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Voltage Sag Reduction by ANFIS in Wind Turbine Generation Units

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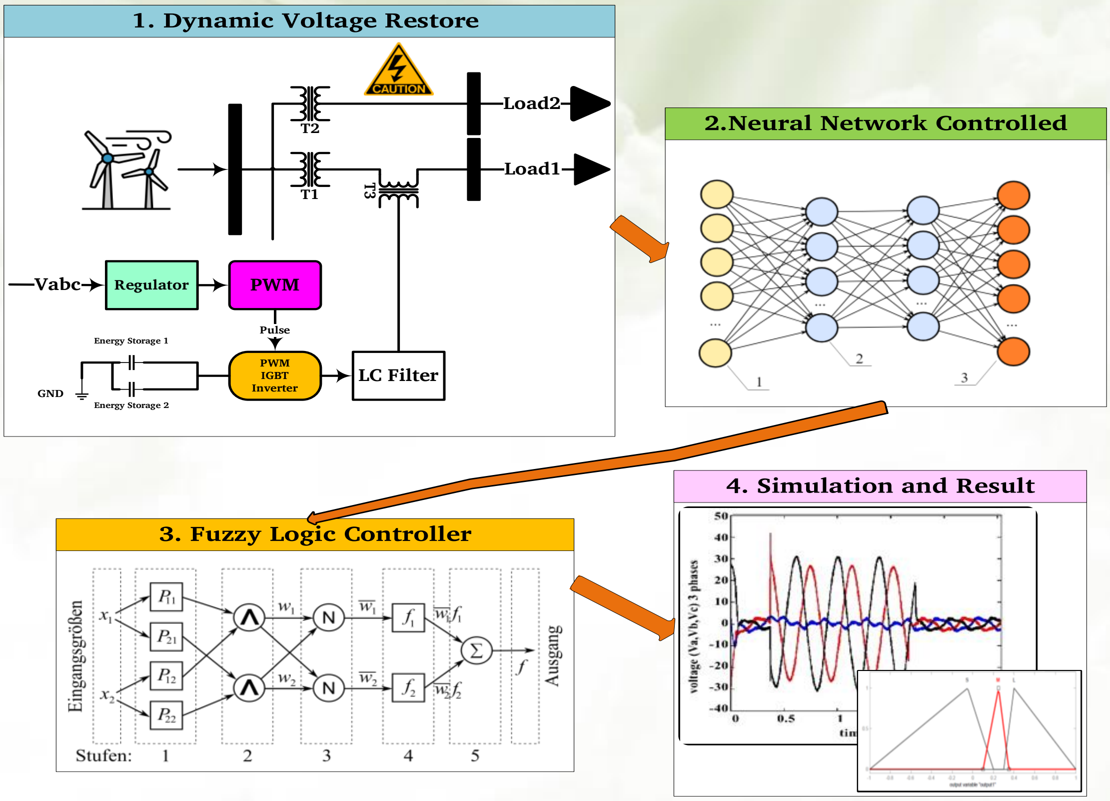
Highlight

- Adoption of a modified d-q converted three-phase voltage regulator
- Operation using an NN, FL, ANFIS, or PI controller instead of a three-phase regulator
- Rectifying voltage irregularities by promptly restoring the voltage to the nominal magnitude

Graphical Abstract



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Voltage Sag Reduction by ANFIS in Wind Turbine Generation Units

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ABSTRACT

The Power Quality (PQ) issue refers to the occurrence of irregular voltage, current, or frequency that leads to failure or incorrect functioning of equipment used by end users. The PQ meter is utilized to monitor a diverse range of power supply characteristics, all of which possess the capacity to impact the effectiveness of both operational procedures and machinery. The dynamic voltage restorer (DVR) performs the role of a specialized power device employed to mitigate the voltage drop experienced at the terminal of a sensitive load. DVR can be controlled by various control designs. This work conducts a comparative analysis on a normally managed voltage system and a medium-power DVR controlled by a neural network (NN), fuzzy logic (FL), or adaptive neuro-fuzzy inference system (ANFIS) by utilizing an output voltage regulator. The identification and rapid compensation of voltage perturbations, such as voltage sag, are essential elements in monitoring and controlling DVRs. The conventional PI controller is commonly employed in regulating DVRs. While the traditional controller possesses certain merits, it is not free of limitations. One such downside pertains to its utilization of constant gains, which can impede its capability to provide optimal control performance in instances where system parameters undergo fluctuations. Possible solutions have been proposed to effectively tackle this issue, such as the use of NNs, FL, or ANFIS controllers. Furthermore, to attain both rapid dynamic response and robustness, a modified d-q converted three-phase voltage regulator was adopted. Instead of employing a conventional three-phase regulator, this particular regulator is operated by means of an NN, FL, ANFIS, or PI controller. The suggested voltage regulator offers a prompt solution for rectifying voltage irregularities, such as voltage sag, by promptly restoring the voltage to the nominal magnitude. The primary source of power adopted in this study is a wind turbine unit.

1. Introduction

In a review of previous articles and research, it can be seen that the increasing prevalence of extremely responsive end-user devices has garnered the interest of both end consumers and providers concerning power quality [1]. The observed phenomenon can be attributed to the growing prevalence of a wide array of advanced electrical and electronic devices, including but not limited to computers, programmable logic controllers, and variable-speed drives. Today, the demand for electricity is so high that it is almost impossible to even imagine human life without it. This has imposed a lot of strain on governments to meet the huge demands for electricity. Therefore, the provision of quality energy has turned into one of the basic foundations of any country's macro-policies [2]. Voltage fluctuations can occur throughout or across a substantial segment of the system due to issues arising at either the transmission or distribution level.

Furthermore, under heavy load conditions, the system may experience a significant voltage drop. Voltage sags can occur at any given point in time, with magnitudes ranging from 10 to 90 percent and durations spanning from half a cycle to one minute [3]. Moreover, the nature of faults might vary, resulting in either balanced or unbalanced conditions, with magnitudes that may deviate from anticipated values. These magnitudes are impacted by factors such as the proximity to the fault and the interconnections among transformers.

In contrast, voltage swell is a sudden rise in the supplied voltage, measuring between 110% and 180% of the root-mean-square (RMS) voltage at the fundamental frequency of the network. This phenomenon persists for a duration spanning from 0.5 cycles to 60 seconds [3]. The relative infrequency of voltage swells in distribution networks diminishes their significance in comparison to voltage sags.

Several potential approaches to preventing voltage sag have been discussed in [4], including previous research in the field. The equipment and approaches that had been utilized were all taken into consideration with regard to voltage sags in radial and mesh grids. Within the scope of these investigations, the publications about issues that are associated with voltage sag have been categorized according to a set of predetermined criteria. Among these aspects is the evaluation of the unpredictability of the demand for electricity or the availability of renewable sources. A presentation has been made regarding the recommendations that pertain to the voltage sag research. The incorporation of the uncertainties associated with renewable energy sources and the usage of electricity serve as the foundation for these proposals. Reference [5] makes a contribution to creating a mitigation mechanism that is both cost-effective and efficient for voltage sag situations, both with and without the presence of distributed generation (DG) and renewable energy resources (RES). In [6], the optimal placement of DG units is determined in a network with unbalanced loads. To address this, parametric and cost functions have been developed to formulate the problem. A novel approach is employed to solve the unbalanced load flow problem, specifically utilizing the group search optimizer algorithm, which is a newly modified swarm intelligence algorithm discussed in this paper. The technique that has been provided in [7] is capable of evaluating the performance of voltage sag at wind turbine connection sites in a manner that is both efficient and precise. Furthermore, it offers a reliable long-term performance evaluation of the tendency and degree of voltage sag occurrence anticipated to generate wind turbine disconnection. The reduction and control of voltage sag in wind turbines, which is quite intriguing, have been the subject of articles published [8]. The primary objective of [9] is to investigate the impact that a voltage drop has on a wind turbine system equipped with a double-fed induction generator. Wind power converting systems can be modeled by space vector technology. Several different grid voltage disturbances are taken into consideration in this paper, and the performance of the system is analyzed.

The identification of voltage disturbances, such as voltage sag, and the prompt adjustment to mitigate these disturbances are two essential elements of DVR control. In a given scenario, it is commonly observed that a single-phase ground fault is responsible for inducing the most significant voltage drop. It can be inferred from this observation that the equilibrium of the voltage's typical waveforms is disrupted as the voltage decreases. When the d-q transformation is used for the three balanced power line voltages, the resulting value will be equivalent to the DC value that is directly related to the peak input voltage. This will enable accurate detection of voltage disturbances. In this instance, it is sufficient to compare the DC peak with the reference value [10] so that the voltage disturbance is accurately identified. Conversely, if the three input voltages are not in a state of balance, the result of the d-q transformation will encompass both the component of current ripple and the component of direct current. In the given situation, the inclusion of a low-pass filter (LPF) is important to effectively attenuate the alternating current (AC) component and accurately discern the precise occurrence of the voltage perturbation. Although the LPF may effectively attenuate the AC ripple, it is incapable of bypassing the inherent time delay necessary for accurately detecting the precise occurrence of a voltage disturbance. Furthermore, due to the prevalence of unbalanced line voltages during normal sag voltage scenarios, it becomes imperative to provide a zero-sequence voltage into the line. To facilitate the provision of a zero-phase sequence voltage, the system necessitates the incorporation of three single-phase inverters, along with either a five-leg transformer or three single-phase transformers. In the given case, it is unfeasible to use the commonly used three-phase d-q transformed voltage control method [11-12] to regulate the output voltage. To rectify the asymmetrical voltage disruption, it is important to employ a voltage regulation mechanism for the inverter.

Currently, there is a notable increase in public interest in many techniques encompassed under artificial intelligence (AI), including NNs, FL, and genetic algorithms (GA). A novel method for detecting voltage disturbances is formulated and suggested, employing NNs, FL, or ANFIS control, in this research as its novelty and main contributions.

The identification of voltage disturbances can be achieved even in scenarios characterized by very imbalanced voltage conditions. The reason for this is that these methodologies enable the measurement of the magnitude of the three-phase voltage. An alternative approach to attaining a rapid dynamic response involves the utilization of a modified d-q transformed voltage regulator in the context of an inverter. The control of the regulator for the three voltage phases in this approach is achieved by the utilization of various control mechanisms, such as NNs, FL, ANFIS, or PI controllers. The application of voltage regulators enables the quick adjustment of voltage perturbations, such as voltage sag, thereby restoring the voltage level to its nominal value promptly.

The employment of a DVR is commonly acknowledged as a highly economical strategy for addressing voltage sags and swells, notwithstanding the existence of various alternative options. The incorporation of a PI controller in a DVR result in a design that is both uncomplicated and capable of delivering satisfactory performance in a wide range of operational scenarios. The fundamental concern that necessitates attention in the context of conventional controllers pertains to the tuning of controller gains. There is a potential for the controller to exhibit inadequate control performance using fixed gains when changes occur in the quantities of the system and operation status and one of the motivations and the necessity of this research is to solve this problem.

The use of NNs, FL, or ANFIS methodologies can be employed to effectively address a diverse set of operational scenarios. Nevertheless, a challenge occurs concerning the parameters linked to the number of neurons in the NN approach or membership functions in the fuzzy method, along with the rules, which heavily rely on the expertise of the professionals. In the case that it becomes necessary to modify the settings, the sole method available is a process of experimentation and refinement. The ANFIS method is employed to effectively tackle the previously mentioned problem and improve the controller's adaptability. The ANFIS approach involves the generation of a fuzzy inference system by employing a chosen set of input and output data. In contrast, the outcomes of the simulation revealed that both an NN and a simplistic FL controller exhibit a satisfactory disposition. This implies that the utilization of an ANFIS controller structure may not be essential for achieving improved outcomes. However, it would also indicate that building an ANFIS controller is comparatively less complex than alternative methodologies. This paper presents an analysis of the DVR and its underlying functioning concept. Furthermore, the present study examines the suggested controller, which encompasses potential options, such as an NN, FL, or ANFIS controller. Subsequently, the outcomes of the simulations conducted using the MATLAB/Simulink platform provide a comparative analysis of the suggested solutions regarding their performance in voltage sag and swell, respectively. After conducting a comparative analysis of the injection voltages employed in different methodologies, the findings are presented in this article along with detailed explanations and a concluding statement.

The paper is organized as follows. Section 2 explains the DVR. Then, Section 3 discusses its operating principles. Section 4 presents the DVR scheme. Section 5 presents the neural network-controlled disturbance detector. Voltage regulator by adopting a modified d-q transformation method is discussed in Section 6. The neural network method is implemented in Section 7. Section 8 is dedicated to the fuzzy logic control of the DVR. Section 9 is related to the design of the DVR with an ANFIS controller, and Sections 10-12 present the simulation results and suggestions for future research.

2. Dynamic Voltage Restorer (DVR)

The DVR is connected in series to provide voltage to the system so that load voltage is properly regulated. The DVR was developed around three decades ago [13]. The customary placement site for this component is within a distribution system, more precisely positioned between the power source and the feeder responsible for the

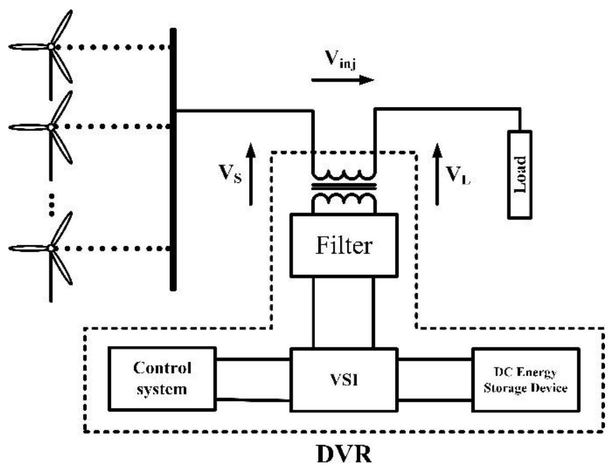

Figure 1. A schematic of a DVR.

important load. If a disturbance occurs, its primary objective is to promptly raise the load voltage to avert any power interruptions to the load mentioned [14]. Various control algorithms and circuit topologies can be employed to develop a DVR [15-16].

In addition to its core function of voltage oscillation compensation, a DVR may be enhanced with supplementary features, including the adjustment of voltage harmonics, the mitigation of voltage transients, and the restriction of fault currents [17]. The full design of a DVR consists of several key components, namely a voltage injection transformer, an output filter, energy storage equipment, a voltage source inverter (VSI), and a control platform. Figure 1 shows the ultimate arrangement of the DVR.

2.1. Voltage Injection Transformer

By utilizing the high-voltage windings, this transformer facilitates the establishment of a connection between the DVR and the distribution network. Moreover, it is capable of effectively integrating the injected compensating voltages produced by the VSCs with the supply voltage. This transformer's design holds significant relevance due to its susceptibility to saturation, overrating, overheating, cost, and performance. It is conceivable that the injected voltage may encompass fundamental harmonics, switching harmonics, and potential components of the DC voltage [18]. When the transformer design is not acceptable, the injected voltage could possibly cause saturation in the transformer. This saturation could result in the DVR not operating effectively [19].

2.2. Output Filter

The major function of the output filter is to mitigate the presence of high-frequency switching harmonics. This filter is tasked with regulating the harmonic voltage content generated by the VSI, ensuring its compliance with relevant standards. The rating of the load VA is approximately 2% [20], which is a low value.

2.3. Voltage Source Inverter

A VSI is a power electronic system comprising switching devices such as IGCTs, IGBTs, and GTOs. It can generate a sinusoidal voltage with adjustable frequency, magnitude, and phase angle as required. The utilization of the VSI in the DVR application serves the purpose of either temporarily substituting the supply voltage or creating the missing portion of the supply voltage [21].

2.4. DC Energy Storage Device

The DC energy storage device is responsible for providing the DVR with the necessary power during the compensatory procedure. Various alternative storage methods have been suggested, including flywheel energy storage [22], superconducting magnetic energy storage (SMES) [23], and supercapacitors [24-25]. These possess the advantage of exhibiting a rapid response time. The utilization of a lead-acid battery represents an alternate option [21-22]. The time-consuming process of extracting energy from batteries has led to the perception that batteries have limited suitability for usage in DVR applications [16]. Finally, conventional capacitors are an alternative that can be employed [26-27].

2.5. Control system

The primary goal of the control system is to preserve a consistent voltage at the load connection point, even in the presence of disturbances within the system. The inclusion of a voltage correction mechanism is a common practice in the control system of the general design. The function is responsible for ascertaining the appropriate reference voltage to be injected by the DVR. Moreover, the VSI control, as elucidated in this study, consists of a Pulse Width Modulation (PWM) controller integrated with a PI controller. The controller input is a type of error signal that is obtained by comparing the reference voltage with the injected voltage value, as depicted in Figure 2. Once a PI controller processes the error, the resulting output is fed into a PWM signal generator. This generator is responsible for regulating the operation of the DVR inverter, ensuring the appropriate injected voltage is provided.

3. Operating Principle of DVR

One of the principal roles of the DVR is to dynamically regulate the bus voltage by injecting a voltage, denoted by Vinj. This is achieved by employing a voltage injection transformer. The management of the momentary magnitudes of the three injected phase voltages is designed to mitigate or prevent any adverse effects that may arise from a bus malfunction on the load voltage VL. This suggests that any variations in voltage resulting from disruptions in the alternating current feeder will be counterbalanced by a corresponding voltage. There is no discernible association between the nature of a malfunction or any event that transpires within the system and the operational capacity

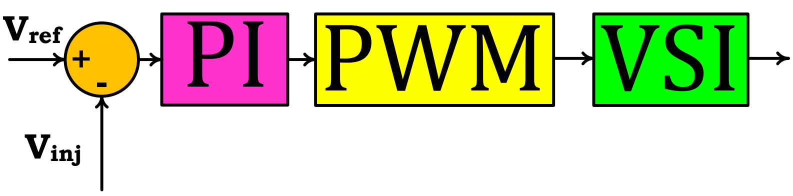

Figure 2. A classical PI controller.

of the DVR. Due to the infinite impedance of the step-down transformer for the zero-sequence component, it is possible to achieve a more economic configuration by solely addressing the positive and negative sequence components of the voltage disturbance observed at the input of the DVR. This argument holds true for the majority of practical instances.

The DVR offers two operational modes: standby mode and turbo mode. During the standby state (V_{inj} =0) of the voltage injection transformer, the low voltage winding is found to be short through the converter. The absence of semiconductor switching is a characteristic of this operational mode, as the triggering of individual inverter legs is designed to create a short-circuit path for the transformer connection. The DVR will mostly utilize this mode for the majority of its operational duration. During the boost mode, characterized by a positive V_{inj}, the DVR encounters a disruption in its supply voltage. Consequently, it responds by introducing a compensatory voltage via the voltage injection transformer.

4. DVR scheme

The conventional power circuit of a DVR comprises several components as depicted in Figure 3. Switches S1, S2, and S3 are employed for maintenance. Both the charging transformer (TR1) and the rectifier (REC) possess a power rating that is significantly inadequate. In the standby state of operation, the sole requirement is to charge the capacitor responsible for energy storage. During the standby state, it is observed that all switches in the inverter are in the off mode. Additionally, the secondary winding of the series transformer (TR2) is found to be short-circuited by bypass thyristors (BS).
In standby settings, the series transformer must possess a low leakage reactance to minimize the undesired voltage drop across the transformer. In the event of a voltage distribution breakdown, the bypass switches (BS) are deactivated by means of control over the inverter. The process involves introducing the regulated voltage into the series transformer, thereby transferring the energy held in the DC capacitor. After deactivating all bypass switches, the inverter is regulated to rectify the voltage disturbance. The control block diagram of the DVR consists of three main components, namely the voltage regulator component, the phase tracking component (PLL), and the voltage magnitude tracking control component, as depicted in Figure 4.

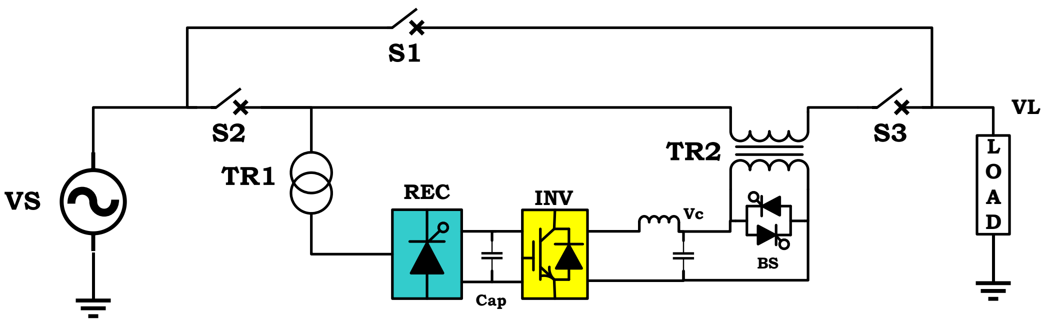

Figure 3. The configuration of the DVR.

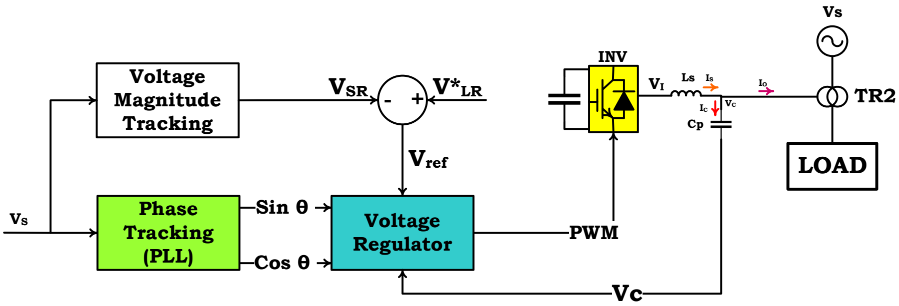

Figure 4. The control configuration of the DVR.

The initial stage involves the utilization of NN, FL, or ANFIS control methods by the magnitude tracking component to ascertain the magnitude of the input voltage Vs(t). The aforementioned methodologies possess the capability to expeditiously monitor the magnitude of the input voltage, particularly in instances where voltage perturbations, such as voltage sag, are present.

Additionally, the phase tracking component is tasked with ascertaining the phase angle of the input voltage Vs(t) during the system's standby state. Conversely, in the event of a phase leap and voltage sag occurring in the input voltage waveform, the phase tracking component generates a reference waveform that remains unaffected by the fluctuations in the input voltage waveform. The phase-locked loop (PLL) module is tasked with the responsibility of accurately monitoring and adjusting the phase of the input voltage signal. Its primary objective is to produce a sinusoidal reference waveform in-phase with the input signal. This synchronized reference waveform is then utilized for control objectives.

The voltage regulator assumes the responsibility of regulating the single-phase inverter to rectify any disruptions in the input voltage. The achievement of this objective is facilitated by employing the outcomes of the phase tracking module and the voltage magnitude tracking module.

The voltage regulator block generates a signal known as PWM. Figure 4 illustrates that the voltage regulator acquires phase information from the phase tracking component and magnitude information from the magnitude tracking portion. These components will be further elaborated upon in the following sections. The load voltage reference V_{LR}^* is generated by monitoring the magnitude of the input voltage. When the input voltage level is within acceptable limits, the value of V_{LR}^* will be equivalent to the magnitude (V_{SR}) of the input voltage. Conversely, when the input voltage exceeds the voltage tolerance threshold, the magnitude of V_{LR}^* will assume a fixed value equivalent to the reference voltage. In the context of a single-phase inverter, the voltage regulator's voltage reference is established based on the disparity between the input voltage's magnitude and the magnitude of the reference voltage.

5. Neural Network Controlled Disturbance Detector

Previous studies have shown evidence that NNs possess the capability to undergo training processes that enable them to perform intricate tasks across several fields of application. These tasks encompass but are not limited to pattern recognition, identification, classification, speech processing, visual analysis, and control systems.

The artificial neural network (ANN) control system is classified as a non-linear control method. The system possesses the capability to adapt and arrange itself. ANN enables the monitoring of nonlinear interactions by utilizing input and output data, hence eliminating the requirement for a comprehensive mathematical model [28]. The categorization of ANN control can be based on the network's architecture, which often falls into four distinct categories: feedforward neural networks, feedback NNs, local approximation NNs, and fuzzy NNs.

Considering the input voltage as $v = V_m \sin(\omega t + \theta)$, it can be rewritten as Equation (1) by adopting the trigonometric formula.

$$v = V_m \cos(\theta) \sin(\omega t) + V_m \sin(\theta) \cos(\omega t) \tag{1}$$

Equation (1) reveals that the equation consists of sinusoidal terms, including $\sin(\omega t)$ and $\cos(\omega t)$, along with magnitude terms that are contingent upon θ.

Equation (2) can be derived from Equation (1) by applying the delta rule of the NN, as stated in reference [28].

$$Y = WX \tag{2}$$

Where Y denotes the estimated value by the delta rule. Also, W and X are calculated by Equation (3) as follows:

$$\begin{aligned} W &= [V_m \cos(\theta) \quad V_m \sin(\theta)] \\ X &= [\sin(\omega t) \quad \rightleftarrows\rightleftarrows \cos(\omega t)]^T \end{aligned} \tag{3}$$

Figure 5 depicts an instance of the adaptive linear combiner that is controlled by an NN and employs the delta rule. In the given context, the output of this specific instance is determined by a linear combination of its two inputs, denoted by $\sin(\omega t)$ and $\cos(\omega t)$.

The weight vector W is utilized to assign weights to the components of the input vector, thereby forming several coefficients. Subsequently, the weighted inputs are calculated, leading to the generation of a linear output known as the inner product Y. X might consist of either continuous analog values or binary data. Both types of values are potentially attainable. This implies that the weights undergo continuous fluctuations and can assume values that are either positive or negative.

During the training phase, the linear combiner is provided with input patterns and their corresponding desired replies. The adaptation method automatically sets the weights to ensure that the output responses to the input patterns closely approximate the desired responses for each pattern. A potential formulation of the equation that characterizes the adaptation process can be denoted as Equation (4).

$$W(k+1) = W(k) + \mu X(k) e(k) \tag{4}$$

Where μ is the training rate.

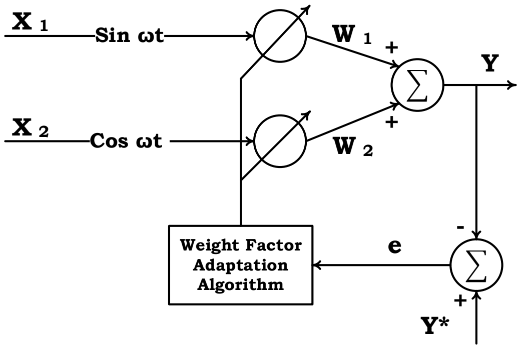

Figure 5. An NN-controlled adaptive linear combiner.

The weighting factor, represented by W, will attain its maximum value of Y if the training operation is successful. By monitoring W, it was feasible to obtain the maximum value of the input voltage instantaneously without any temporal delay.

Additionally, the utilization of an NN-driven approach enables the independent tracking of the peak phase voltages, hence presenting another advantageous aspect of this methodology. If a disturbance affects solely one- or two-phase voltages, it becomes feasible to exclusively regulate the phase voltages associated with those specific disturbances. In the context of the synchronous reference frame approach, however, the task of independently identifying and regulating corresponding phases poses significant challenges.

6. Voltage regulator by adopting a modified d-q transformation method

Figure 6 displays the control design of a voltage regulator for a single-phase inverter. The utilization of a standard voltage regulator with three-phase d-q transformation in [29-30] was rendered impracticable due to the discrepancy between the controlled inverter system, which is a single-phase inverter, and the required three-phase inverter. Alternatively, if it is feasible to find the q-axis component (V_{qs}) in Figure 6, despite the anticipated voltage of the inverter capacitor being the d-axis component (V_{ds}), the commonly used three-phase d-q transform can be employed. The utilization of the phase shift filter is a technique that can be employed to obtain the q-axis variable, commonly referred to as V_{qs}. Nevertheless, this approach exhibits a high degree of sensitivity towards variations in the frequency of the voltage employed as the input. Furthermore, the performance of a phase shift filter is notably suboptimal when utilized for voltage transients, such as instances of voltage sag. In the context of this article, it is assumed that the energy storage remains constant, while the voltage regulator is tasked with initiating PWM. The normal three-phase voltage regulator is modified to function as a single-phase voltage regulator, as seen in Figure 6.

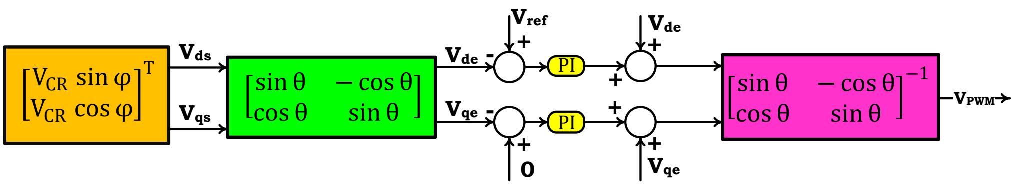

Figure 6. The control block diagram of the voltage regulator for single-phase inverter.

The q-axis variable can be defined with the assumption that the voltage of the inverter filter capacitor is a d-axis variable.

$$V_{ds} = V_c(t) = V_{CR} \sin\varphi \quad (5)$$

$$V_{qs} = V_{CR} \cos\varphi \quad (6)$$

in which ϕ denotes the phase shift between the voltage of the capacitor and the voltage of the utility input, $v_s(t)$. By utilizing the control block configuration depicted in Figure 6, it becomes feasible to attain Equations (7-8).

$$V_{de} = V_{CR} \sin\varphi \sin\theta + V_{CR} \cos\varphi \cos\theta \quad (7)$$

$$V_{qe} = V_{CR} \cos\varphi \sin\theta - V_{CR} \sin\varphi \cos\theta \quad (8)$$

Assuming that the inverter capacitor voltage is properly regulated, we have $V_{CR} = V_{ref}$ and $\phi = \theta$. Thereby, Equations (9-10) will be expressed noting Equations (7-8) as follows:

$$V_{de} = V_{ref} \quad (9)$$

$$V_{qe} = 0 \quad (10)$$

Considering the q-axis variable, we have

$$V_{qs} = V_{ref} \cos\theta \quad (11)$$

$$V_{ref} = V_{SR} - V_{LR}^{*} \quad (12)$$

However, Equations (9-10) can only be effectively used in ideal circumstances. In reality, it becomes imperative to account for other factors, such as compensating for the time delay caused by the inverter LC filter and the adverse impacts of dead time on the inverter switches. To mitigate the suboptimal effects, a PI controller and a feed-forward control scheme incorporating V_{de} and V_{qe} components have been employed. The magnitude (V_{qe}) is effectively regulated to a value of zero, resulting in the utilization of the d-axis controller's output for the generation of the PWM signal. It is crucial to consider that the q-axis variable (V_{qs}) can solely be obtained from Equation (11) by the utilization of the voltage reference (V_{ref}) and phase tracking information $(\cos\theta)$ as mentioned in references [31-32].

7. Implementation of Neural network method

The utilization of the synchronous reference frame (SRF) approach is based on the instantaneous values of the source voltage (v_{sa}, v_{sb}, v_{sc}). This approach is employed to generate the reference voltages $(V_{ca}^{*}, V_{cb}^{*}, V_{cc}^{*})$ necessary for implementing the neural network method [33]. The adoption of reference voltages is necessary for the implementation of the NN approach. Abnormal situations and deviations in supply voltage can be identified by examining the disparity between the d-voltage of the supply and the d-reference value. This action is undertaken in the event of an occurrence that deviates from the usual, commonly known as an abnormal state. The control methodology generates a reference voltage that accurately represents the three phases. The reference voltage is transmitted via a controller, subsequently generating a switching signal to facilitate the activation of the power switching components within the VSI. This guarantees that the DVR will effectively provide the necessary reference voltage as demanded by the system. Lastly, it is imperative to guarantee that the load voltage remains consistent with its designated reference standard.

This method has the potential to be employed for the mitigation of other forms of voltage oscillations, such as voltage sag/swell, voltage unbalance, and harmonic voltage. However, the focus of this study is solely on investigating voltage sag/swell as a form of voltage disturbance. The load-rated voltage is produced by applying the voltage difference between the reference voltage and the injected voltage to the voltage source, resulting in the generation of the load-rated voltage, as illustrated in Figure 7. The DVR operates in a state of low power consumption throughout its normal functioning, hence avoiding any instances of voltage sag or swell. The DVR is considered to be in a state of constant equilibrium during its operation under these specified conditions.

The Multilayer Feed Forward Neural Network (MLFFN) is a widely adopted topology in contemporary applications [34-35]. This specific network is comprised of several output neurons and some intermediate neurons, also called hidden layers. Initially, the transmission of data across the network is facilitated by the input layer. Subsequently, the information propagates through the concealed levels and ultimately emerges via the output layer. Figure 8 illustrates a block diagram of a three-layer MLFFN interconnected by weight matrices W and bias vectors b. These weight matrices and bias vectors serve as the free parameters inside the network.

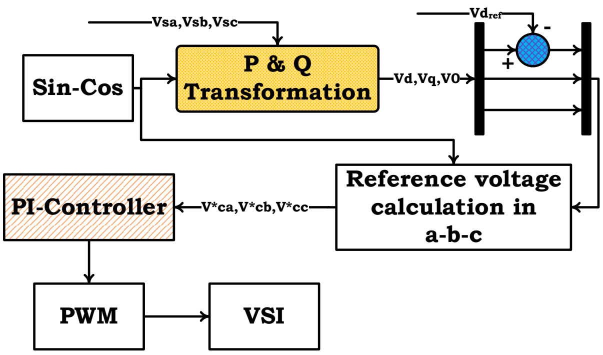

Figure 7. The control of the injected voltage by adopting the traditional PI controller (CPI).

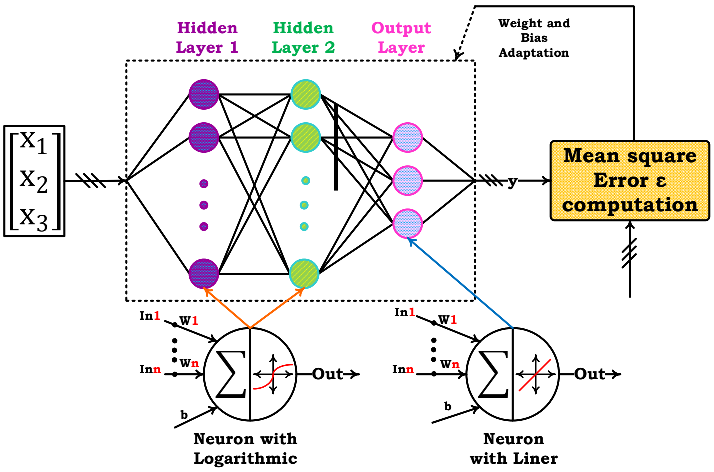

Figure 8. An NN for modeling.

The ANN utilizes training to modify the weight matrix (W) and bias vector (b). The ANN is designed to approximate its function to that of the system in a manner that is executed. Furthermore, the ANN aims to reduce the discrepancy between the observed output y and the reference function, given by ε. Each of the inputs in the input column vector x is allocated with a suitable weight, represented by W. The transfer function f receives an input that consists of the sum of the weighted inputs, in addition to the bias term. The activation vector, denoted as a, is calculated by Equation (13):

$$a = \sum(w.x + b) \tag{13}$$

In the context of generating their output, neurons possess the capability to utilize a wide range of differentiable transfer functions. The tan-sigmoid transfer function, commonly referred to as the tansig function, is employed in both the input layer and the hidden layer in this specific case.

$$tan\,s\,ig(a) = \frac{2}{1+e^{-2a}} - 1 \tag{14}$$

In contrast, the output layer employs the linear transfer function known as *purelin*.

$$purelin(a) = a \tag{15}$$

The present study used the least mean square error (*LMS*) approach for training supervision. During this procedure, the learning rule is applied based on a predetermined set of desired network behaviors, encompassing the subsequent aspects:

$$\{x_1, y_1\}, \{x_2, y_2\}, \dots \{x_n, y_n\} \tag{16}$$

in which the variable x denotes an input provided to the network, while the variable y indicates the related output that aligns with the target. After each input is applied to the network, the network's output is assessed in relation to the target. A distinction exists between the goal output and the network output, and this distinction is utilized to ascertain the inaccuracy. The average of the sum of the errors is calculated as follows:

$$\varepsilon = \frac{1}{n}\sum_{k=1}^{n} e(k)^2 \tag{17}$$

$$\varepsilon = \frac{1}{n}\sum_{k=1}^{n} \left(y(k) - y'(k)\right)^2 \tag{18}$$

The potential output of the network is y', whereas the output of the target can be denoted by y. The primary objective of the LMS method is to iteratively modify the weights and biases of the linear network to find the minimum mean square error to the greatest extent possible [36].

8. Fuzzy Logic Control of DVR

Due to the increasing adoption of power semiconductor switches in bespoke power devices, the system exhibits non-linear characteristics, rendering it challenging to conceptually characterize and intricate in nature. The fuzzy logic system is an exceptional and robust approach that exhibits the ability to concurrently employ quantitative information and experiential knowledge [37]. FL is an approach applied in the control system method and can be incorporated in various systems, spanning from compact, embedded microcontrollers to extensive, networked, multi-channel PC or workstation-based data gathering and control systems [38-39]. It is a computational approach that can be employed for problem-solving in the domain of control systems.

In recent years, there has been an increasing demand for FL-controlled applications because of the advancing complexity of contemporary technology. In several cases pertaining to the control process, the absence of a mathematical model or the excessive computational demands in relation to available computer processing power and memory may impede its implementation. In these particular cases, a system that relies on empirical criteria may demonstrate more efficacy. Furthermore, FL proves to be a highly suitable option for cost-effective applications that rely on affordable sensors, low-resolution analog-to-digital converters, and single-chip microcontroller processors with a capacity of either four bits or eight bits. The enhancement of system performance can be achieved by the incorporation of additional rules, while the integration of new features facilitates seamless system upgrades. The integration of an additional layer of intelligence into the preexisting control mechanism represents one of the various methods by which fuzzy control can be employed to augment the efficacy of conventional controller systems that are currently operational.

An additional approach to exert control is through the utilization of FL control in the context of voltage injection within a DVR. This design philosophy deviates from previous approaches by incorporating the expertise of controller design specialists. The concept originates from the fuzzy set theory. There exist scenarios where it is not feasible to establish accurate mathematical formulations, thus making FL controllers an attractive substitute. One benefit of utilizing this controller is its ability to mitigate the inaccuracy and transient overshoot associated with PWM.

The conventional PI controller is substituted with the fuzzy logic controller (FLC) to attain the intended outcomes. The voltages produced by the three-phase source undergo a conversion process into the d and q coordinates, as described in reference [38]. A comparison is conducted between the reference values for V_d and V_q and the altered values, resulting in the acquisition of voltage errors. The processing of these problems is carried out by a pair of FL controllers. In order to generate PWM inverter signals, the outputs produced are subsequently converted back into the three-phase domain and subsequently compared with a carrier signal.

Contrary to conventional controllers, the application of a mathematical model of the regulated system process is not a prerequisite for the implementation of a fuzzy logic controller. Therefore, it is necessary to possess a comprehensive understanding of the system's operational procedures and the associated control prerequisites. The designer of the fuzzy controller must establish the control input variable, control strategy and decision, and solution output variable to determine the information data that enters the system, how they are processed, and the information data that exit the system. The FLC comprises three main components that serve as its building blocks. The user's text does not contain any information to be rewritten. The three components are the fuzzifier, inference engine, and defuzzifier.

8.1. Fuzzifer

To guarantee the effective functioning of the FLC, it is imperative that all control and solution variables, which play a crucial role in creating the control surface, are formulated using fuzzy set notations accompanied by linguistic labels. The process of decomposing each system variable into fuzzy regions is achieved by employing a set of three distinct classes of linguistic labels, which are described by their respective membership grades. This is undertaken to streamline the procedure. One method for quantifying the extent to which a variable is linked to a certain category or label is to employ the concept of membership grade. The term "fuzzification" refers to the procedure of converting input/output variables into linguistic labels. When the program is executed, it utilizes reference fuzzy sets for the inputs d and q, as depicted in Figures 9 and 10. The fuzzy sets are subsequently employed to establish a fuzzy set that expresses the notion corresponding to the label in a semantic manner. To ensure a seamless and solid control surface, it is important to establish an overlap between successive labels. The design of the overlap should be such that the cumulative vertical points of the overlap do not exceed a value of one.

The membership function of input-d and input-q is constructed using a direct method, as depicted in Figures 9 and 10. The use of an error rate signal, such as the discrepancy between the actual signal and its converted version, is a prudent choice. However, the input signals themselves are employed in this study to simplify and expedite the response time for the FL approach.

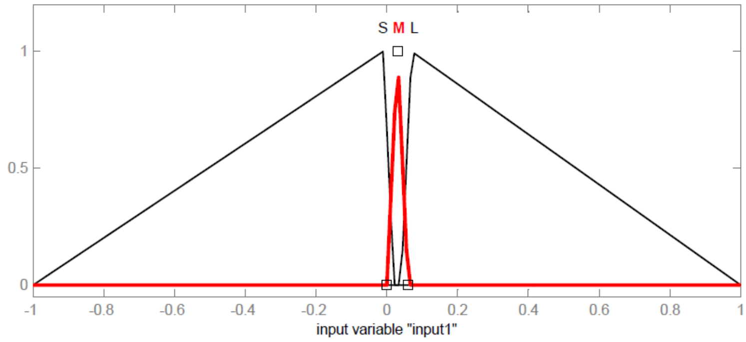

Figure 9. Membership function input-d.

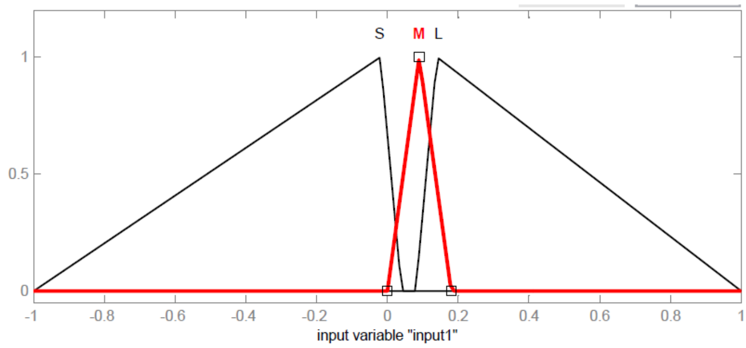

Figure 10. Membership function input-q.

8.2. Inference Engine

The control surface is subject to a set of regulations that dictate its functioning, specifically in terms of establishing a connection between the input variables of the system and the corresponding output variables. The proposition (fuzzy proposition) implies (fuzzy proposition), exemplifying a frequently employed rule. The set of rules for the fuzzy controller is obtained from the MacVicar-Whelan decision table, as shown in Table 1. The table shown in this context proposes a clear and specific course of action for a particular set of uncomplicated rules since it solely necessitates a single input. These principles are employed to ascertain the most appropriate course of action for control. Every rule that contains at least some level of truth (a value greater than zero for membership grade) in its premises is activated upon reading a set of input variables. This action facilitates the development of the control surface by its proper modification. In the case a given set of input variables is received, every rule is triggered. Once all the rules have been executed, the final control surface is characterized as a fuzzy set. This is achieved by utilizing linguistic labels defined by membership grades. The purpose of this representation is to symbolically reflect the output of the controller.

8.3. Defuzzifier

For the system to function efficiently, it is necessary to transform the fuzzy set that represents the controller output in linguistic labels into a crisp solution variable for which a defuzzifier is utilized. There are several different defuzzification strategies from which one might choose. When it comes to estimation, the two methods that are utilized the most frequently are the Mean of Maxima (MOM) and the Center of Area (COA). It is typical practice to implement this method in the majority of control applications. This method delivers a result that is very responsive to all of the rules that are being executed, and it does so by calculating the centroid of the ultimate fuzzy region, which is also widely referred to as the control surface. As a consequence, the results tend to transmit without interruption throughout the control surface. It is executed using reference fuzzy sets shown in Figures 11 and 12 for outputs d and q.

Table 1. The fuzzy control rules.

No.	Rule
1	If input 1 is S, then output 1 is S.
2	If input 1 is M, then output 1 is M.
3	If input 1 is L, then output 1 is L.

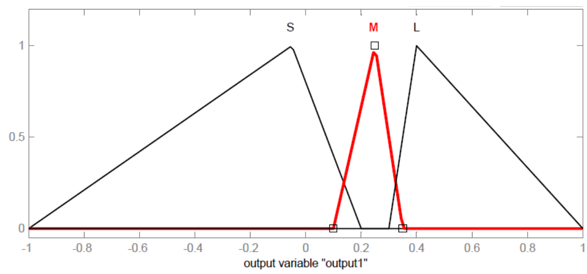

Figure 11. The membership function output-d.

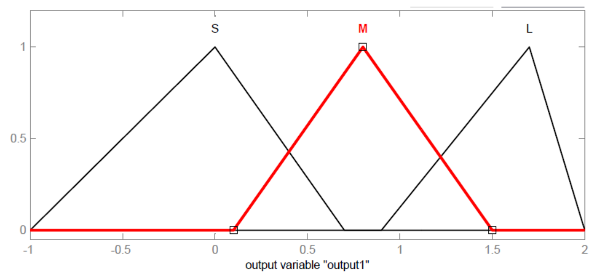

Figure 12. The membership function output-q.

9. Design of DVR with ANFIS Controller

The Adaptive-Neuro-based Fuzzy Inference System (ANFIS) is a variant of the Fuzzy Inference System (FIS) that may be integrated into adaptive networks. The ANFIS serves as a fundamental framework for developing a collection of fuzzy rule bases, which incorporate the necessary membership functions to establish the desired input and output pairings as defined. The produced Fuzzy Inference System (FIS) transfers the qualities of the input to the membership functions of the input, thus influencing the rule base. A correspondence exists between the established rules and a collection of output attributes, whereby the output attributes are converted into the output membership function to generate a singular, definitive result.

9.1. Creating Neuro-Fuzzy Inference System

The proposed ANFIS controller is trained using the generated FIS by mapping the calculated input-output data. A hybrid learning algorithm is used to train the proposed ANFIS controller during 45 epochs. Figure 13 shows the structure of the generated FIS with two inputs and a single output, each having two membership functions. Here, unlike the FL, which is described later, there are two inputs for each structure, one of which is the actual signal (*Vp* or *Vq*) and an error rate signal between this actual signal, and the transformed actual signal is another input.

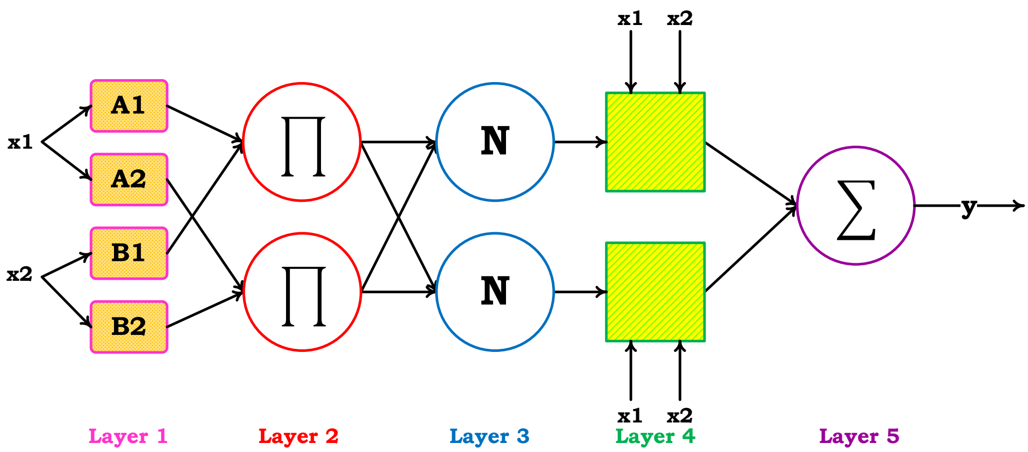

Figure 13. The structure of the generated neuro-fuzzy inference system.

Table 2. System and DVR parameters and constants.

Voltage source	22.5 kV, 50 Hz	
Basic load	2000 kVA	
Load	2500 kVA	
Tr. basic load	2.5kV, 20000,380	
Tr. load	2.5kV, 20000,380	
DVR	DC link voltage	100V
	PWM frequency	10 kHz
	Filter L	6 mH, 0.2 Ohm
	Filter C	20 uF, 0.2 Ohm
	Injection Tr.	1.5kV,100,1000

10. Simulation

The performance enhancement of the DVR in mitigating voltage sag and swell is demonstrated by the simulation of a simplified distribution system in MATLAB/SIMULINK, using the suggested controller. Table 2 presents a summary of the system's parameters and the constant value. It is assumed that the load bus voltage remains constant at 1 per unit (p.u.) during voltage sags and swells. Several figures depict the simulation findings that were deemed to be the most noteworthy.

The phrase "line voltage notch" pertains to a decrease in the supplied voltage that manifests as a dip in the waveform of the line voltage. This phenomenon is observed when the electrical current transitions between the phases. During the notching interval, a transient short circuit occurs between the two commutating phases, leading to a decrease in the line voltage. The supply impedance is the primary determinant of the extent to which voltage reduction is limited.

The use utilization of the conventional PI controller is a widespread practice in the regulation of DVRs. Nonetheless, this traditional controller relies on constant gains, which may result in inadequate control performance in the presence of parameter fluctuations within the system. Throughout this inquiry, a comprehensive analysis has been conducted to compare the performance of the DVR under two distinct scenarios: one utilizing the standard PI controller, and the other employing advanced control techniques such as NN, FL, or ANFIS controllers. In the initial situation, the DVR is tasked with showcasing the smoothness and appropriateness of the signal shape of the injected voltage. In the second scenario, the waveform of the load voltage signal is susceptible to either being accepted or rejected. Implementation of the NN, FL, ANFIS, and PI controller for three phases is shown in Figure 14.

The main structure of all four methods is the same and only the voltage regulator design differs from each other. For example, the voltage regulator design of NN, FL, and PI methods are demonstrated in Figures (15-17), respectively.

DVR system has some structure inside, e.g., the LC filter of DVR shown in Figure 18.

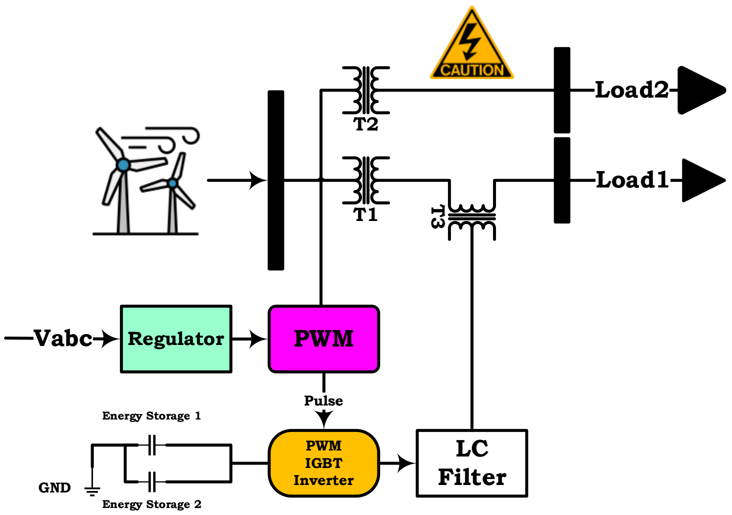

Figure 14. A schematic of DVR implementation by MATLAB/SIMULINK software.

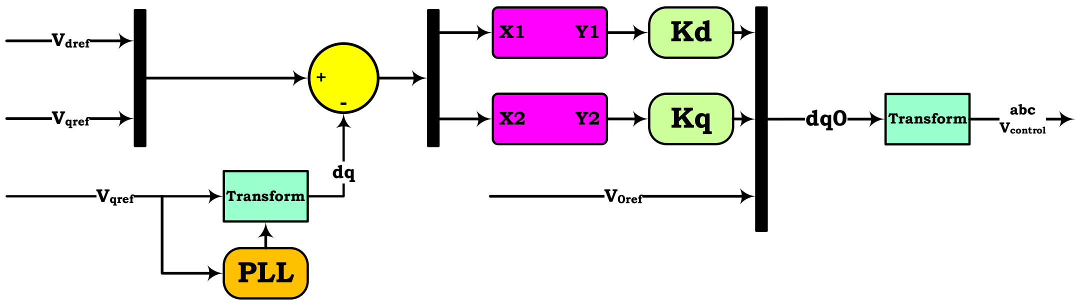

Figure 15. The regulator structure of DVR for NN.

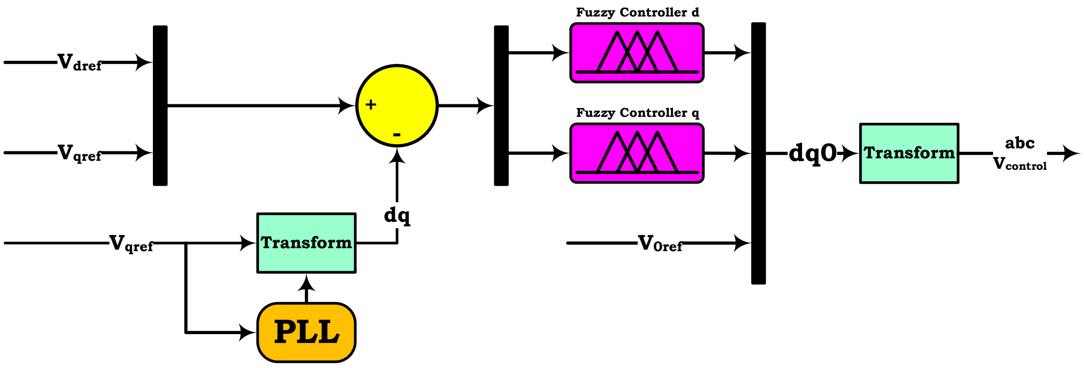

Figure 16. The voltage regulator structure of DVR for FL.

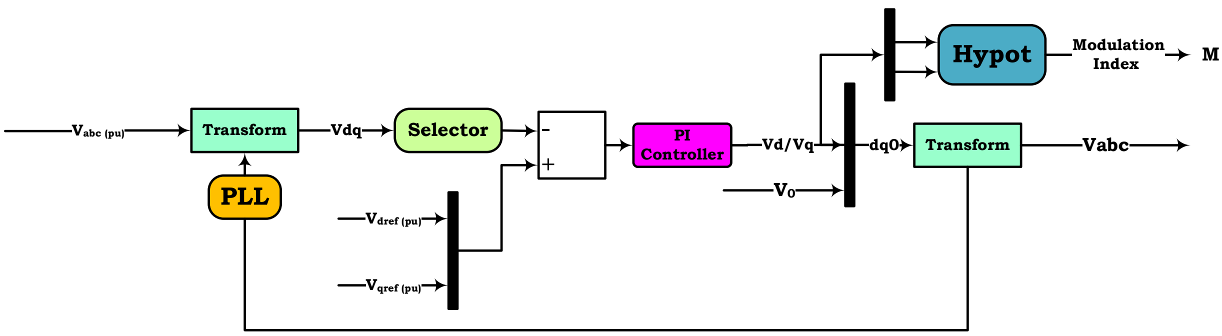

Figure 17. The voltage regulator structure of DVR for PI controller.

Figures 19 and 20 show a three-phase voltage sag simulated for PI and NN methods, respectively. The simulation started with a supply voltage of 100% and a phase (B)-to-ground fault with 1.8 Ohm fault resistance occurs from 0.019 sec to 0.085 sec, resulting in sagging as per Figures 19(a-e) and 20(a-e) for the PI and NN methods, respectively. Furthermore, Figures 19(c) and 20(c) illustrate the voltage injected by the DVR, along with the related load voltage after correction. The load voltage is sustained at a value of 1 p.u. due to the presence of the DVR. The comparison of these two signals in Figures 19(c) and 20(c) demonstrates the better injection of voltage by the NN method. The load voltages of the two methods are acceptable but, the se of the NN method results in more balanced and better shape of voltage. Figure 21 is a comparison between the sSource voltage and the critical load voltage in NN, showing that an acceptable compensation is done.

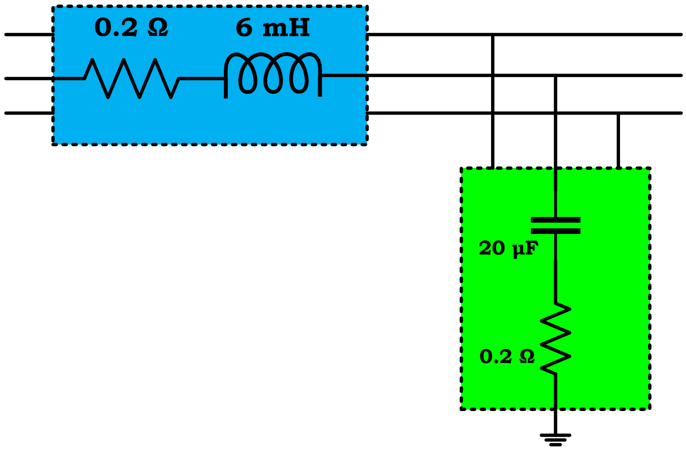

Figure 18. The LC filter structure of DVR.

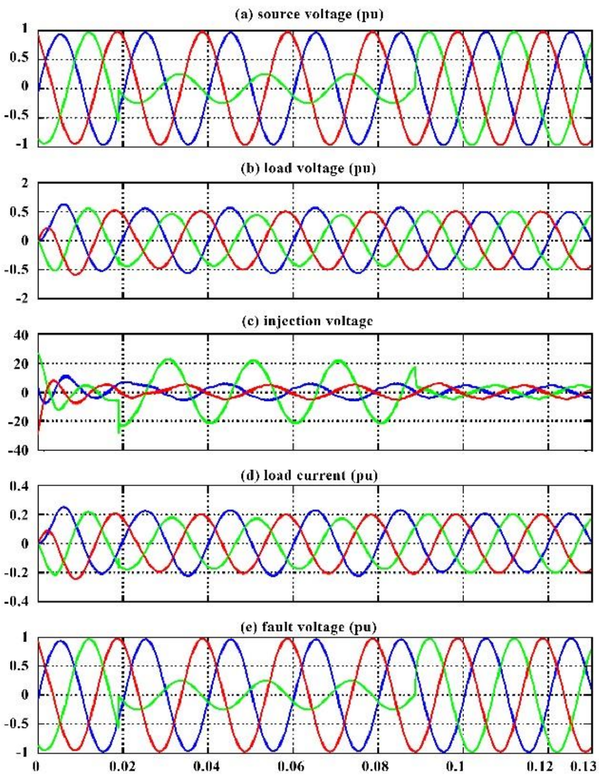

Figure 19. The PI controller signals 1 Phase (B) to ground fault, (a) Source Voltage [pu], (b) Load Voltage [pu], (c) Injection Voltage, (d) Load Current [pu], (e) Fault Voltage [pu].

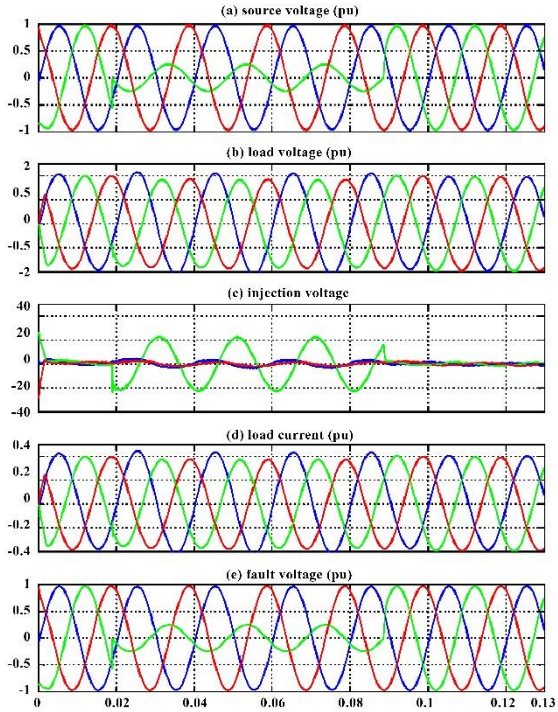

Figure 20. NN controller signals1 Phase (B)-to-ground fault, (a) source voltage [pu], (b) load voltage [pu], (c) injection voltage, (d) load current [pu], and (e) fault voltage [pu].

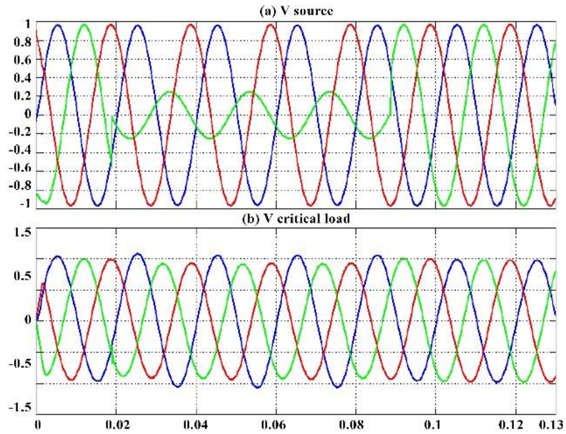

Figure 21. NN controller signals1 Phase (B)-to-ground fault, (a) V source, and (b) V critical load.

Figure 22 shows the three-phase voltage sag simulated for the FL method. The simulation started with a supply voltage of 100% and two phases (B and C)-to-ground faults with 0.1 Ohm fault resistance, each phase occurring from 0.019sec to 0.085sec and causing sagging as shown in Figure 22(a-e) for the FL method. Furthermore, Figure 22(c) illustrates the voltage injected by the DVR and the corresponding load voltage with correction. The load voltage is sustained at a value of 1 p.u. due to the presence of the DVR. The load voltage of this method is acceptable. Figure 23 is a comparison between the source voltage and critical load voltage in FL, reflecting an acceptable compensation. The ANFIS method is modeled as shown in Figure 24. Values of *d* and *q* assumptions as actual signals and an error rate signal between the actual signal and transformed actual signal make two inputs.

Here, the ANFIS method could be designed like the FL method, but as there is no need to define a membership function in this method and it itself does that, this method is more comfortable and somehow more accurate than the FL method. For example, Figure 25 shows the membership function of input1-q that is designed by the ANFIS method. To check the accuracy of the ANFIS work, there is a training data check and test shown in Figure 26.

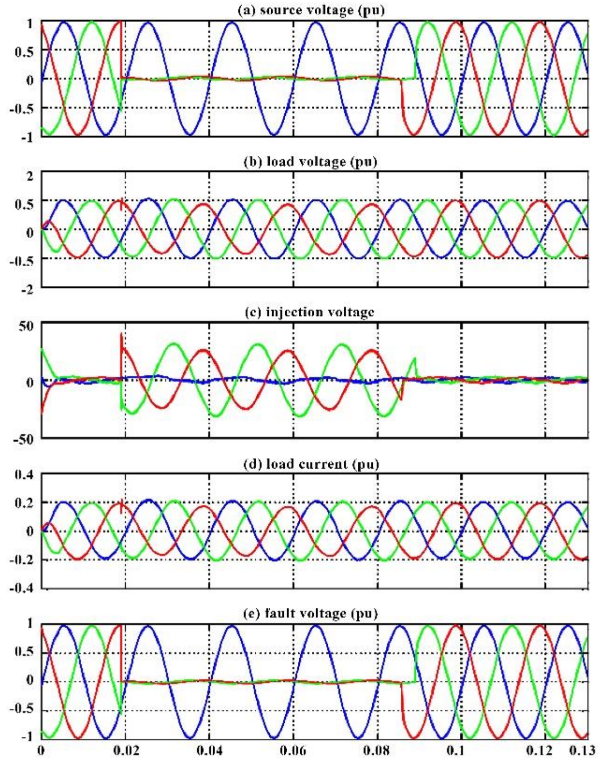

Figure 22. FLC signals 2 Phases- (B and C)-to-ground faults, (a) source voltage [pu], (b) load voltage [pu], (c) injection voltage, (d) load current [pu], and (e) fault voltage [pu].

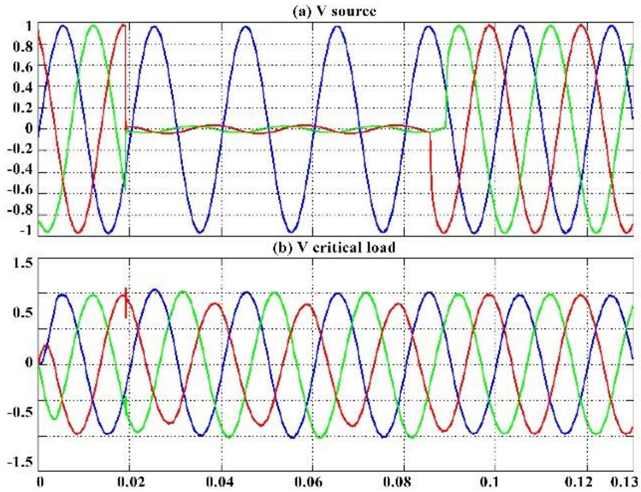

Figure 23. FLC signals 2 phases (B and C)-to-ground faults, (a) V source, and (b) V critical load.

Figure 27 shows a three-phase voltage sag simulated for the ANFIS method. The simulation started with a supply voltage of 100% and two phase (B and C)-to-ground faults with 0.1 Ohm fault resistance, each occurring from 0.019sec to 0.085sec and causing sagging as shown in Figure 27(a-e) for the ANFIS method.

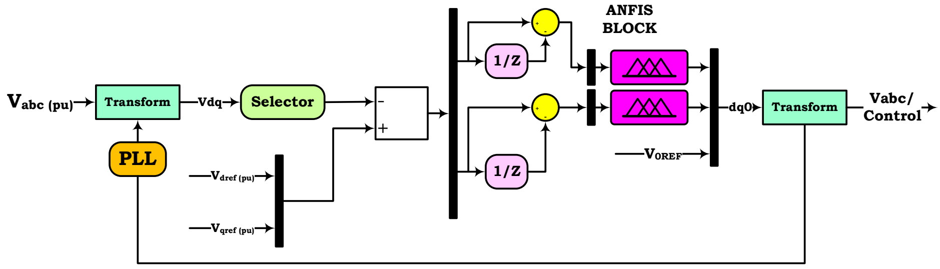

Figure 24. The voltage regulator structure of DVR for FL.

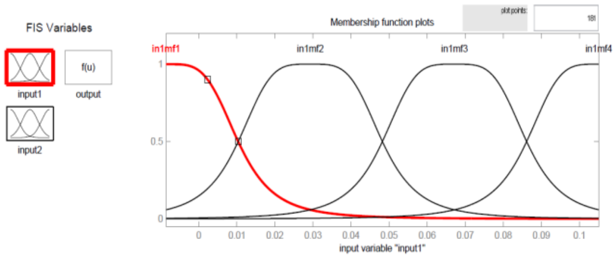

Figure 25. The membership function input1-q.

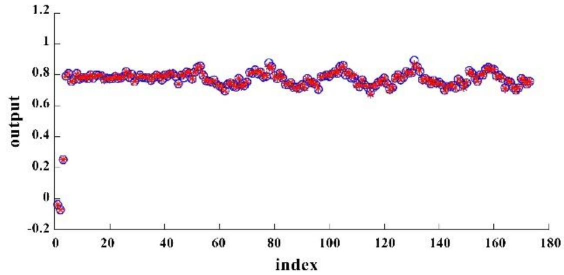

Figure 26. The ANFIS training data test.

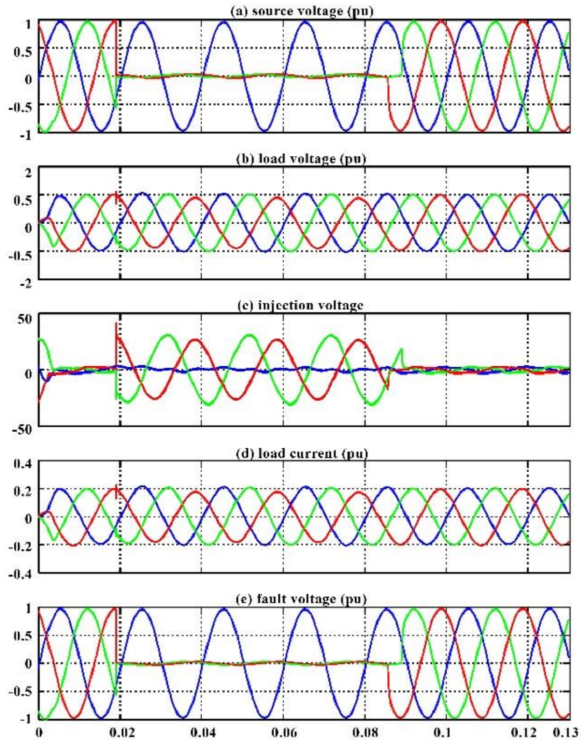

Figure 27. ANFIS controller signals two phases (B and C)-to-ground faults, (a) source voltage [pu], (b) load voltage [pu], (c) injection voltage, (d) load current [pu], and (e) fault voltage [pu].

11. Comparing Injection Voltages of The Methods

Three injection voltages of the controllers of various methods in the same conditions (fault in B & C phases with R_f=0.1 Ohm) are shown in Figures 28-31. There aren't any special parameters that show which method can possibly better measure Total Harmonic Distortion (THD) in various DVRs so their comparison may turn out to be a good practice. However, it seems that all methods are acceptable, but as shown in these figures, the PI controller doesn't perform as accurately as the other methods. Finally, the ANFIS method is a good choice because of its simpler design.

12. Conclusion

A DVR is a highly efficient device designed to mitigate the voltage drop experienced in distribution networks. This article discussed the control strategies that can be employed to mitigate voltage sag by utilizing the DVR technology. The recommended controller was constructed by utilizing the usual PI controller, NN, FL, and ANFIS training methodologies. The controller was subsequently trained using the input and output data that were provided. The efficiency of the recommended DVR with NN, FL, and ANFIS controller was

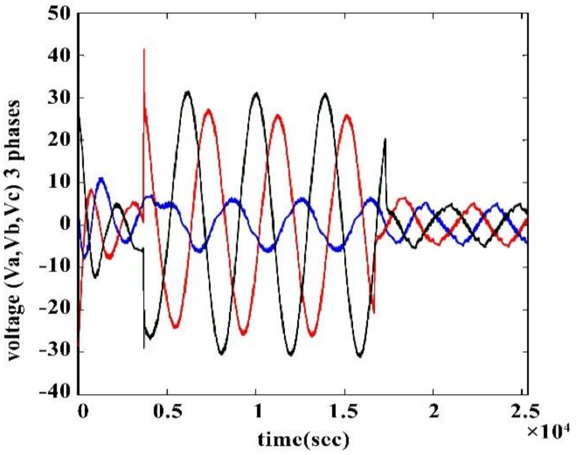

Figure 28. The PI controller injection voltages.

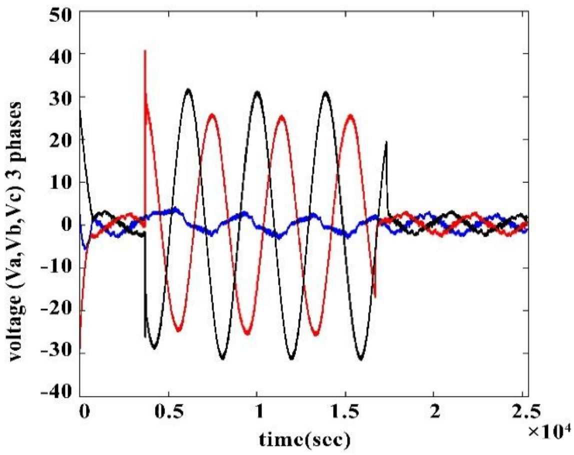

Figure 29. The FLC injection voltages.

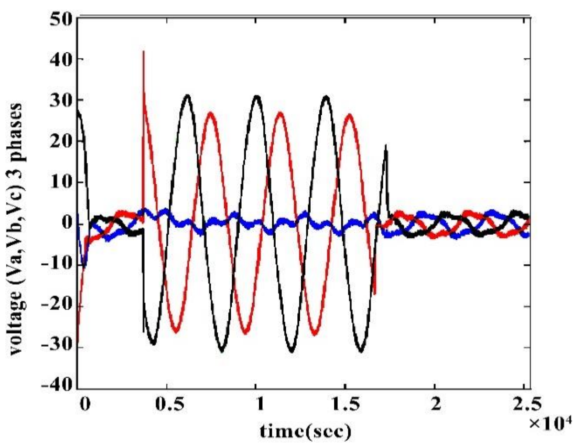

Figure 30. The ANFIS controller injection voltages.

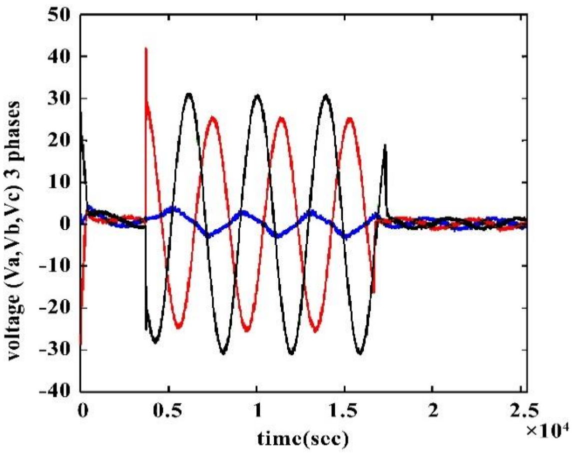

Figure 31. The NN controller injection voltages.

superior to that of the traditional PI controller in mitigating the voltage sag on the test system under investigation. This scenario pertained to the evaluation of the application of a one or two-phase to ground fault.

This study demonstrated the application of MATLAB/Simulink for modeling and simulating a DVR. A control system was developed by the d-q-o approach. The control mechanism in question utilized a scaled error between the source side of the DVR and its reference in order to correct for sags and swells. The simulation findings demonstrated that the performance of various DVRs across four distinct approaches was satisfactory in mitigating voltage sags and swells. The accuracy of the PI controller was comparatively lower than that of the alternative methodologies. Upon careful consideration, it can be argued that the ANFIS technique was a prudent selection due to its relative ease of construction.

Furthermore, the results of the simulation indicated that the DVR exhibited commendable voltage control capabilities and effectively mitigated voltage sags and swells. The DVR exhibited the ability to effectively manage both balanced and unbalanced conditions with ease. Additionally, it introduced the requisite voltage component to promptly rectify any deviation in the input voltage, hence facilitating the preservation of the output voltage at a consistent level and guaranteeing its equilibrium. The final achievements of this research were as follows:

- Constructing a controller by utilizing the usual PI controller, NN, FL, and ANFIS training methodologies and using the input and output data
- Improving the efficiency of the recommended DVR with NN, FL, and ANFIS controller versus the traditional PI controller in mitigating the voltage sag on the test system under investigation
- Using a scaled error between the source side of the DVR and its reference to correct for sags and swells
- The ability to effectively manage both balanced and unbalanced conditions with ease

In future research, other methods can be used instead of the ANFIS method. Also, the evaluation indices of the proposed method can be considered stricter to help improve the quality of the network voltage.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Saman Darvish Kermani: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Roles/Writing - original draft. **Ali Morsagh Dezfuli:** Methodology, Resources, Roles/Writing - original draft. **Abdolreza Behvandi:** Conceptualization, Methodology, Supervision, Roles/Writing - original draft. **Mehrdad Kankanan:** Resources, Validation, Visualization, Roles/Writing - original draft.

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