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Dynamic voltage restoration using neural networks for grid-connected wind turbine

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ABSTRACT

Wind energy is being integrated into the grid as a renewable energy source to meet the world's electricity needs. Grid-connected wind turbines are often disrupted by grid fault problems. Fault ride-through (FRT) ability has become the most important grid connection necessity for wind energy conversion systems (WECS). In the event of a voltage dip fault, the low voltage ride-through (LVRT) capacity is an imperative key to successful grid integration. This paper proposes a dynamic voltage restorer (DVR) controlled through an artificial neural network (ANN) to improve the LVRT capability of a grid-connected wind turbine (WT) based permanent magnet synchronous generator (PMSG). The DVR injects series voltage into the system through a series-connected transformer. The DVR can then restore the voltage to the pre-fault value. The injection transformer is connected to the line linking the PMSG-based wind turbine output to the utility grid. Design and simulation of the low voltage ride-through applied to symmetrical and asymmetrical fault conditions were performed in MATLAB/Simulink software. Simulation results approve that the performance of the technique fully demonstrates its effectiveness and practicality.

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1. INTRODUCTION

Electrical energy remains a global commodity that is seen as a need of everyday consumers [1]. The growing energy demand conflicts with fossil fuel shortage is becoming increasingly serious [2]. Promoting the integration of renewable energy into power systems has been recognized as a critical solution for achieving sustainable socio-economic development. Due to the adverse effects of traditional energy sources on the environment, wind power has made inroads as a renewable energy option [3]. The widespread integration of wind energy into electrical grids has become a new trend observed in several countries [4]. However, power quality problems are identified as a major concern, that is why power quality is a fundamental aspect of the stability of electric power systems. Therefore, performance of the wind turbine conversion system is significantly constrained by the low voltage ride through (LVRT) ability which is mandated respect the grid codes to function during faults [5]. Currently, a significant number of countries have come up with different grid codes (GC) to effectively address renewable energy integration issues and also to ensure the stability of power systems [6]. For example, the Moroccan LVRT grid, as presented in

Figure 1, necessitates that the wind turbines (WTs) stay coupled to the electric grid when there are voltage dips of 10% to 80% of the nominal voltage within a time frame from a few milliseconds to 600 ms [7].

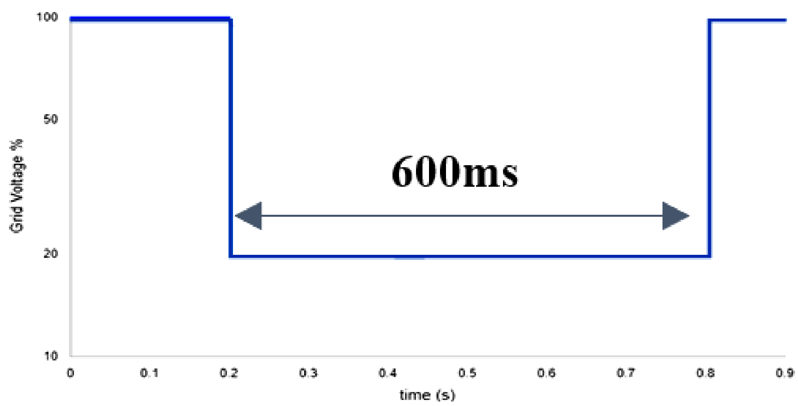


Figure 1. LVRT according to the Moroccan grid code [8]

On the subject of ways of enhancing fault ride-through (FRT) in wind turbines, in the literature various technics have been proposed by researchers [9]–[11]. We typically categorize current approaches as either software or hardware. A software solution consists in improving the control strategy without incurring additional costs. Improving the control strategy of WTs offers a cost-effective approach [12]. Software solutions include: the modified pitch angle control proposed in [13] and the modified converter control provided in [14], but this solution is only suitable for handling moderate fault conditions [15]. To enhance the PMSG-WT LVRT, a grey wolf optimizer was suggested for machine side converter (MSC) and grid side converter (GSC) [16]. Similarly, an LVRT system using a proportional resonant (PR) controller is presented in [17]. In simulation, results demonstrate that the recommended software procedures can improve the FRT capacity at lower cost. Though, they cannot completely ride through significant voltage dips. Alternatively, an effective solution is to modify the converter hardware or add protective devices, like an energy storage system (ESS) [18], crowbar [19], series dynamic resistor [20] and DC link chopper [21]. Within chopper circuit, gate bipolar transistors (IGBTs) are frequently used as switches. They offer the advantages of a simple control and modest cost [22]. Yet, this technique's performance was insufficient as the DC link had a lower LVRT than a normal crowbar. Deployment of reactive power compensation devices aids in maintaining the voltage level at the wind farm's point of common coupling (PCC) [23], such as with the static-synchronous compensator device (STATCOM) [24], and dynamic voltage restorer (DVR) [25]. The study [26] involved a converter and capacitor, functioning as a STATCOM. Similarly, in [27], STATCOM was employed by authors as a means of compensating for the loss in reactive current capacity suffered by wind energy conversion systems (WECS) during grid faults. Mahmoud *et al.* [28] made a comparison between an active crowbar and a thyristor-switched capacitor (TSC). The enhanced fault ride through capability for grid-connected PMSG could be achieved through the utilization of active crowbar and TSC. The DVR system is a series-connected device able to supply absorb real and reactive power [29]. The hardware solution applying one or more devices with an associated cost, but it is well able to deal with severe short-circuit faults. In addition, the series DVR, as opposed to the parallel-connected STATCOM as well as SVC, is considered even most efficient, as it effectively isolates the wind farm's PCC from the grid voltage perturbations and hold a near-constant voltage level at the PCC [30]. Using a high-frequency link transformer, the performance of the DVR is examined in [31]. Various topologies and control techniques are presented for DVR, such as linear control that comprises the feed-forward approach. The procedure entails detecting the variance between pre-sag and sag voltage, followed by computing the extent of voltage to be infused [32]. As for non-linear controllers, namely the fuzzy logic controller, genetic algorithm, and artificial neural network (ANN), they are utilized to regulate the inverters of DVR in situations where linear control proves infeasible [33]. Artificial neural network is characterized by the ability to implement control without the need for an extensive mathematical model of the system [34].

This paper is dedicated to the DVR employment using the ANN control strategy. employing the DVR based on the ANN strategy control voltage as a solution to mitigate and compensate the voltage sags, since grid faults, particularly voltage sag problem, can disrupt the functionality of sensitive equipment. The contribution consists in improving the LVRT capability of the grid-connected PMSG machine-based wind energy conversion chain with the ANN-controlled DVR system. The LVRT ability is evaluated for symmetrical and asymmetrical sag fault conditions on the grid side. A comparison was made regarding the total harmonic distortion (THD) rate between the results of the present method and those obtained by other previous works. The DVR with the current approach succeeded in reducing the THD rate. MATLAB/Simulink simulations have confirmed the efficacy and performance of this work's method, suggesting that it improves LVRT capability.

The present work is assembled as follows. Section 2 is devoted to present the DVR operation principle; the ANN control approach is also provided in this section. We discuss the simulation results in section 3. Finally, the conclusion is covered.

2. METHOD FOR VOLTAGE SAG MITIGATION

2.1. Dynamic voltage restorer integration

The WECS basic structure, as can be seen in Figure 2, is made up of a WT, PMSG, MSC, DC link and GSC. Simulation parameters of the PMSG generator and turbine are presented in Table 1. The DVR is the power device related to the grid and to the WECS linked to a linear load at the PCC. It is employed to improve its LVRT capability by injecting voltage to correct the voltage sag fault. The DVR is a competent voltage compensation, it continuously and quickly regulates the WT side voltage in case of power quality issues: voltage sag happened on the grid voltage. The essential components of DVR, as shown in Figure 3, are the voltage source inverter (VSI), energy storage, LC filter, and controller.

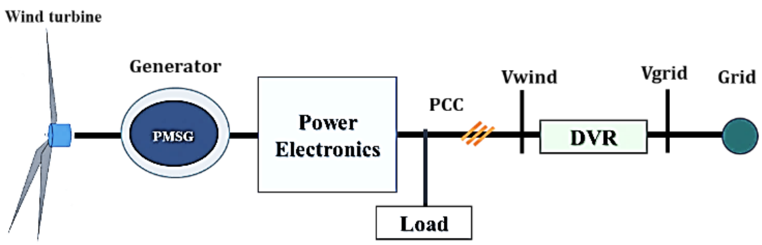


Figure 2. Topology of grid-connected PMSG wind turbine with integrated DVR [35]

Table 1. PMSG generator and turbine parameters

Equipment	Parameter	Value
Wind turbine	Output power	1 MW
	Radius of the turbine blade: R	55 m
	Density of air: ρ	1.22 Kg/m^3
	Tip-speed ratio: λ	7
Generator	Type	PMSG
	Number of phases	3
	Mechanical input	Torque (Tm) N.m
	Stator phase resistance	0.00625 Ω
	Flux linkage	11.14 V.s
	Number of Poles pair	75

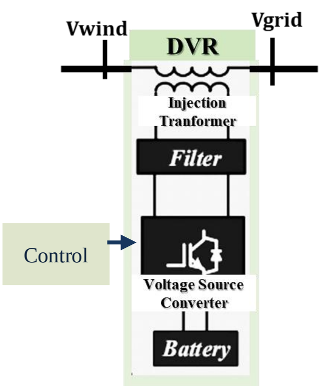


Figure 3. Block diagram of DVR components [36]

The insulated gate bipolar transistor (IGBT)-based VSI injects adequate voltage restoring across the injection transformer and filter supplied by an external energy storage unit. This two-level inverter features IGBTs, each with a diode in parallel. The IGBTs are controlled by pulse-width modulation (PWM). Nevertheless, the VSI produces an output with a waveform containing high-frequency harmonics. To alleviate this problem and deliver a quality power supply, we employ an LC filter. This filter is placed next to the VSI, reducing high frequency switching harmonics. In this way, the harmonic-free supply passes through the transformer. To connect the DVR device to the distribution system, the injection transformer is used. It introduces the compensating voltage produced by VSI whenever the control system detects any anomalies. As for the primary side of the transformer, it is connected in series to the distribution line, whereas the secondary side is linked to the DVR circuit. The DVR system under study is designed by assembling the main components within the MATLAB/Simulink environment. The modeled DVR structure is illustrated in Figure 4. The main principle behind DVR operation is that it provides a voltage waveform through an injection transformer which is the difference between: pre-fault and fault voltage. It made possible by the supply of required active power from an energy storage device. The response time of DVR is remarkably fast and is limited by the power electronics devices and the fault detection time. As the grid codes require voltage fault compensation through fault conditions, the DVR is designed to restore the power of the wind turbine side [37]. The DVR power rating is as (1):

$$S_{DVR} = \sum_{n=a,b,c} V_{i,n}^{ref} * I_L \tag{1}$$

where V_i is the three-phase AC voltage from the VSI, and I_L is the load current. The active power exchanged between the DVR and the grid is as (2):

$$P_{DVR} = P_L - P_G \tag{2}$$

where P_L is the active power in the load side, and P_G is the power in the grid side.

$$P_{DVR} = (3 * I_L * V_L * cos(\varphi)) - \sum_{n=a,b,c}(V_{i,n}^{ref} * I_L * cos(\varphi)) \tag{3}$$

From (2) and (3) we can observe that the active power supplied by the DVR to the system is determined through the difference between the active power in the grid and the load, thus the DVR is controlled by the in-phase compensation procedure.

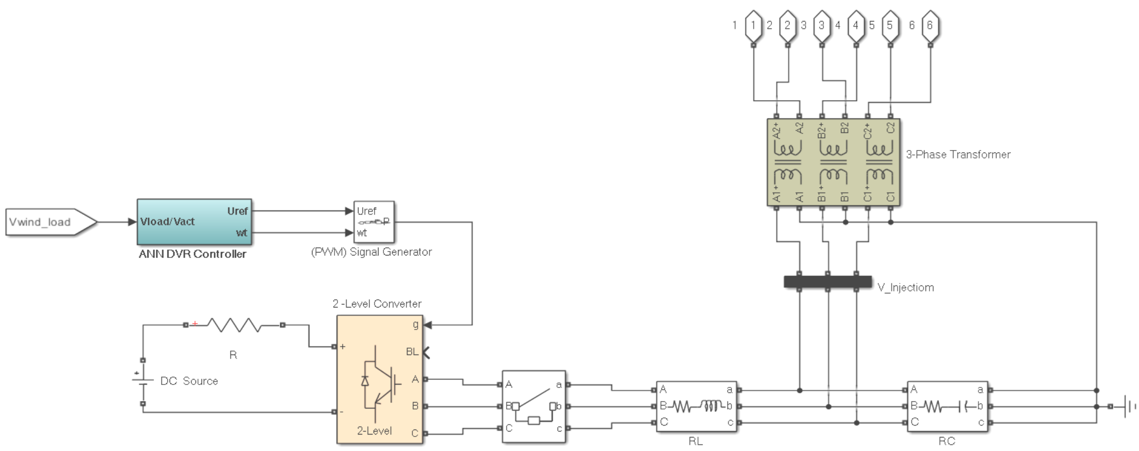


Figure 4. DVR power circuit model

2.2. Artificial neural network control approach

The DVR method of voltage compensation involves holding a constant voltage on the wind turbine side as a function of voltage magnitude and phase angle. The pre-sag voltage is then used to ensure that the voltage and phase angle are maintained in the system. At this point, PWM signals are sent from the controller and converted into the necessary voltage. The present work suggests the employment of an artificial neural network as a DVR control system compensating for the voltage sag fault. Neural networks are composed of elements functioning in parallel like biological nervous system. This computational method consists of an assembly of many nodes turns as neurons. Neurons as a nonlinear element represents generally a series of interconnected nonlinear elements that have the capability to adapt and learn. After receiving the information, each node transmits it to the next node, after carrying out the necessary operations. The neurons are arranged into layers. For any given task to be executed by ANN all the nodes need to be trained with relevant data. In this work, the ANN comes into play as a voltage compensation algorithm. First, dataset needs to be trained on the network and then deployed on a DVR. The current network has two inputs and one hidden layer made up of 10 cells and one output layer made up of one cell. The proposed ANN flow diagram can be found in Figure 5, showing the dataset for training collected on the basis of the conventional proportional-integral (PI) controller applied to same model on the DVR. The principal of the PI control is a feedback controller that is driven by the sum of the error and the integral of these values. The input to the PI controller is the error between the actual voltage (wind turbine side) and the reference voltage. The reference voltage for the d-coordinate is 1 per unit (pu) and the q-coordinate is 0 pu. At first, data from the PI controller in the workspace was stored, and then, used for the neural network controller offline training. For training the ANN controller, 12.000 datasets were selected. The data used to train the ANN: 70%, to test the results of the training data: 15% and to validate network system: the remaining 15%.

To solve a given problem, neural networks are trained using learning algorithms, known as experience learning. In this context, the Levenberg-Marquardt algorithm (LM) is seen as the faster learning algorithm for achieving convergence is used as a training algorithm in the ANN controller [38]. The LM back propagation algorithm is the second order optimization, more robust and it finds a solution even if it does begin very far from the final optimum. At its input, the ANN controller takes the error and the change in the error signals of the *dq* coordinate system, The output of the ANN controller then converts the *dq* components into *abc*. Discreet PWM generates firing pulses to trigger the IGBT switches. An error function of the ANN controller is the mean-square error (MSE), which shows the error between input values and target values.

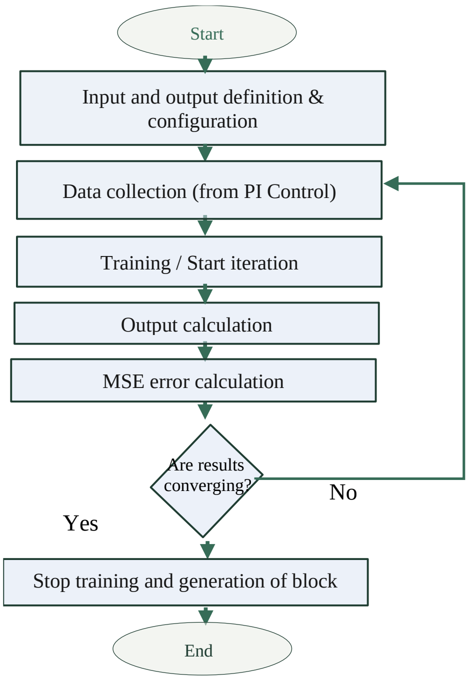


Figure 5. ANN algorithm flowchart

3. RESULTS AND DISCUSSION

Modelling of the proposed chain in which the DVR is controlled with ANN technique was simulated using MATLAB/Simulink software in terms of enhancing symmetrical and asymmetrical voltages sag that occurred on the grid side. In this simulation model, to meet FRT capability requirements, we verify the efficacy of the proposed control algorithm on DVR. This device is being deployed to protect a linear load linked in parallel to the grid and the wind turbine based PMSG. DVR-based ANN controller performance analysis is described through simulation and tabulation. The simulation results of the model using the DVR mechanism in the event of a 35% symmetrical voltage sag fault conditions is illustrated in Figure 6.

Figure 6(a) shows the grid voltage, Figure 6(b) represents the wind turbine's output voltage, and Figure 6(c) displays the DVR injected voltage. Once a short-circuit appears, each phase of the source voltage decreases. Figure 6(a) reveals that the voltage sag created is 0.35 pu, and the duration of fault is from 0.3 to 0.4 s. In the second waveform, Figure 6(b) gives the resultant voltage waveforms from wind conversion chain presenting also the load voltage which is the results of mitigating voltage provided by DVR which adds a voltage drop at WT terminal. So, WT based PMSG maintains normal operating condition with constant terminal voltage. The injected voltage from the DVR based on the ANN control is shown in Figure 6(c) and demonstrates the way in which the ANN controller has succeeded in maintaining the voltage at the required level. The test system shows all voltage values per unit.

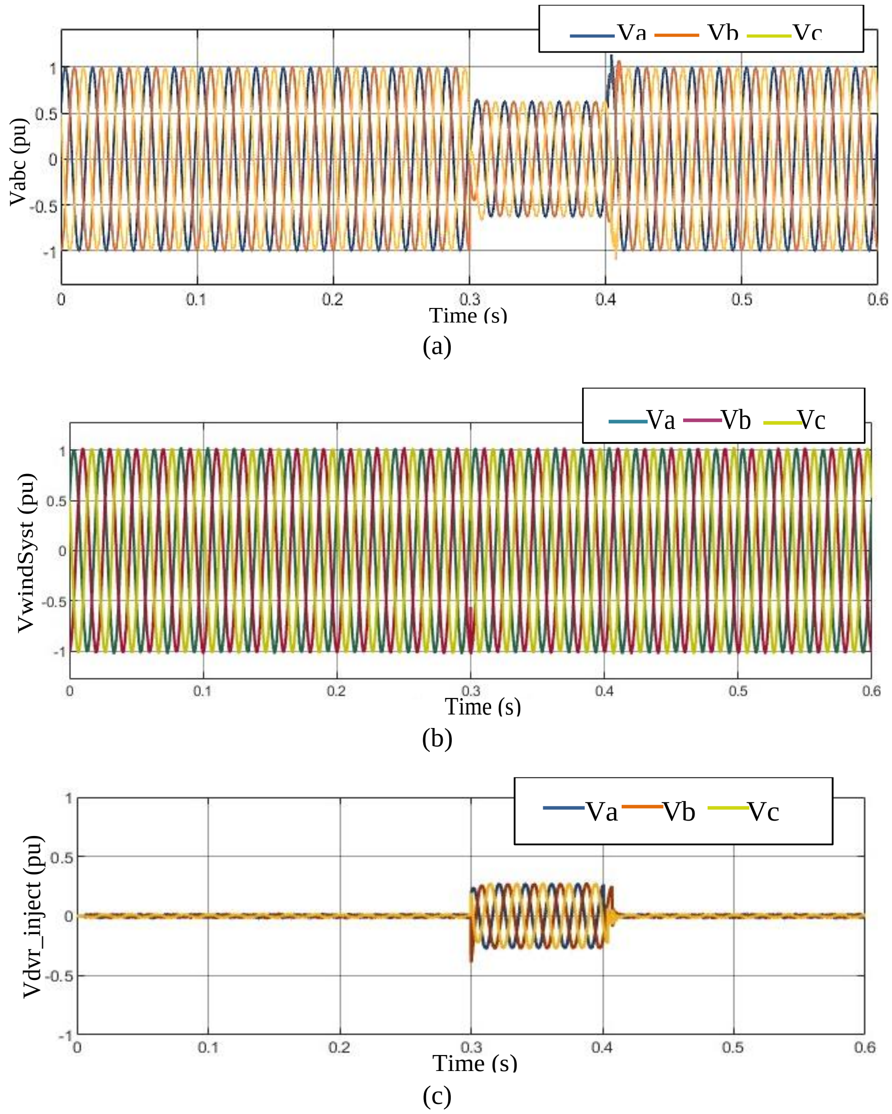
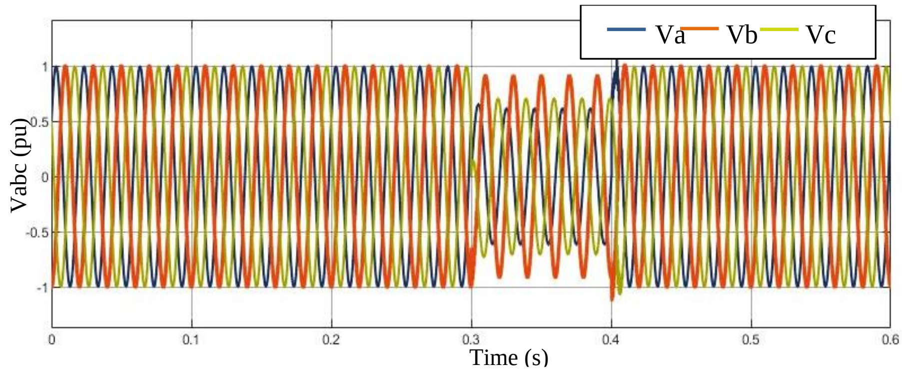
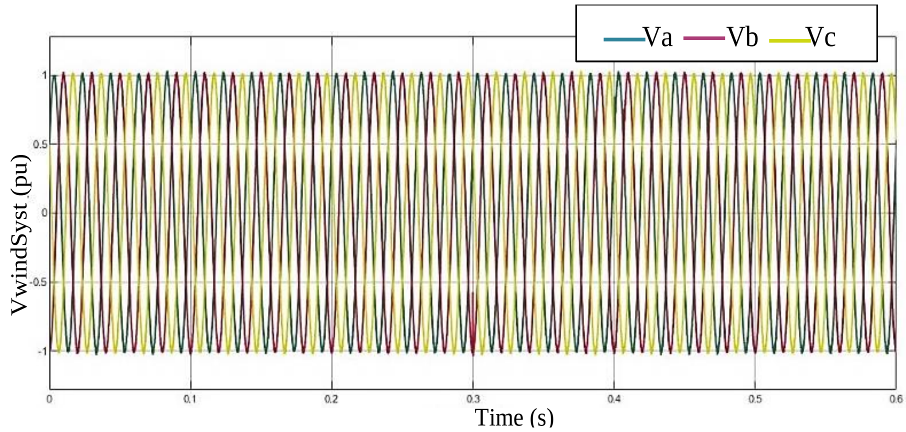


Figure 6. Voltage in pu for (a) $Vabc$ grid under 35% symmetrical sag, (b) resultant voltage of WT, and (c) DVR injected voltage

System performance when exposed to an asymmetrical voltage sag of 0.35pu is represented in Figure 7. This figure clearly reveals the application of the fault to phase A and phase C. Figure 7(a) shows the grid side asymmetrical voltage sag in volts. The fault time is between 0.3s and 0.4s. The waveform in Figure 7(b), presents the output voltage waveform of wind conversion system in Volt after compensation, solving the double-phase fault problem. As illustrated in Figure 7(c), the DVR provides the compensating voltage for mitigating the level of voltage under two phase A, C to ground fault (LLG). For the duration of the fault, the ANN-based DVR sends out the suitable voltage, after the end of the fault duration, the voltage is switched off.



(a)



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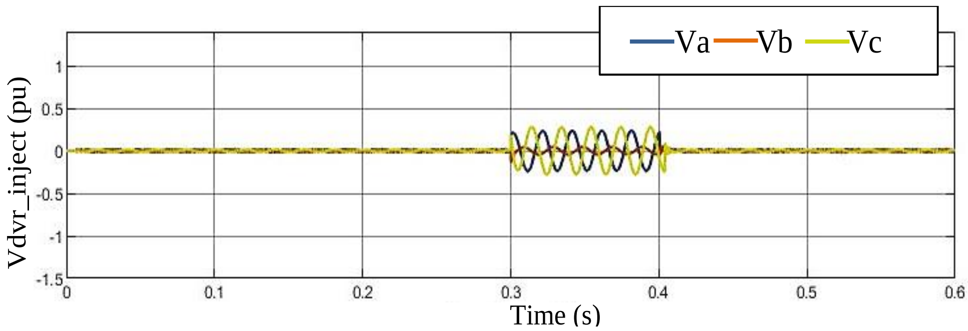


(c)

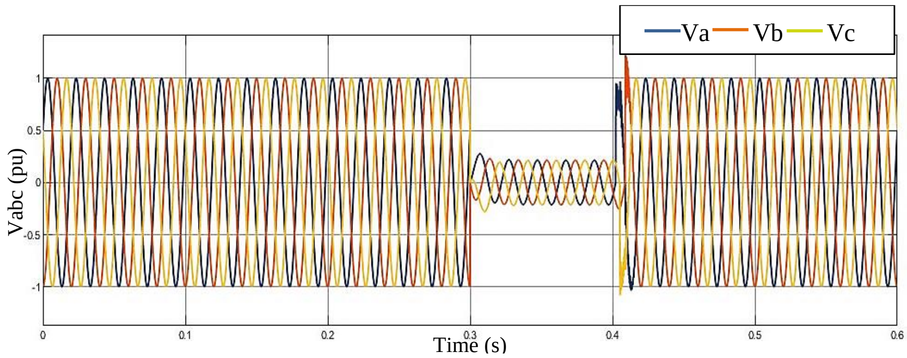
Figure 7. Voltage in pu for (a) *Vabc* grid under 35% asymmetrical sag, (b) resultant voltage of WT, and (c) DVR injected voltage

In the other case, 70% voltage sagging conditions are taken to evaluate the effectiveness of the ANN controller proposed for DVR to boost system performance. The simulation result is illustrated in Figure 8(a) clearly shows the three-phase fault applied from 0.3 to 0.4 s. Figure 8(b) displays the terminal voltage waveforms of wind turbine. The three-phase instantaneous voltages remain stable, and no obvious waveform distortion can be observed under this fault situation. The DVR injects the required voltage on the three phases and then enhances the system's voltage profile as exposed in Figure 8(c).

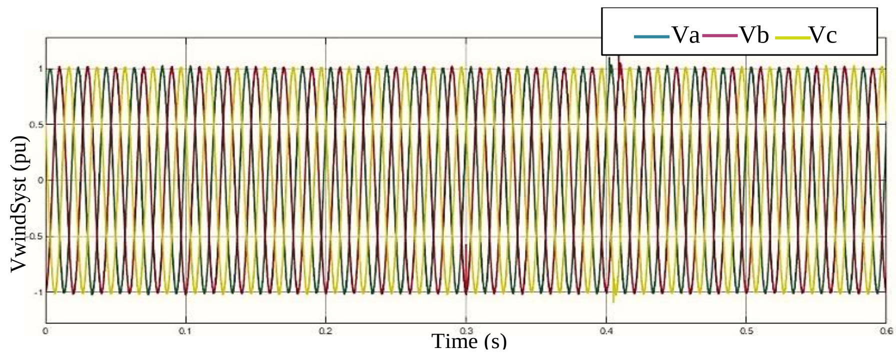
We further simulate double-phase fault (phase-A and phase-C) at $t = 0.3$ s, and fault duration is 0.1 s. Figure 9(a) shows the distorted source voltage resulting from an applied 70% asymmetrical voltage sag which occurs in the utility grid. The wind turbine terminal voltage remains nearly unchanged as is presented in Figure 9(b). Two phases to ground (LLG) fault compensation with a drop of 70% using an ANN controller-based DVR is illustrated in Figure 9(c).

To illustrate harmonic performance, THD rate is calculated, and a comparison is provided in Table 2. THD is calculated for a 50% symmetrical voltage fault, with a duration of 0.04 s from time 0.08 s, which occurs in the grid. Under the specified fault conditions and for the DVR-based proportional-integral (PI) control, DVR-based hybrid control (PI control and fuzzy logic) adopted in [39], and for the adopted DVR-based ANN control, the THD is determined. To calculate and compare THD, the voltage of phase A, B, and C at the wind turbine terminal that is related to linear load is taken into account.

The results showed that the THD in phase C, using DVR based PI was reduced to 2.14%, and reduced to 1.57 using hybrid control (PI+FLC), though the adopted ANN controller was successfully reduced to 1.47% for 50% three-phase voltage sag restoration. The PI method generates a large number of harmonics with noticeable waveform distortion. The output of the hybrid PI and Fuzzy controller, which has fewer harmonics than the PI method, contains slight waveform distortion throughout. By contrast, the proposed ANN method restores the voltage without noticeable distortion or harmonics, demonstrating its superiority over the other two. Accordingly, the model provided, with DVR-based ANN control, successfully reduces the THD, thus, improving low-voltage ride-through (LVRT) capability, by effectively handling voltage drop problem. This comparison proves the superiority of ANN, which outperforms PI and the hybrid (PI+FLC) and delivers a significantly lower THD than the two previous methods. However, this superior performance is accompanied by a higher cost, but this limitation is acceptable in view of the greater accuracy.



(a)



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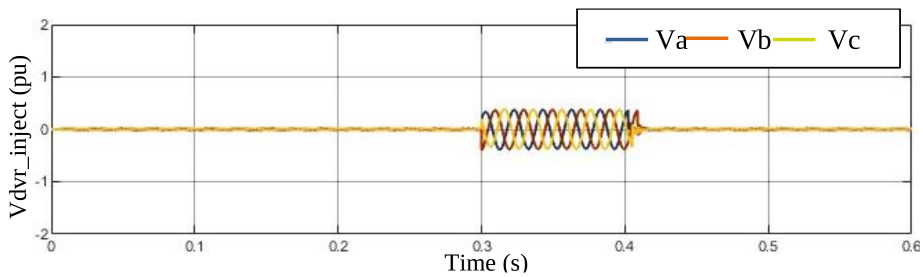
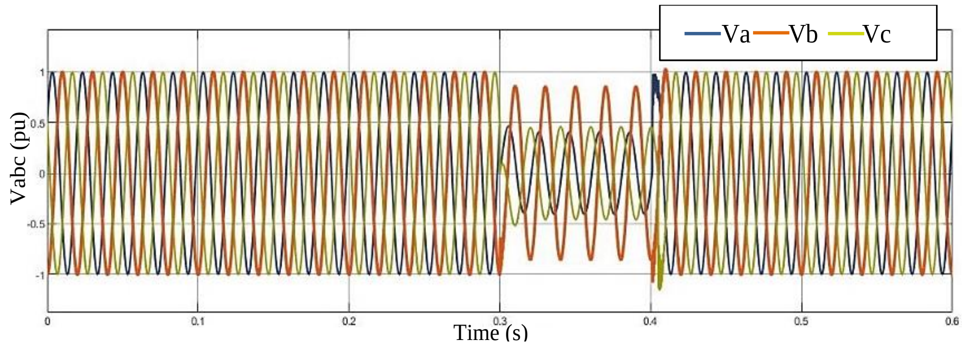
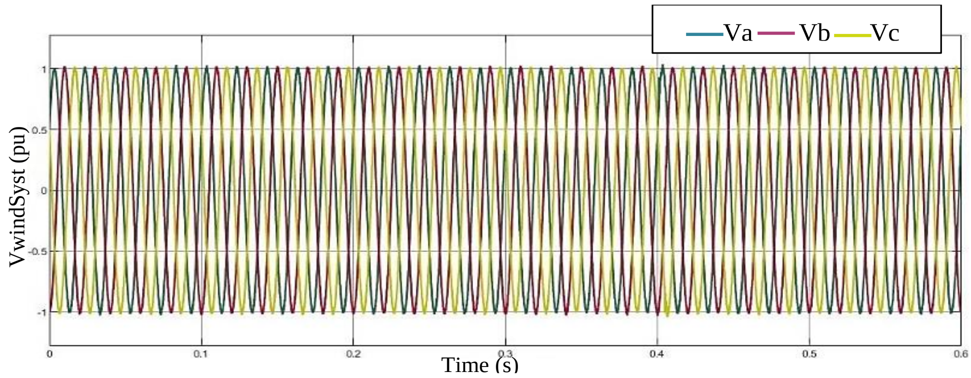


(c)

Figure 8. Voltage in pu for (a) *Vabc* grid under 70% symmetrical sag, (b) resultant voltage of WT, and (c) DVR injected voltage



(a)



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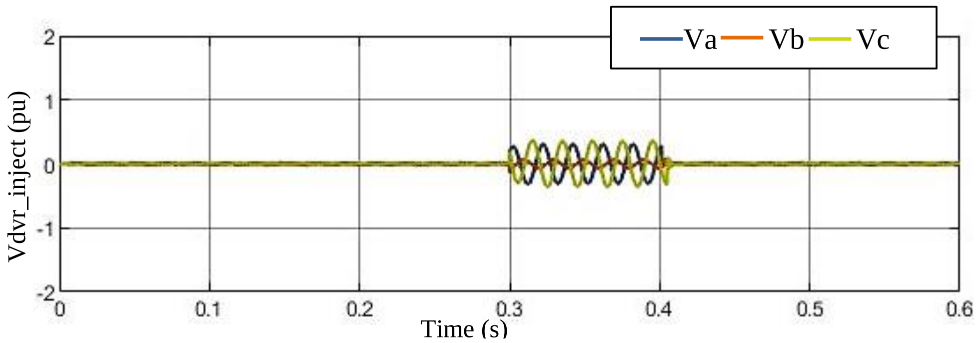

(c)

Figure 9. Voltage in pu for (a) *Vabc* grid under 70% asymmetrical sag, (b) resultant voltage of WT, and (c) DVR injected voltage

Table 2. THD for each phase for diverse compensation methods.

% THD Calculation at sag case	Fault case: 50% symmetrical voltage sag		
	DVR with PI [39]	DVR with PI+FLC [39]	DVR with ANN
Phase A	0.08	0.06	1.38
Phase B	2.12	1.55	1.45
Phase C	2.14	1.57	1.47

4. CONCLUSION

Dynamic voltage restoration has proved to be a promising solution for improving power quality in power systems. Through the platform of MATLAB/Simulink, a simulation model of DVR for a wind turbine system based on a permanent magnet synchronous generator is carried out. In this work, the application of the ANN control to operate DVR for providing better performance to mitigate voltage sag introduced at the grid side has been demonstrated. Simulation results for the grid, the resulting wind turbine voltage and the voltages injected by the DVR are analyzed for symmetrical and asymmetrical voltage sag conditions. Based on the results, the proposed DVR-based ANN control strategy is shown to be effective in compensating faults. A comparison of the proposed technique with the control PI, and the hybrid PI and fuzzy controller has been taken, where the proposed ANN controller maintains a more stable and smoother voltage profile with low harmonic content. The comparison tests were held to verify the effectiveness and performance of the adopted control strategy, which appears to be the best option for restoring system voltage. We can therefore guarantee LVRT capacity enhancement to satisfy the FRT capacity demands of the PMSG-based wind turbine, thus meeting the grid code requirements for integrating wind turbines into utility grids. In the near future, the study can be enriched by including optimization approaches, besides tests for prototyping and validating the ANN control adopted for the DVR.

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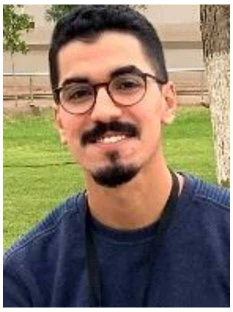

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