data attributes that the trained ANFIS is designed to mimic.

2. Method and Design

In this section, the structure and design of the proposed DVR are revealed, in addition to the way in which it is integrated into the system.

2.1 The Proposed DVR

The DVR system consists essentially of four main parts:

- Voltage source converter
- Energy storing device (DC source)
- Coupling Transformer

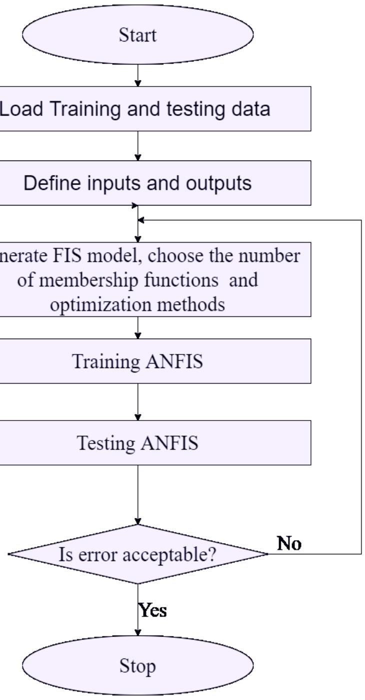

Figure 1. Process flow of training ANFIS

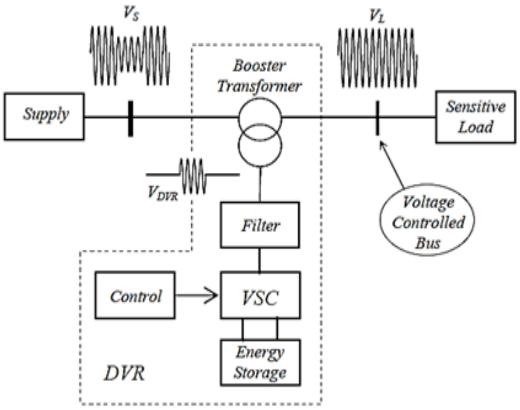

Figure 2. DVR Block diagram

- Controller.

The DVR block diagram shown in Figure 2 consists of a sensitive load connected to a power source and a DVR which further consists of an energy storage device, a voltage source converter, filter, and a transformer to step-up DVR voltage.

A control block adjusts the output of DVR as per requirement. The proposed model of the DVR is shown in Figure 3. It is composed of the following blocks

- The list of simulation parameters of DVR.
- 2-level voltage source inverter
- PWM generator
- Controller block
- LC filter
- The coupling transformer

Figure 4 explains the DVR controler for voltage fluctuation detection and compensation. Three-phase load voltage signals are first converted into a rotating reference frame using abc to dq block. The two values d and q represent the peak and angle of three-phase load voltage, respectively. As the measurement is done in a per-unit system, parameter d is compared with '1'

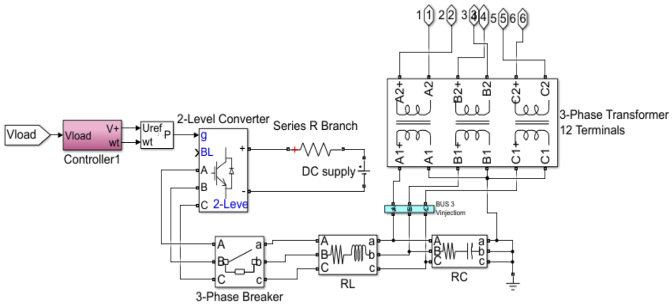

Figure 3. Proposed DVR model.

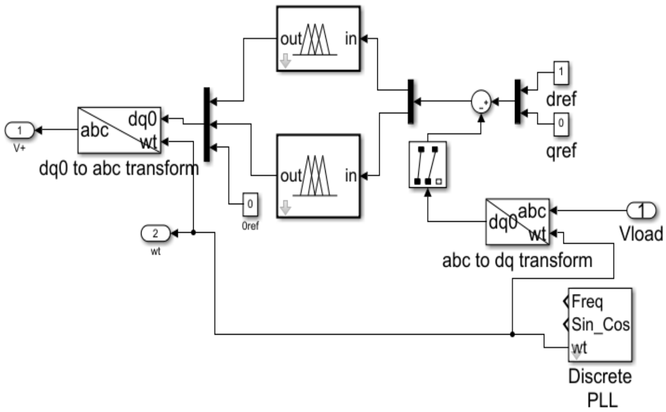

Figure 4. ANFIS controller

to keep load voltage 100percent, and q is compared with constant '0' to keep zero phase shift in angle. Two ANFIS controllers for the d and q axis regulate the output nearer to reference or keep error zero. The two dc variables 'd' and 'are then converted back to abc (time-varying form).

The layers of the neural network the ANFIS are shown in Figure 5. The first layer consists of inputs through which input membership functions are generated. The two inputs are error and integration of error. The error is the difference in reference and feedback of voltage and angle on the d-axis and q-axis respectively. These inputs are fuzzified or converted into linguistic (human language) variables i.e large very large etc. The second layer consists of membership functions for inputs. The third layer consists of rules (if...then) through which input and output membership functions are connected. The output is obtained by the fifth layer which defuzzifies the results back from linguistic to crips values.

2.2 *The Test System*

The proposed system is shown in figure 6, which consists of

- Three-phase voltage source
- Transformer
- Load
- 100kw PV system

2.2.1 *Three-phase Source*

A three-phase sinusoidal voltage with time-varying parameters can be made using this block. The temporal variation for the amplitude, phase, or frequency of the source's basic component can be programmed. Two harmonics can also be programmed and overlaid on the characteristic signal. The parameters of this source are given in Table II.

Table II.
Parameters of the three-phase source

Parameters	Value
Frequency	50hz
Voltage Vrms	11kV

Table III.
One MVA transformer parameters

Parameters	Value
Power (MVA)	1
Frequency (Hz)	50
Winding1 kV Ph-Ph (RMS)	11
Winding1R(PU)	0.002
Winding1 L(PU)	0.08
Winding2 V ph-ph (RMS)	400
Winding2 R(PU)	.002
Winding2 L(PU)	0.08

2.2.2 Transformer

Three-phase two winding transformers are used to step down the voltage at the generation side from 11kv to 400v to suit the distribution level, as shown in Table III.

2.2.3 Load

As a parallel collection of RLC components, the 3-Phase parallel RLC Load block executes a three-phase balanced load. The load has a steady impedance at the declared frequency. The active and reactive powers of the load are proportional to the square of the applied voltage.

2.2.4 100 kw PV System

Figure 7 demonstrates a 100kw MPPT-based PV system model. PV array is used with a series-parallel combination of cells and modules to reach 100kw power. Two inputs, irradiance, and temperature are given as ramp functions to vary the PV module generation. A DC-DC converter equipped with an MPPT algorithm maintains the PV output voltage such that to achieve maximum power. A three-phase voltage source inverter converts DC to three-phase AC which is attached to the grid.

2.3 Data Collection Tools

Data collection is based on the system generation in MATLAB Simulink shown in Figure 6. It consists of a three-phase voltage source and a transformer connecting the grid side to the load end. The proposed device called DVR is attached at load sides. Data is collected by experimenting with the system under different fault conditions.

3. Fındings

The results of the proposed DVR model tested in the system are shown in this section.

3.1 Obtaining the Training Set

The conventional DVR controller block using the PI controller is shown in Figure 8. This controller is used to obtain the training dataset used to train the ANFIS. Input voltages are first converted into DC values by using abc to d, q

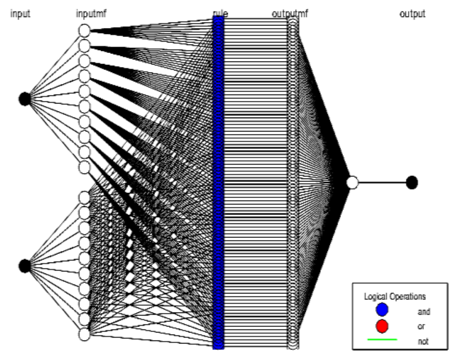

Figure 5. Structure of the proposed ANFIS

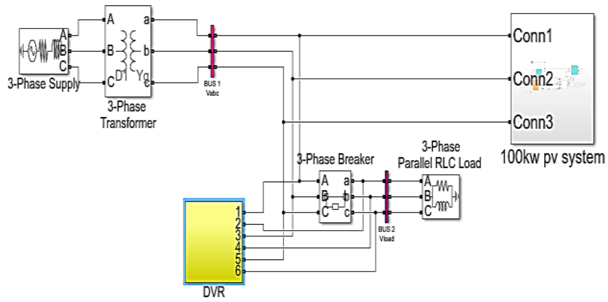

Figure 6. The proposed PV integrated system with DVR

transformation. These values are then compared with d and q references to generate the error. These two errors are fed to q-axis and d-axis PI controllers. The output of these PI controllers is then converted back to abc form. The error, integration of error, and output of PI controllers of both the q and d axis are exported to MATLAB workspace using to workspace block.

3.2 Training the ANFIS controller

This section shows the results of training the proposed ANFIS controller. The controller is built using different Epochs, and error was calculated for each iteration. Figure 9 shows the error vs epochs plot. The controller is trained up to 30 epochs using the data obtained by the conventional controller.

Figure 10 describes the effect of temperature and irradiance on the PV output. In Figure 10(a) the change in solar irradiance is shown clearly. The solar irradiance is the main factor that causes the voltage fluctuation in PV system power, which in turn affects the voltage at the PCC. When the solar irradiance decreases, the power generated by the PV systems decreases. In other words, the current fed by the PV system to the grid decreases, which means the voltage will decrease. Figure 10(b) demonstrates another main factor that causes irradiance, and the temperature significantly affects the power and voltage fluctuation. When the temperature varies, it disturbs the profile of the PV system. To sum up variation in solar irradiance and the temperature significantly affects the power profile of the PV system as shown in figure 10(c).

The performance of the proposed DVR controller in the presence of the PV system is shown in Figure11. Figure 11(a) shows how the voltage fluctuates at the PV system terminal due to the varying temperature and solar irradiance. Figure 11(b) shows the response of DVR to compensate for the voltage fluctuation in Figure 11(a). Figure 11(c) shows the voltage

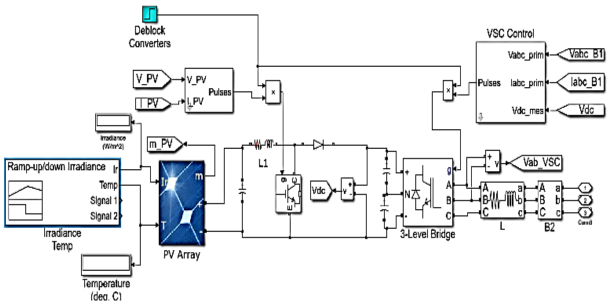

Figure 7. MPPT based PV system model.

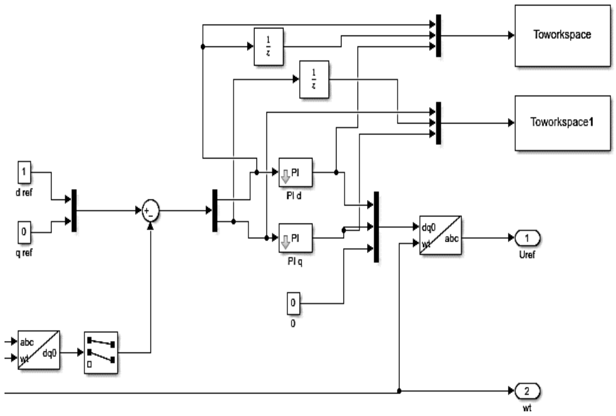

Figure 8. Exporting inputs and outputs datasets from the conventional PI controller.

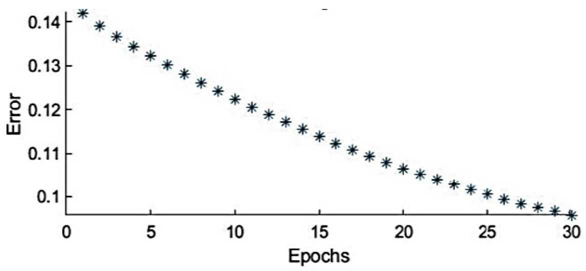

Figure 9. Error vs epochs resulting from training the proposed ANFIS controller

profile at the PCC after the DVR managed to compensate for the voltage fluctuation. It is seen that the voltage profile at the PCC has been improved. In the presence of DVR, the effect of voltage fluctuation between the time 0.5s to 0.7s is eliminated and the load voltage is kept in its normal range.

4. *Discussion and contribution*

In this research, an ANFIS-based DVR is developed with synchronous reference frame theory. The block diagram of the controller is shown in Figure 2. The model consists of a voltage source inverter with a DC input source and the controller. The DVR design is tested for voltage profile and quality of grid to which the 100 kW photovoltaic system (Figure 7) is tied. PV system output power variation can be seen due to the change in solar irradiance and temperature as shown in Figure 10(a) 10(b) 10(c). The varying output power of a grid-tied PV system causes fluctuation in grid voltage level and its quality. Voltage fluctuations due to varying PV system voltages are eliminated by DVR to protect the critical load. The results show that harmonics created on the grid side are filtered by DVR and load

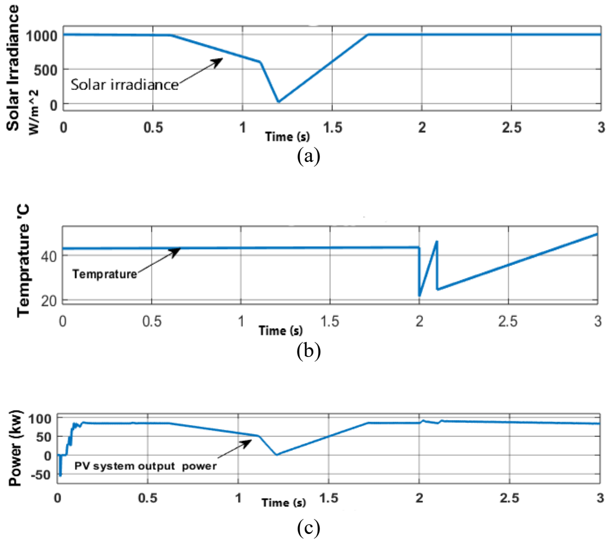

Figure 10. Effect of temperature and irradiance on PV system output: (a) Irradiance; (b) Temperature; (c) PV power output

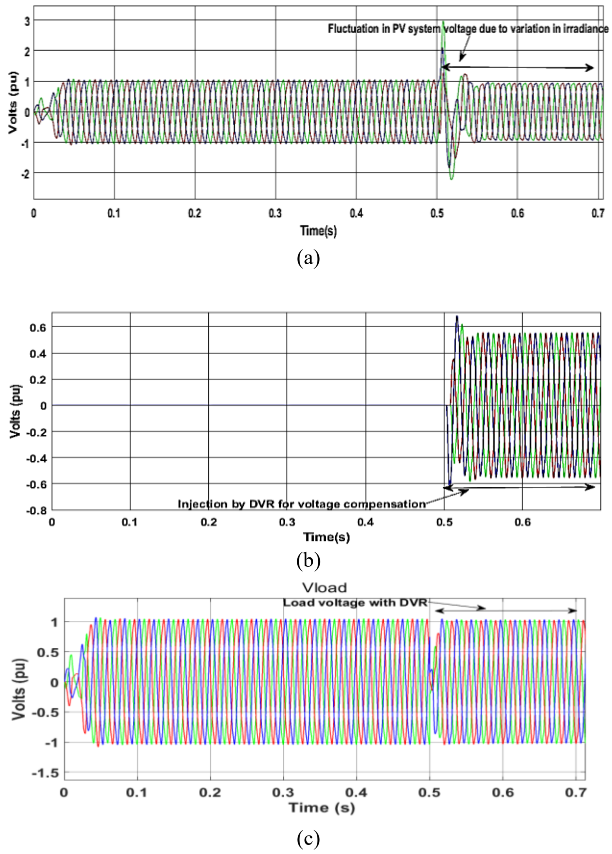

Figure 11. The proposed DVR controller performance in the presence of fluctuant PV power output: (a) PV output voltage; (b) Compensated voltage using the proposed DVR; (c) The voltage profile at the PCC

side THD remains less than 2%. The results discussed above show how the proposed DVR improves the voltage profile of a PV-based grid.

5. *Conclusion and Recommendations*

In this work, the power quality problems resulting from fluctuant PV output power are mitigated by a controller, namely an ANFIS-based DVR. The project details the architecture and deployment of the DVR driven by the ANFIS controller to improve the voltage profile at the PCC. A three-phase voltage source inverter consisting of six IGBTs is used which is driven by the sine pulse width modulation technique (SPWM). The complete DVR model is attached to a 100Kw PV system connected to the grid to overcome voltage profile issues caused by the PV source. The results show that the voltage fluctuations caused by the PV source are mitigated by DVR. The control technique, ANFIS has been evaluated in several operational environments and has often been found to be quite stable. The proposed DVR design is implemented in MATLAB Simulink software which is a powerful graphic tool. The suggested solution is examined and seen to be useful to overcome the problem. The work can be implemented in hardware for future work. In the genuine experimental setting, the benefit of harmonics on the network and the voltage drop generated by the DVR connection may be tested.

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