Neural control of DVR for wind turbine grid fault mitigation with PIL validation

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ABSTRACT

Power quality issues that include voltage sag and swell challenge grid stability, not least for renewable energy systems such as wind turbines (WTs). Occurrence of these voltage disturbances impacts severely the performance of WT systems, compromising their fault ride-through (FRT) capabilities. This work investigates the application of an artificial neural network (ANN) as a controller mechanism for a dynamic voltage restorer, aimed at improving the FRT capabilities of a WT equipped with a permanent magnet synchronous generator. The approach includes employing series compensation to maintain the terminal voltage of the WT during fault conditions. This is performed by injecting voltage at the interface where the system connects to the grid, thus stabilizing the terminal voltage within the wind energy system. The control of the dynamic voltage restorer (DVR) is fundamental to improve the FRT capability. An ANN approach, as control technique is applied to drive the DVR. Training data used for ANN are obtained from a proportional-integral controller, and the proposed system is comprehensively modeled with MATLAB/Simulink. The proposed method demonstrates effective voltage restoration, under two fault scenarios: voltage sag and swell. Besides, the processor in-the-loop (PIL) test proves that the suggested control is practically implementable.

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1. INTRODUCTION

Renewable energy sources are being integrated into the power grid to meet the challenge of climate change and growing demand for electricity. Within the renewable sources of energy, wind energy conversion systems (WECS) are considered to be the fastest-growing renewable resource technology [1]-[3]. In the current wind energy technology, commonly used generators include doubly fed induction generator (DFIG) and permanent magnet synchronous generators (PMSG) [4], [5]. The PMSG typically employs a full-scale converter, whereas the DFIG generally utilizes a partial-scale converter and needs a gearbox [6]. Nowadays, PMSG has attracted considerable interest owing to the advantages it offers over other dominant systems, these advantages include enhanced efficiency, maximum power extraction, reliability, and operation at low speeds while providing high torque. Based on PMSG or DFIG, grid-connected wind power conversion systems are subject to disturbances due to grid failures, thus generating power quality degradation and posing a number of problems. Hence, for wind power integration into the grid, fault ride-through (FRT) ability poses major challenges for wind turbines (WTs) [7], [8]. Wind power systems are no longer authorized to disconnect in the event of a fault, and are instead expected to stay connected, as required by grid codes in several countries [9]. Although the FRT ability of the PMSG-led wind conversion system is superior to that of the DFIG-based conversion system, there is still a need to enhance its FRT capability, as the DC link experiences overvoltage, due to grid faults, which can then lead to overall system tripping. Both low voltage ride through (LVRT) and high voltage ride through (HVRT) are termed FRT, it refers to the ability to handle both voltage dips and swells [10].

Various approaches have been proposed to improve the FRT capacity of grid-connected WTs [11], [12]. There are two main categories of approach: software-based FRT solution through internal control, and a hardware-based FRT method that requires additional hardware to be installed. Software-based solutions involve the internal system improvements. Internal control methods include hysteresis control, pitch control and feed-transient control. Recent progress in control strategies covers sliding mode control, model predictive control (MPC), and fuzzy logic control (FLC) [13].

Morgan *et al.* [14] stated, under the software-based solutions that meet the requirements of the grid code a grey wolf optimizer is recommended to improve PMSG-(WT) LVRT, for both machine side converter (MSC) and grid side converter (GSC). The obtained results from the grey wolf optimizer (GWO) algorithm are compared with those attained using the simplex method and genetic algorithm. An LVRT scheme involving a resonant proportional controller is outlined in the work cited as [15]. As suggested in [16], the model predictive controller (MPC), during the fault, converts the excess power generated into rotor kinetic energy to mitigate the power imbalance. In the case of voltage deep, the grid code defines the need for reactive current compensation, and this requirement was covered. Moreover, as a software control technique, linear quadratic regulator through integrator (LQRI) is proposed to enhance the LVRT of the DFIG-WECS [17]. Although software controls are used as conventional control techniques as they are less pricey and require no added hardware, they struggle to sustain performance under significant voltage dips as well as add complexity to the system [18]. Seen as the best-suited technique for WTs systems, the external hardware-based are considered to be the replacement of modules that were adapted to affect the converter's original design [19]. In such cases, the supplementary device must be connected to the WT system in order to increase the LVRT and HVRT ability [20].

The static voltage compensator (SVC), unified power flow controller (UPFC), static synchronous compensator (STATCOM), and dynamic voltage restorer (DVR), represent some of the most potentially effective reactive power injection-based devices that can address the LVRT capability of the DFIG system. They are usually classified into shunt and series compensation-based devices [21]. Both SVC and STATCOM are employed to provide reactive current compensation to the system, helping to recover the voltage and improving LVRT capability. Yet the high cost, complexity and grid-specific efficiency are the drawbacks, complicating implementation for certain utilities. To overcome the LVRT and ensure a stable supply voltage for sensitive loads, the DVR is therefore implemented. When voltage drops occur in grid due to disturbances, the DVR identifies the fault and supplies compensating voltage, thus restoring power quality for associated equipments. Falehi and Rafiee [22] mentioned, a DVR was proposed to compensate voltage drops, with enhanced performance in the case of symmetrical faults. An optimized proportional-integral (PI) control method that utilizes a gradient-adaptive variable learning rate least mean square algorithm is provided in [23], to achieve adaptability through step size adjustment, which makes it highly robust under dynamic system conditions. Using the DVR-based particle swarm optimization (PSO) with optimized control characteristics, Salman *et al.* [24] have recently proposed this approach. The FLC-based DVR control approach employed in a hybrid microgrid system to decrease power quality problems was given by Thaha and Prakash [25]. Levenberg Marquardt's backpropagation approach and the adaptive neuro-fuzzy inference system model found in the publication [26], demonstrate enhanced accuracy and improved power quality. Although these approaches have shown promising results, the potential challenges involving the complexity of implementing advanced artificial intelligence techniques still need to be addressed.

In pursuit of the above states, this paper's contributing is to address the voltage sag and swell faults by means of the DVR employing an artificial neural network (ANN) controller. The main achievement of the ANN-based DVR method, as well be presented in this paper, is its integration with a wind energy conversion chain. The effectiveness of the ANN driven DVR system is assessed on the MATLAB/Simulink platform, indicating that the chosen control method is efficient. In addition, to evaluate and validate the suggested system, the Simulink model is configured to carry out the processor in the loop (PIL) test using the Texas Instruments F28069M launch board. In this way, hardware verification of the control algorithm applied to the DVR is achieved.

The remainder of the manuscript is arranged as follows. Section 2 covers the DVR based on the ANN control adopted, and the validation methodology using a PIL test is reported. In section 3, results and discussions are provided. Finally, conclusions are given.

2. METHOD
2.1. ANN control-based DVR
When it comes to wind power, the stability of the electricity network is crucial. DVR controlled via ANNs is deployed to address voltage turbulences, which like sags and swells, often compromise the quality and the reliability of the system. The present power electronics device is intended to maintain the network voltage at a constant level. It is placed in series between the grid and the load, in our scenario, the WT utilizes a PMSG linked to electronic power converters, which consist of a rectifier controlled by a non-linear-backstepping and a DC-DC boost converter managed by ANN control. Additionally, an inverter is also controlled using non-linear-backstepping approach and is subsequently connected to a linear load at the point of common coupling (PCC), as revealed in Figure 1. The DVR works by injecting the voltage difference required into the grid when a voltage dip disturbance is detected. In the event of a swell, it absorbs the excess voltage. This rapid and precise action protects sensitive equipment and maintains the quality of the energy. The DVR's main components are a voltage inverter (VSI), an injection transformer, a LC filter, and an energy storage system [27]. The VSI provides the compensating voltage signals required to release the mains voltage to its nominal value. Here, this inverter is controlled by a control algorithm that closely observes the grid voltage and adjusts the inverter output accordingly.

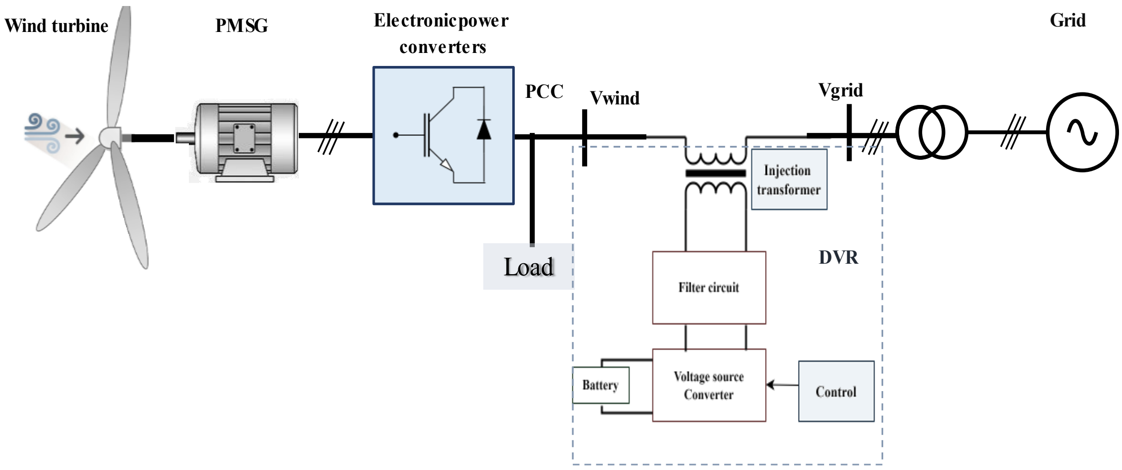


Figure 1. Grid-connected PMSG WT topology integrating DVR components [28]

Moreover, the DVR is equipped with energy storage devices, including capacitors or batteries, which store excess energy during normal operation and instantly deliver it in the event of a disturbance. This energy storage capacity enables the DVR to react quickly to voltage variations. As for the LC filter located next to the VSI, it is used to reduce high-frequency switching harmonics. As a result, harmonic-free power is forwarded through the transformer. The injection transformer is positioned for connecting the DVR to the grid, permitting the transmission of the compensation voltage produced by the VSI. Grid codes insist that voltage faults be compensated through fault circumstances, so the DVR device is thus inserted to help restore power on the side of the WT. The DVR's power rating can be expressed as a function of the 3-phase voltage from the VSI: $V_{i,n}^{ref}$, and as a function of the load current: I_{ch} ,as outlined [29].

$$S_r = \sum_{n=a,b,c} V_{i,n}^{ref} * I_{ch} \tag{1}$$

The expression for the active power transfer between the DVR and the grid can be derived by [30].

$$\begin{aligned} P_{ADVR} &= P_{ch} - P_R \\ &= (3 * I_{ch} * V_L * cos(\varphi)) - \sum_{n=a,b,c}(V_{i,n}^{ref} * I_{ch} * cos(\varphi)) \end{aligned} \tag{2}$$

Considering P_{ch} as the load-side active power, and P_R as the grid-side power.

This equation basically describes the balance between the injected power from the DVR and the variations in grid voltage. Furthermore, by incorporating advanced control algorithms into the control mechanism, these systems can provide fast and accurate voltage restoration.

Neural network control algorithm suggested in the present work can adjust DVR operation dynamically to deal with voltage disturbances. Neural networks consist of interconnected components that function simultaneously in a parallel way, as does the human brain, the ANN is made up of interconnected neurons, which are non-linear components. It is fundamentally a group of interconnected non-linear units, capable of learning from data and adapting to complex and changing situations. The information is propagated sequentially through the layers of the network, with each neuron processing and transmitting the data to the next. The neurons are arranged in layers, consisting of three main types: the input layer, the hidden layer, and the output layer. This architecture allows the network to learn complex non-linear relationships between the input and output data. In our case, to optimize the DVR's performance, a neural network-based control system is created, consisting of two inputs, a hidden layer composed of 10 neurons and an output layer with one neuron. We selected a dataset consisting of 12,000 observations, with 70% allocated for training the ANN, 15% for testing the trained data, and the last 15% for validating the network system. Since the PI controller is commonly used in power systems, the ANN is trained using the data generated by the PI controller. This data is stored in the MATLAB workspace and used for offline training of the neural network controller. The PI controller regulates the control output by taking into account both the current error and the errors accumulated in the past. And so, its functioning is based on a feedback mechanism that responds to overall error sum and its integral over time. In this case, the PI controller receives the input error, that represents the deviation between the measured voltage on the WT terminal and the target voltage. In this study, the ANN learns appropriate control actions from the Levenberg-Marquardt algorithm, such as experience learning. This algorithm is a powerful optimization technique for improving the accuracy of neural network models. In addition, the Levenberg-Marquardt algorithm, which is well known for its efficiency in neural network learning, enables rapid convergence during the training phase. At the input to the ANN controller comes the difference between the actual voltage value and the reference in d-q coordinate system. This difference is used to generate discrete pulse width modulation (PWM) firing pulses, responsible for triggering the IGBT switches at the output.

2.2. PIL approach

Computer simulation is a procedure for creating a mathematical representation of significant aspects of the system under study. The PIL approach serves as intermediary step, it enables transition from computational modeling to practical system validation. The ANN algorithm proposed for controlling the DVR is validated using an experimental device based on a PIL, carried out in MATLAB/Simulink. This allows the system to be analyzed when operating with defined inputs and to observe more clearly the expected or even unexpected behavior of the system, by having testing control strategies on the digital signal processor precedes their integration into real electrical systems. This approach includes integrating a physical processor into the simulation setting in order to offer a more precise representation of the real-world scenario. As illustrated in Figure 2, the control section is the part that runs on the board. Integrating a processor enables real-time communication between the neural network model and the simulation environment. In the proposed PIL-based setup, a LAUNCHXL-F28069M DSP board is employed.

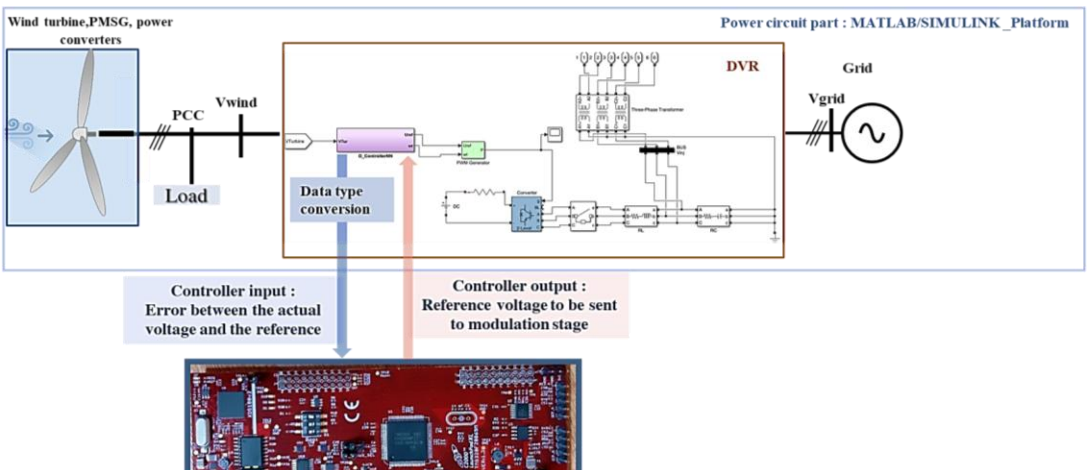


Figure 2. PIL procedure structure

Once the control algorithm part is established via MATLAB/Simulink, the first step in setting up a PIL system is to configure the simulation environment to interact with the processor. At this point, we choose the DSP board as target hardware, and we assign inputs and outputs to the control system. In a subsequent step, the control software is compiled and loaded onto the processor. Communication between Simulink and the DSP board is established via a USB connection, as illustrated in Figure 3. In the final step, the control model is transmitted to the DSP board for execution.

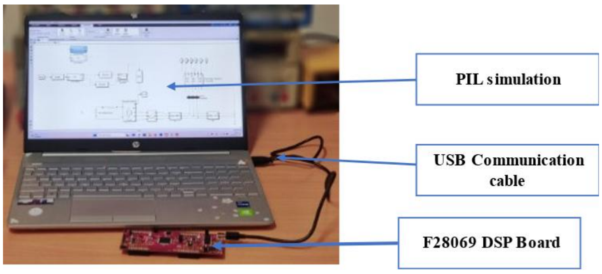


Figure 3. Processor in the loop PIL adopted platform

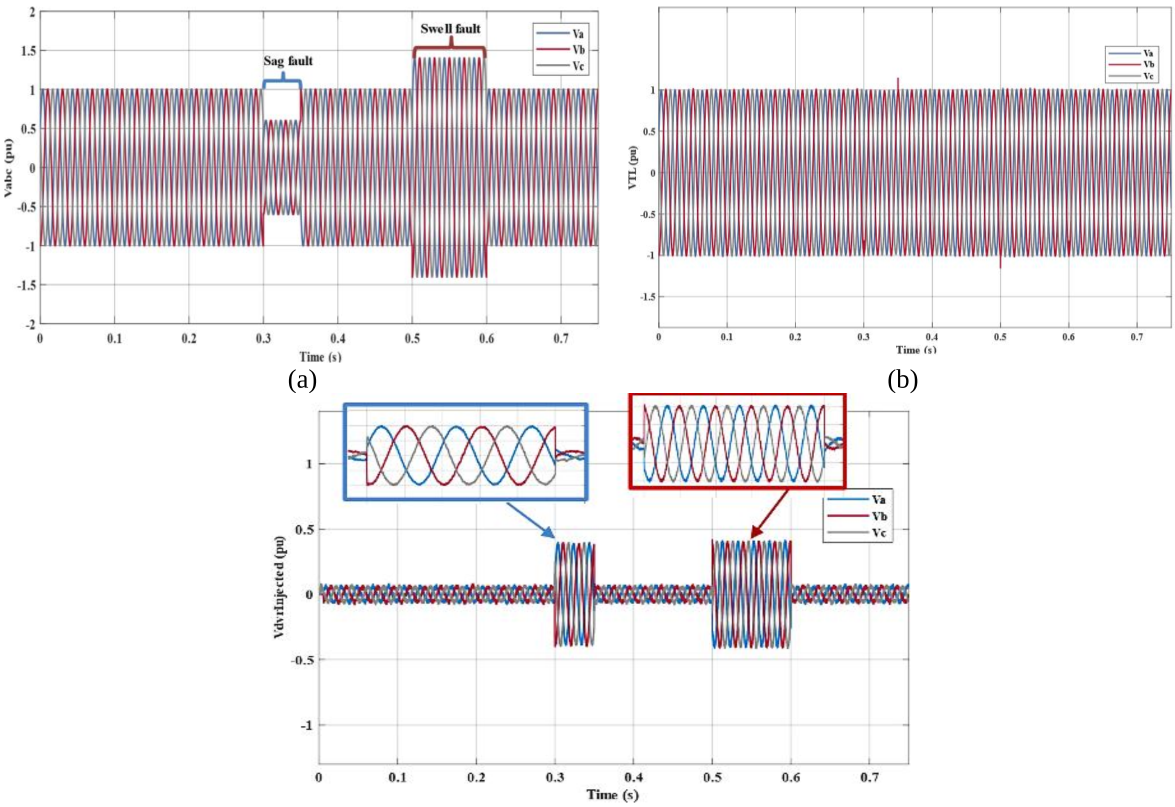
3. RESULTS AND DISCUSSION

Addressing voltage instabilities: sags and swells that occur in the grid associated to the wind system is achieved in this work, by using a dynamic voltage restoration device. This work investigated the effects of ANN-based DVR control on mitigating voltage disturbances in grid-connected wind systems. While earlier studies have explored the impact of DVRs on grid voltage quality, they have not explicitly addressed its influence on real-time performance using processor in the loop validation. Suggested model of the system, in which the DVR is controlled by means of an ANN, has been simulated in MATLAB/Simulink. Then, the applied ANN control is further evaluated through the PIL procedure. The purpose of the simulation is to validate the effectiveness of the DVR control algorithm in meeting FRT capability requirements. The DVR is designed to protect a linear load connected to a grid-connected permanent magnet synchronous generator WT. The applied ANN controller is further evaluated by the PIL procedure.

Simulation results obtained for a 40% symmetrical voltage sag and 40% voltage swell fault are shown in Figure 4. The grid voltage is exposed in Figure 4(a), the turbine output voltage is shown in Figure 4(b) and the voltage injected by the DVR is shown in Figure 4(c). Figure 4(a) shows that the voltage dip formed is 0.40 pu, and that the fault extent is between 0.3 seconds and 0.35 seconds, while the swell fault lasts in the range 0.5 seconds and 0.6 seconds. For the second curve, Figure 4(b) demonstrates the voltage waveform at the output of the wind energy chain, where the PMSG-based WT maintains normal operation with a constant terminal voltage. Figure 4(c) provides the voltage injected by the ANN-based controller, demonstrating how the ANN technique effectively maintains the voltage at the desired level. During the voltage sag, the DVR injects a series voltage to maintain the load voltage at its nominal level. The amplitude and phase of this voltage are defined based on the depth and duration of the sag. In the case of voltage swelling, the amplitude of the grid voltage increases by approximately 40% compared with its nominal voltage. The DVR effectively absorbs the excess, injecting voltages with a phase shift of 180° at the PCC point. Such rapid and precise action not only protects sensitive equipment, but also maintains the power quality supplied to the grid. We found that the voltage injection correlates with the grid stability. The method presented in this study demonstrated higher proportion of voltage restoration as grid protection.

The effectiveness of DVR is evaluated to assess harmonic performance, based on the ability to reduce total harmonic distortion (THD) and restore voltage levels. THD rate is calculated and compared to the finding of a recent study using combined PI control and fuzzy logic hybrid control as referenced in [31], as presented in Table 1. The THD is specifically evaluated during a 50% symmetrical Sag and swell voltage fault that lasts for 0.04 seconds, starting at 0.08 seconds, as it occurs on the grid. Subject to these fault conditions, for the purpose of calculation and comparison, the voltages of the A, B, and C phases at the terminal of the WT are considered.

The results indicated that the THD in phase B obtained is 2.12% with DVR-based PI control, while the hybrid control method (PI combined with FLC) achieved a reduction to 1.55% in the sag faut event. In comparison, the ANN controller magnificently degressed the THD to 1.45% during the restoration of a 50% three-phase voltage sag. The total harmonic distortion percentage of the load voltage in phase C, measured under swell conditions, was slightly minimized to 1.46%. The hybrid PI and FLC produces fewer harmonics than the PI approach. As inferred from the table, the suggested ANN method will recover the voltage without significant harmonics or distortion. Such comparison highlights the advantages of the ANN approach, which outperforms both the PI and hybrid methods, achieving a minimal THD. Nevertheless, it is worth noting that this improvement in performance comes at a higher cost, this is considered an acceptable compromise, given the improved accuracy.



(a) (b)

(c)

Figure 4. System response under symmetrical 40% sag and swell (in pu): (a) grid voltage Vabc, (b) voltage resulting from WECS, and (c) voltage injected by the DVR

Table 1. THD by phase for various compensation methods during faults (sag and swell)

% THD calculation at sag case	Fault case: 50% A symmetrical voltage sag			50% A symmetrical voltage swell		
	DVR with PI [31]	DVR with PI+FLC [31]	DVR with ANN	DVR with PI [31]	DVR with PI+FLC [31]	Adopted DVR with ANN
Phase A	0.08	0.06	1.38	0.08	0.06	1.37
Phase B	2.12	1.55	1.45	2.11	1.54	1.45
Phase C	2.14	1.57	1.47	2.13	1.55	1.46

While the simulation software models the behavior of the system, the real-time processor is the interface to the physical components of the system. The in-loop processor is designed to test and validate ANN control without the need for expensive hardware prototypes. To demonstrate the system's performance, a 40% symmetrical voltage sag (Figure 5) is applied at 0.3 seconds for a duration of 0.15 seconds. Focusing on the voltage sag, Figure 5(a) displays the imposed sag event, while Figure 5(b) shows that, throughout this period, the load voltages remain unaffected, accentuating the robustness of the DVR compensation controlled by the ANN approach. Figure 5(c) details the DVR's role, illustrating the voltage injection in phase with the PCC voltage during the fault. Turning to the symmetric voltage swell scenario, Figure 6(a) illustrates the occurrence of the voltage swell, Figure 6(b) confirms again that the load voltages are preserved during the event, and Figure 6(c) highlights the DVR's rapid response, as it injects the appropriate negative voltage component to correct the grid voltage. This clearly reveals the effectiveness of the ANN technique applied to the DVR during balanced sag and swell fault events. Our findings provide conclusive evidence that this ANN-based control strategy represents a significant advancement in dynamic voltage restoration.

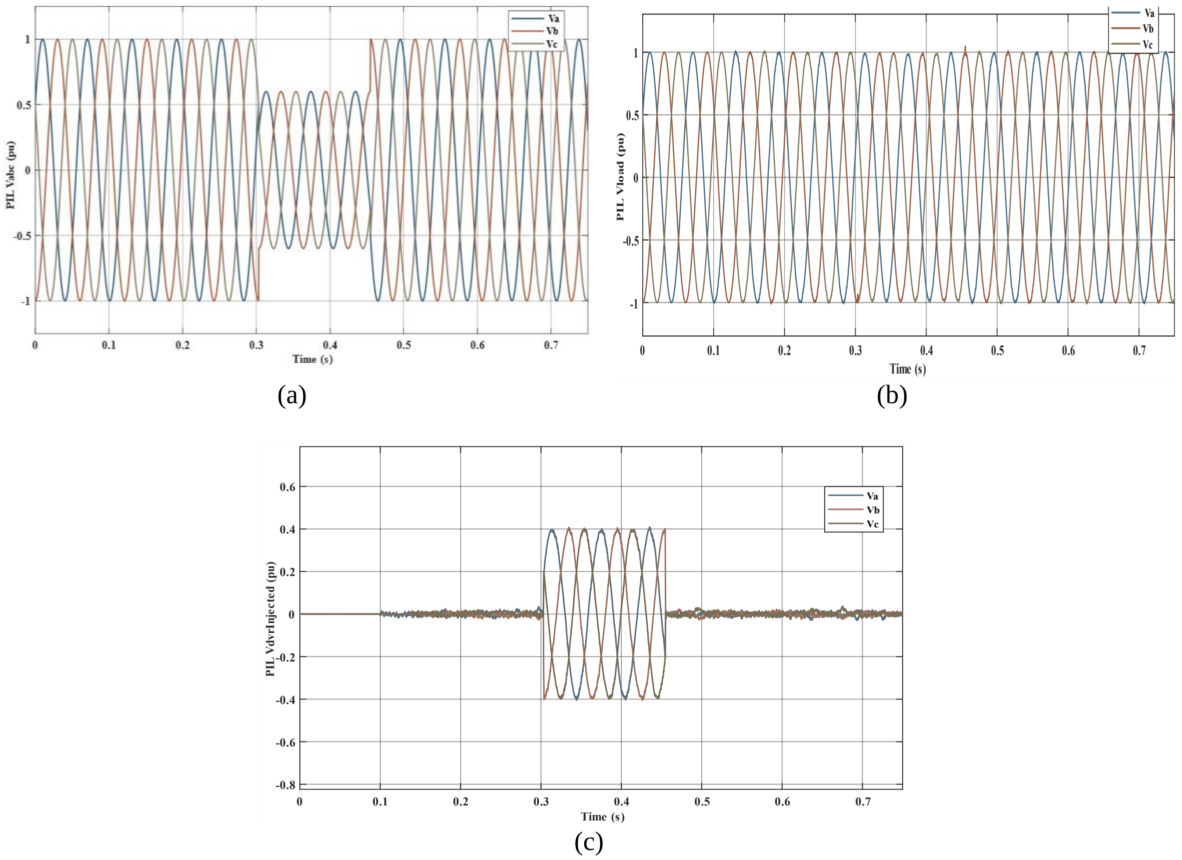


Figure 5. System response under 40% sag with PIL (in pu): (a) grid voltage Vabc under symmetrical sag, (b) voltage resulting from WECS, and (c) voltage injected by the DVR

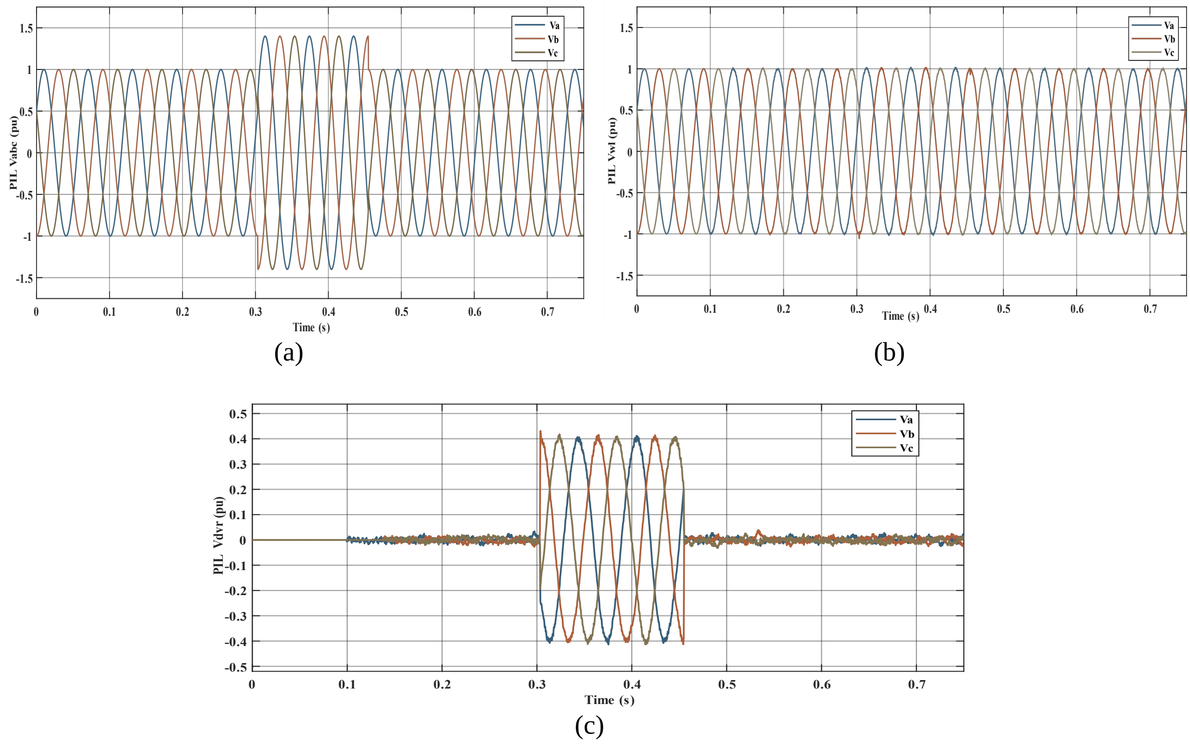


Figure 6. Response to 40% symmetrical voltage swell with PIL (in pu): (a) grid voltage Vabc under symmetrical swell, (b) voltage resulting from WECS, and (c) DVR injected voltage using PIL

4. CONCLUSION

The stability of the power grid is a significant concern when integrating wind energy. Voltage disturbances, including symmetrical sag and swell, affect the quality of power and the effectiveness of the system. To confront these issues, in the present paper, a dynamic voltage restoration system controlled by ANN is suggested. This device aims to mitigate voltage disruptions in wind energy systems linked to the grid, especially during grid-side faults. Simulation results offer valuable insights into the effectiveness of the ANN-based method for restoring voltage sags and swells. A comparative analysis of the proposed method against the PI controller and the hybrid PI and the FLC has been conducted. While conventional controllers have been traditionally used, our work conclusively demonstrates that the ANN controller exhibits a more stable voltage characterized by reduced harmonic distortion. Consequently, we can state that enhancements in LVRT and HVRT capabilities are achieved to meet the FRT ability requirements of the PMSG-driven WT, accordingly conforming to grid code specifications for the integration of WTs into utility power systems. Effectiveness of the ANN managed DVR system is confirmed through PIL testing, without requiring hardware prototypes, reduces development costs, and enables rapid evaluation. In the forthcoming future, the investigation may be further supported by the HIL testing approach, incorporating additional advanced optimization techniques to enhance DVR performance.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Belkasem Imodane	✓	✓	✓							✓	✓			
Said Mailal				✓		✓	✓		✓	✓	✓			
Brahim Bouachrine				✓	✓							✓		✓
Mohamed Ajaamoum					✓		✓			✓		✓	✓	✓
Mhand Oubella							✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that all data supporting the findings of this study are available within the article and its supplementary materials.

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