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APPLICATION OF DYNAMIC VOLTAGE RESTORER TO IMPROVE POWER QUALITY IN STAND-ALONE WIND POWER SYSTEMS UNDER VARIABLE OPERATING CONDITIONS

BAĞIMSIZ RÜZGAR ENERJİSİ SİSTEMLERİNDE GÜÇ KALİTESİNİ İYİLEŞTİRMEK İÇİN DEĞİŞKEN ÇALIŞMA KOŞULLARINDA DİNAMİK GERİLİM ONARICININ UYGULANMASI

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ABSTRACT

In power systems where sensitive loads are supplied by renewable energy sources, voltage fluctuations and power outages may result in the voltage demanded by the load not being met or the load being supplied with a voltage with high harmonic distortion. This may damage the sensitive load after a while or even cause the load to become inoperable. In this study, a dynamic voltage restorer (DVR) was implemented in a stand-alone wind turbine power system to improve the power quality. DVR technology continuously monitors the power system and injects series voltage as needed in case of possible voltage sags, swells, or fluctuations. The aim of this study is to increase system reliability and quality by ensuring the load voltage performs at nominal operating conditions even in the event of unexpected electrical faults between the source and the load. The proposed application was tested at different loads (linear and non-linear), wind speeds (14 -16 m/s), phase voltage faults, and source frequencies. In different operating conditions, the THD of the load voltage was kept at <5% (compliant with IEEE-519 standards). Additionally, voltage sags and swells have been successfully compensated and confirming the system stability and reliability.

Keywords: DVR, wind power, power quality, stand-alone systems

ÖZET

Hassas yüklerin yenilenebilir enerji kaynaklarından beslendiği güç sistemlerinde, gerilim dalgalanmaları ve elektrik kesintileri, yükün talep ettiği gerilimin karşılanmaması veya yükün yüksek harmonik bozulmaya sahip bir gerilimle beslenmesiyle sonuçlanabilir. Bu durum, bir süre sonra hassas yüke zarar verebilir hatta yükün çalışamaz hale gelmesine neden olabilir. Bu çalışmada, güç kalitesini iyileştirmek için bağımsız bir rüzgar türbini güç sistemine dinamik gerilim onarıcı (DVR) uygulanmıştır. DVR teknolojisi, güç sistemini sürekli olarak izler ve olası gerilim düşüşleri, yükselmeleri veya dalgalanmaları durumunda sistemin ihtiyaç duyduğu gerilimi belirleyerek, sisteme seri bağlı şekilde enjekte eder. Bu çalışmanın amacı, kaynak ve yük arasında beklenmeyen elektriksel arızalar olması durumunda yük geriliminin nominal çalışma koşullarında performans göstermesini sağlayarak sistem güvenilirliğini ve kalitesini artırmaktır. Önerilen uygulama farklı yüklerde (doğrusal ve doğrusal olmayan), rüzgar hızlarında (14 - 16 m/s), faz gerilim arızalarında ve kaynak frekanslarında test edilmiştir. Farklı çalışma koşullarında, yük geriliminin THD'si <%5'te tutulmuştur (IEEE-519 standartlarına uygun). Ayrıca, gerilim düşüşleri ve yükselmeleri başarıyla telafi edilerek sistemin kararlılığı ve güvenilirliği teyit edilmiştir.

Anahtar Kelimeler: DVR, rüzgar güç sistemi, güç kalitesi, bağımsız yenilenebilir enerji sistemleri

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INTRODUCTION

Advances in electrical generators and power electronics technology have seen the global installed capacity of wind turbines increase rapidly over the past few years, making this energy source competitive in terms of cost per kilowatt compared to traditional fossil fuel based power plants. (Bubshait et al., 2017). In addition, with the developing technology, the increase in power demand in electric power systems has emerged as a natural result, and this causes increase in undesirable situations such as voltage sags, swells, fluctuations and power outages which are defined as negative factors affect the efficiency, reliability and stability of power systems (Eltamaly et al., 2018). However, DVR is an effective power device method for improving power quality and protecting sensitive loads by effectively compensating voltage imbalances and harmonics, with its short-time response to possible unexpected faults, reliability, and low-cost design. In addition, the DVR is a voltage source converter that dynamically controls the system by connecting in series with the power supply, and performs voltage injection by detecting the possible scale error between the source and load voltage with the PI-based control method (Ganthia et al., 2016). Voltage-related issues affecting stability and performance in power systems include swells, sags, flicker and unbalance, while frequency changes, which can lead to system instability and trigger harmonic distortions, typically transients and surges caused by events such as lightning or switching operations, present short-term but potentially harmful disturbances (Parida et al., 2024). However, in this study, voltage sags, swells, frequency differences and harmonic distortions are mostly discussed In addition, energy flow was initiated to the wind turbine with a permanent magnet synchronous generator (PMSG) connection and also, LCL filter was designed and source connection was realized to suppress harmonic distortion that will occur on the source side due to the load connection. In addition, stable and reliable power transfer was realized for linear and non-linear loads by connecting the DVR in series between the load and the point of common coupling (PCC). The proposed system structure and waveforms are detailed in Figure 1.

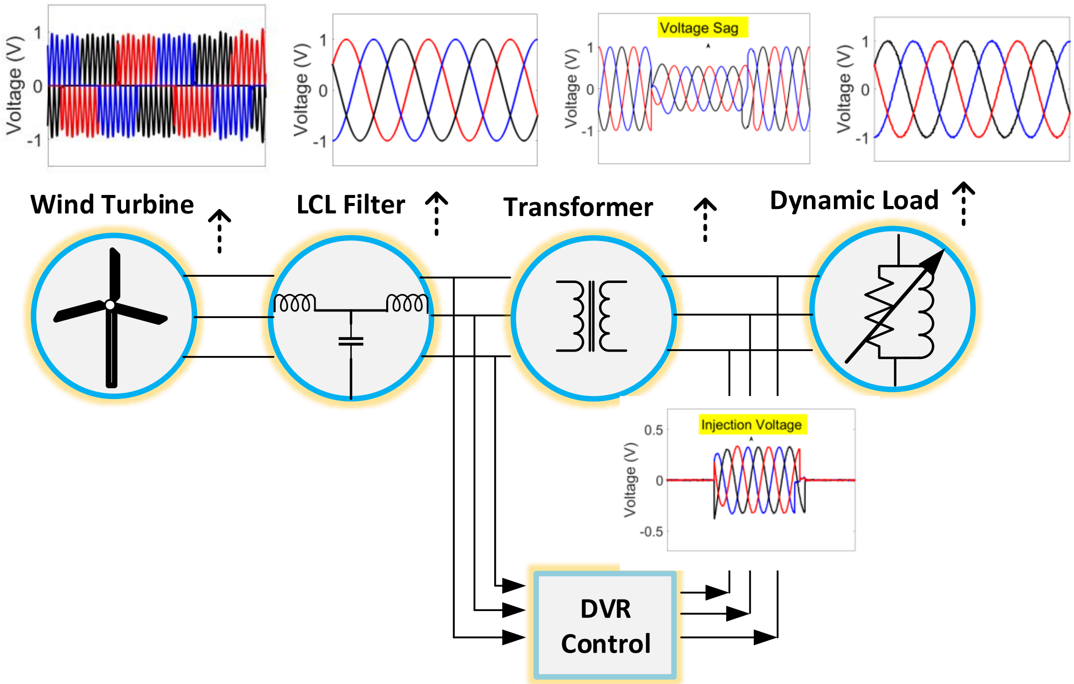


Figure 1. Proposed System Structure and Waveforms

Bubshait et al. proposed a conservative power theory based control method that is used for grid connected wind turbine power system. The power quality is improved by reducing the THD of the grid current. Passive filters are excluded, and a more compact, flexible, and reliable structure of smart grid based control is proposed (Bubshait et al., 2017). Nasrollahi et al. Proposed a control system based on three-phase three-wire dynamic voltage restorer and sliding mode control (SMC) to compensate for the voltage sag and swell. The DVR system presented in the study includes a separate AC/AC converter design for each phase without the need for energy storage and DC link connection. The proposed system has been tested on a 20kW prototype, and its effectiveness in THD suppression has been emphasized (Nasrollahi et al., 2022). Parida et al. propose an approach that aims to improve power quality in grid-connected PV systems by embedding a Type II Fuzzy Logic Controller (FLC) within a Dynamic Voltage Restorer (DVR). It is argued that the proposed work provides improvements in power quality, including voltage sags and swells (THD) (Parida et al., 2024). In addition, similar studies in the literature and the system features suggested in this study are presented together in Table 1.

Table 1. Literature Overview and Proposed Study

Reference	Power Source	Load	Objective
Tu et al., 2018	Grid	Sensitive Load	A new fault current limiter based on a dynamic voltage restorer is proposed to limit the fault current with reduced size and cost compared to traditional methods.
Babu et al., 2021	Hybrid (Grid and PV)	Linear-Non Linear	Realization of low harmonic distortion, high power factor, and voltage fault regulation by means of Predictive Space Vector Transform (PSVT)-PR control based DVR method.
Ye et al., 2019	Grid	Critical Load	correction of the power factor (PF) at the source side using voltage compensation method based on elliptical restoration through a single phase dynamic voltage recovery device (DVR).
Rao et al., 2015	PV System	Resistive Load	Fuzzy-DVR design and also using photovoltaic system instead of traditional dc storage system as the power source of DVR to compensate voltage drops and swells
Prasad & Dhanamjayulu, 2022	Grid	Resistive Inductive	Development of a solar PV-integrated DVR employing a rotating dq reference frame controller to enhance power quality by mitigating issues like voltage sags, swells, and high harmonic distortion
Proposed	Wind Power System	Linear-Non Linear	Improve power quality problems such as voltage sags and swells, harmonic distortion, and also to test the system under linear, non-linear loads and different wind speeds.

SYSTEM DESIGN AND ANALYSIS

Power circuits are needed for system design that prevents voltage changes that may occur in the stand-alone wind turbine system, where sensitive loads are fed from damaging the load and ensure that the load operates at nominal voltage without being affected by variable operating conditions. In this study, wind turbine and PMSG determination stages and features for source modeling, LCL filter design for stable and reliable power transfer at low harmonic distortion were realized. In addition, the DVR structure that continuously controls the system and detects unexpected errors such as sudden voltage drops, increases, frequency changes, and non-linear dynamic feeding, and injects voltage at the reference value, ensuring the load operates at the nominal load was modeled. In addition, PLL structure that monitors and locks the phase and frequency of the source voltage and thus ensures synchronous operation of DVR and load voltage was designed.

Wind Turbine and PMSG

The blades of the horizontal axis wind turbine, which is used to convert the kinetic energy of atmospheric wind, are connected to the turbine shaft and combined with the multi-pole three-phase PMSG machine to produce electrical energy from kinetic energy. PMSG-based wind power systems constitute the power source structure of three-phase connection stand-alone power systems (Mayilsamy et al., 2022).
The aerodynamic power of the wind turbine can be measured by the following mathematical model:

$$P = \frac{1}{2}\rho A V_{\omega}^{3} C_p \tag{1}$$

$$\lambda = \frac{\omega_m V}{R} \tag{2}$$

Where, p is air density, V_{ω} is the velocity of the wind, A is the area covered by the blades, λ is the tip speed ratio. C_p is the power coefficient of the wind turbine ($A=\pi R^2$), R is the radius of the blade, and ω_m is the turbine rotor speed. Additionally, PMSG equations are usually defined on the d−q axis and expressed as follows.

$$\begin{cases} v_{md} = R_s I_{md} + L_{md}\frac{di_{md}}{dt} - w_e L_{mq} i_{mq} \\ v_{mq} = R_s I_{mq} + L_{mq}\frac{di_{mq}}{dt} - w_e L_{md} i_{md} + w_e \Psi_f \end{cases} \tag{3}$$

The electromagnetic torque generated in the PMSG can be found from the following equation.

$$T_e = 1.5P\Psi_f i_{mq} \tag{4}$$

Where R_s is stator winding resistance, L_{md} and L_{mq} are stator winding inductances, Ψ_f is airgap flux, w_e is angular frequency of stator voltages, and I_{md}, I_{mq}, V_{md}, V_{mq} are stator winding currents and voltages respectively, P is pole pair number of PMSG.
The electrical properties, parameters, and values of the wind turbine and PMSG used in this study are presented in Table 2.

Table 2. Wind Turbine and PMSG Parameters

Wind Turbine		PMSG	
Parameter	**Value**	**Parameter**	**Value**
Nominal mechanical output power (W)	12kW	Number of Phases	3
Base power of the electrical generator (VA)	12VA/0.9	Stator phase resistance Rs (Ohm)	0.0485
Base wind speed (m/s)	12m/s	Armature inductance (H)	0.000395
Maximum power at base wind speed (pu of nominal mechanical power)	0.85	Flux linkage	0.1194
Base rotational speed (p.u. of base generator speed)	1.2	Initial conditions	0
Pitch angle beta to display wind-turbine power characteristics (beta >=0) (deg)	0	Pole Pairs	4

LCL Filter design

There are harmonic suppression filters such as L, LC, and LCL in the literature. L filter is larger in size than LC and LCL filters, and voltage drop can be a problem in this filter; and it is not as effective as LCL filter in harmonic suppression. LC filter is also larger in size compared to LCL filter and takes up more space (Ranjan & Giribabu, 2023; Göncü & Yılmaz, 2023). In this study, LCL filter design is realized for harmonic suppression between the load and PMSG. The LCL filter equivalent circuit is presented in Figure 2.
The current and voltage based transfer function and resonant frequency of the LCL filter are defined as follows.

$$\frac{I_{Tr}}{V_{PMSG}} = \frac{1}{L_1 L_2 C_1 s^3 + (L_1 + L_2)s} \tag{5}$$

$$f_{resonant} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C_1}} \tag{6}$$

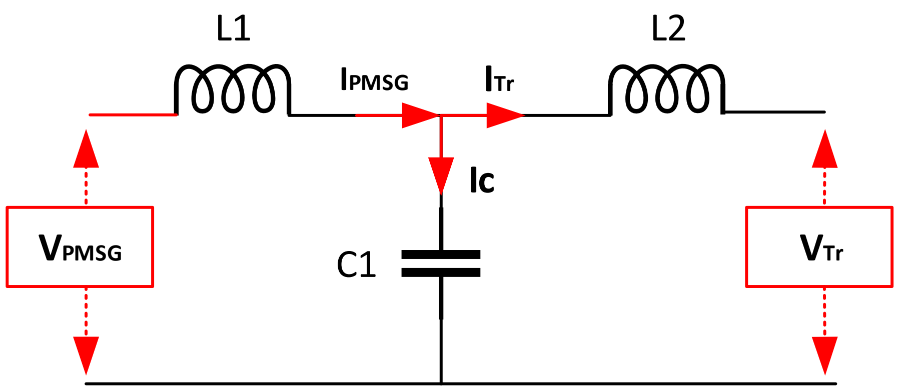


Figure 2. LCL Filter Equivalent Circuit

The Bode diagram of the designed LCL filter, which includes the magnitude and phase responses of the frequency and the resonance frequency, is presented in Figure 3.

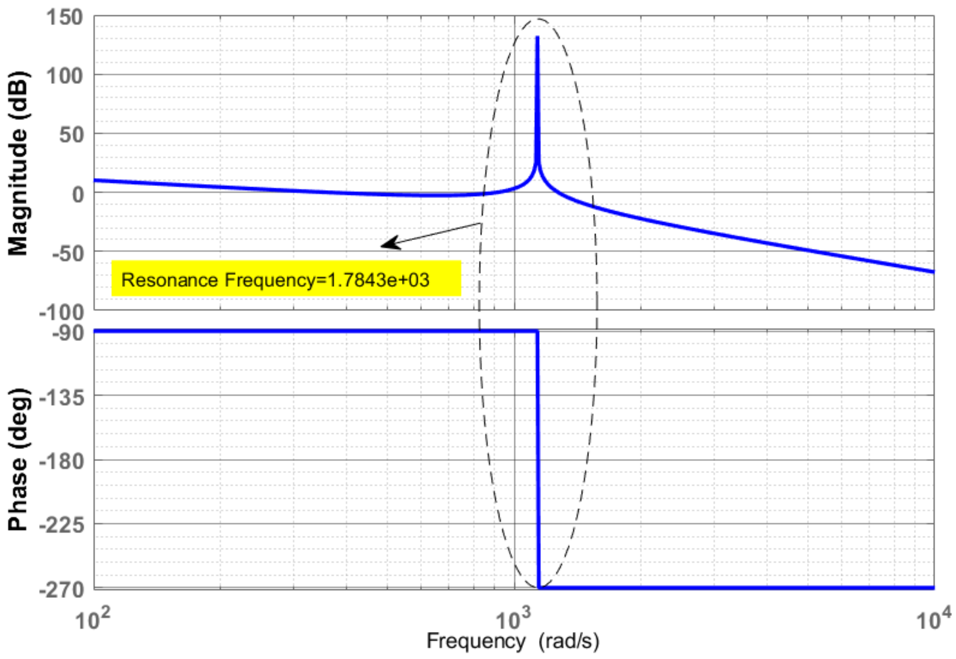


Figure 3. LCL Filter Bode Diagram

Harmonic distortion or THD absorbed by the designed filter is expressed as the ratio of all harmonic components of a quantity (voltage, current) to the fundamental component. Therefore, Voltage THD is expressed by the following equation.

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{N} V_h^2}}{V_1} \tag{7}$$

V_{THD} denotes the total harmonic distortion of the voltage, where V_1 is the fundamental frequency voltage, N is the highest harmonic order included in the analysis, h represents the harmonic order, and V_h is the voltage harmonic corresponding to the h-th order (Kavitha et al., 2023).

Analysis of DVR and PLL technologies

The DVR is a forced-commutated voltage source converter that dynamically regulates bus voltage through a booster transformer, injecting a series voltage to maintain a stable load voltage during fluctuations in the source voltage (Singh & Winston, 2023; Ganthia et al., 2016). Control structures that perform PWM generation play a critical role in DVR applications. Detection of voltage changes and generation of a new reference voltage depending on this change are the main tasks of the control structure within the DVR (Janardhanan & Mulla, 2024; Mbuli, 2023). In this study, the PI-based control method is employed to regulate the pulse-width modulation (PWM) signals governing the semiconductor switches of the inverter, which is connected to a DC power source. Harmonic attenuation is achieved through the implementation of an LC filter, ensuring that the voltage delivered to the load remains consistent with the source. The DVR configuration developed for a stand-alone wind power system is depicted in Figure 4.

The first step of the PI based control method will be to define the three phase signal on the d-q axis by applying Park's d-q-0 transform to the load voltage (Parida et al., 2024; Nasrollahi et al., 2022).

$$V_d = \frac{2}{3}((V_a sin(wt) + V_b sin\left(wt - \frac{2\pi}{3}\right) + V_c \sin(wt + \frac{2\pi}{3})) \tag{8}$$

$$V_q = \frac{2}{3}((V_a cos(wt) + V_b cos\left(wt - \frac{2\pi}{3}\right) + V_c \cos(wt + \frac{2\pi}{3})) \tag{9}$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{10}$$

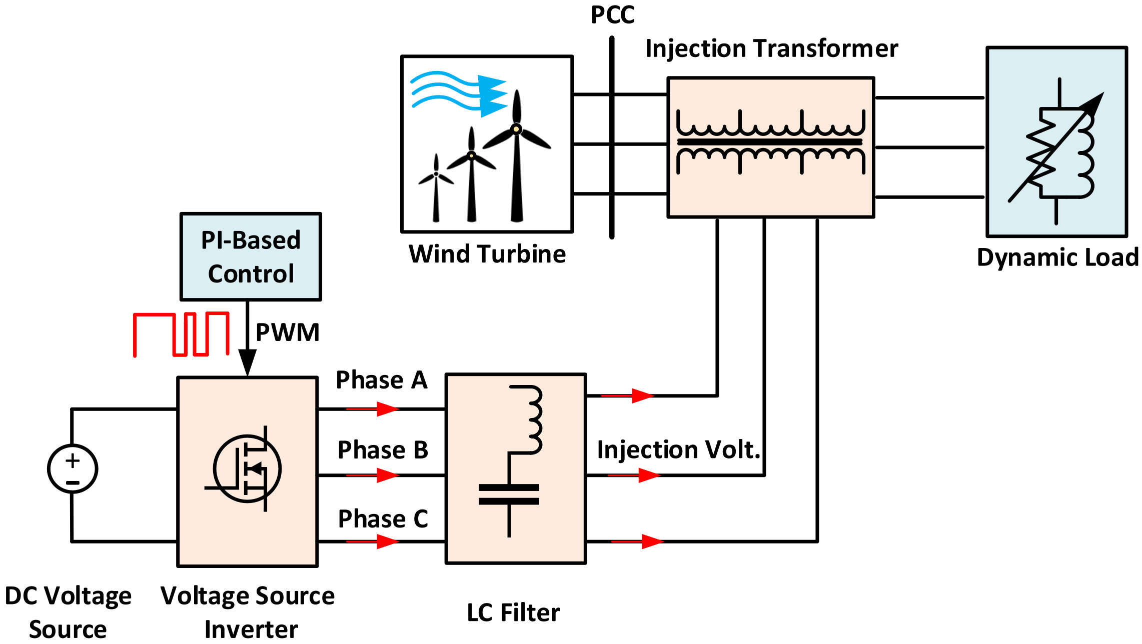


Figure 4. PI Control Based DVR Structure

Possible distortions in the signals transferred to the dq axis are calculated by comparing them with the reference value, then they will be converted back to the three-phase abc system. In addition, a phase-locked loop (PLL) is used to coordinate the frequencies of the load voltage and the voltage to be injected. The error between the actual values of the dq voltage and the reference values is used as the input of the PI controller, and its output supports the generation of PWM for the switching elements (Muktiadji & Oladigbolu, 2021; Mosaad et al., 2019).

$$\begin{cases} e_d = V_{d\,(ref)} - V_d \\ e_q = V_{q\,(ref)} - V_q \end{cases} \tag{11}$$

In addition, the DVR power required to compensate for possible voltage sags and swells in the source voltage is defined by the following equation.

$$P_{dvr} = \left(\frac{V_1 - V_2}{V_1}\right) P_{Load} \tag{12}$$

Where V_1 is the nominal voltage, V_2 is the faulty voltage (sag or swell), and P_{load} is the load power. The block structures of the PI-based control method used for the DVR are presented in detail in Figure 5.

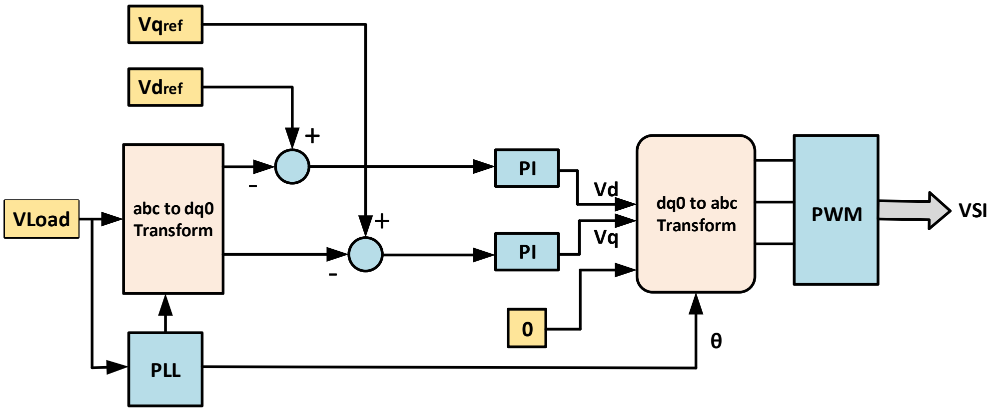


Figure 5. Structure of the PI-based Control in DVR

The applied DVR compensation method (pre-fault) continuously monitors the supply voltage and if it detects any disturbance in this voltage, it injects the difference voltage between the sags or swells in PCC and the ideal pre-fault condition. The Phase Lock Loop (PLL) regulates the load angle and the supply angle transmitted to the PCC, resulting in θ being aligned with the supply voltage. In this way, the load voltage can be returned to pre-fault conditions, and compensation is provided for voltage drops in a load that is sensitive to both phase angle and amplitude (Soomro et al., 2021; Molla & Kuo, 2020). The phasor diagram of the pre-fault compensation method is presented in Figure 6.

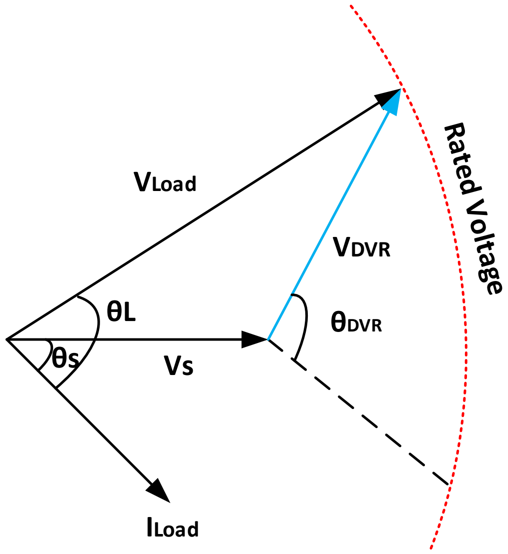


Figure 6. Phasor Diagram of Pre-Fault Compensation

In case of sudden changes in the voltage supplied to sensitive loads, the DVR needs to inject a voltage vector that is the difference between the reference load voltage and the source voltage so that the load voltage amplitude and phase angle are restored to the pre-fault value. The injected apparent power $S_{inj.}$ and injected active power $P_{inj.}$ are as follows (Liu et al., 2024; Tavighi et al., 2013; Moreno-Munoz et al., 2006).

$$S_{inj.} = I_{Load}V_{DVR} = I_{Load}\sqrt{V_{Load}^2 + V_S^2 - 2V_{Load}V_S(\theta_L - \theta_S)} \tag{13}$$

$$P_{inj.} = I_{Load}(V_{Load}Cos\theta_L - V_S Cos\theta_S) \tag{14}$$

To restore the load voltage in terms of maintaining power quality, the magnitude and angle of the voltage to be injected are as follows.

$$V_{DVR} = \sqrt{V_{Load}^2 + V_S^2 - 2V_{Load}V_S(\theta_L - \theta_S)} \tag{15}$$

$$\theta_{DVR} = tan^{-1}\left(\frac{V_{Load}Sin\theta_L - V_S Sin\theta_S}{V_{Load}Cos\theta_L - V_S Cos\theta_S}\right) \tag{16}$$

Here, I_{Load} is the load current, V_{Load} is the load voltage angle, V_{DVR} is the injected voltage, θ_{DVR} is the injected voltage angle, θ_L is the load voltage angle, and θ_s is the voltage angle at PCC.

PLL is a closed loop system that controls a voltage controlled oscillator and serves as one of the basic structures of the DVR method (as presented in Figure 5). It aims to maintain the frequency and phase of the external periodic signal using a feedback loop; however, in the case of feeding sensitive loads from power electronics based systems, it is common to encounter problems such as voltage drops and rises, phase loss, and frequency changes. PLL should be capable of rejecting these errors and maintaining phase lock to the source voltage. The quantities that vary depending on time in three-phase systems are as follows (Panchal et al., 2025; Natesan & Venkatesan, 2016).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = V \begin{bmatrix} Cos(wt) \\ Cos(wt - \frac{2\pi}{3}) \\ Cos(wt - \frac{4\pi}{3}) \end{bmatrix} \tag{17}$$

The first step in transforming three-phase voltages to the rotating reference frame is to transfer the initial projected quantities onto the orthogonal axis (Clarke transform) and is expressed as follows

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & Cos(\frac{2\pi}{3}) & Cos(\frac{4\pi}{3}) \\ 0 & Sin(\frac{2\pi}{3}) & Sin(\frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = V \begin{bmatrix} Cos(wt) \\ Sin(wt) \\ 0 \end{bmatrix} \tag{18}$$

Here, alpha (α) and beta (β) components are the stationary reference frame variables. As presented in Figure 7, the net voltage vector forms an angle θ with the orthogonal axis and rotates at an angular frequency ω. By projecting the components of the stationary reference frame onto this rotating reference frame (Park Transform), the system can be transformed into a DC equivalent and expressed as follows.

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} Cos(\theta) & Sin(\theta) & 0 \\ -Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} \tag{19}$$

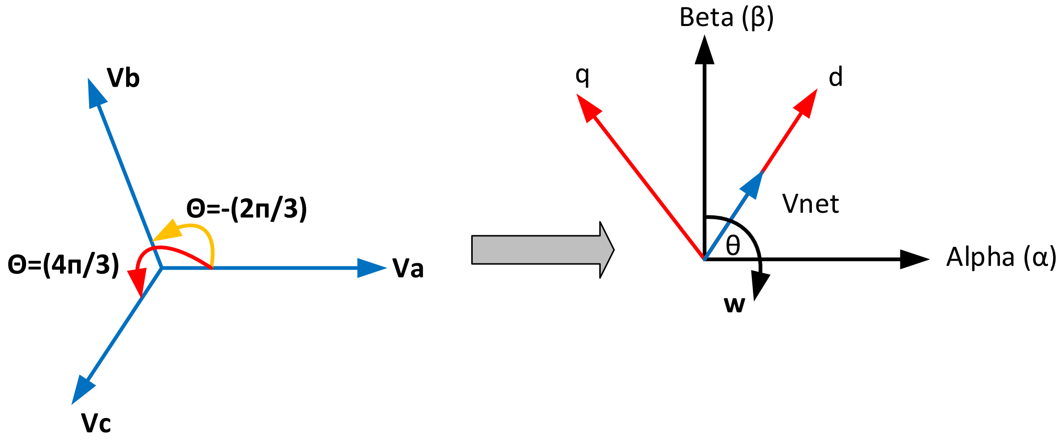


Figure 7. Transforming the Three-phase (abc) Signal into the Dq0 Rotating Reference Frame

Using trigonometric identities, equation 17 can be expanded as follows.

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} Cos(\theta) & Sin(\theta) & 0 \\ -Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} x \begin{bmatrix} Cos(wt) \\ Sin(wt) \\ 0 \end{bmatrix} V \tag{20}$$

When the difference between the angle of the real voltage vector and the angle tracked by the PLL (ωt- θ) is close to zero, sin(wt- θ ≈ wt- θ). Subsequently, when the PLL completes the locking process, it is observed that the q-axis component in the rotating reference frame of a balanced three-phase system drops to zero, in which case, a small error is observed if the locking process does not occur.

$$V_q \approx (wt - \theta) \tag{21}$$

In three-phase systems, the q component is used as the value at which the phase is detected while the voltage quantity is converted to the rotating reference frame. Then, PI controller is used to eliminate the steady-state error. The electrical and modeling parameters of the proposed study are presented in Table 3 along with their values.

Table 3. Parameters and Values of The System Structure

Parameter	Value	Parameter	Value
$L_{1Filter}$	1.55 mH	R_{Load}	200 Ω
$C_{1\ Filter}$	1mF	L_{Load}	8 mH
$L_{2Filter}$	1.55 mH	K_{pd}	32
Load Voltage	400 V_{dc}	K_{id}	124
Frequency	50 Hz	K_{pq}	21
DC Voltage	200 V_{dc}	K_{iq}	250

CASE STUDIES AND RESULTS

In the proposed study, tests were performed under different conditions, including phase-to-ground fault application, different wind speeds, different source frequencies, and dynamic (non-linear load), and the results were analyzed. Figure 8 presents the injected voltage changes and load voltage status through DVR application when the load and source are at the same and different frequencies. While the injected voltage is evident with small oscillations when the source and load are at the same frequency, the voltage injection is performed by taking into account the phase difference between the signals when the load and source are at different frequencies.

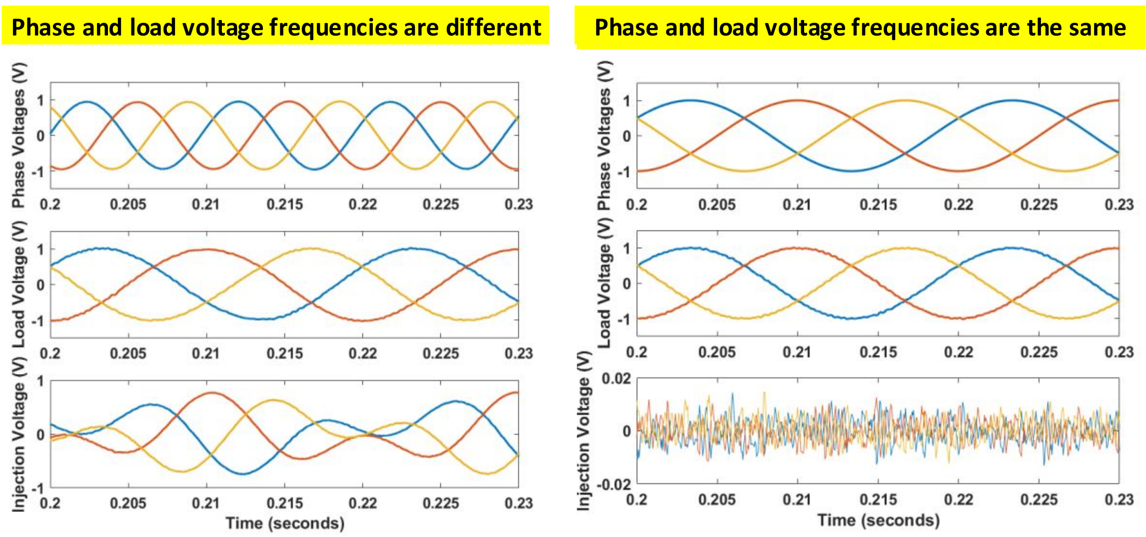


Figure 8. Frequency Based Phase, Load and Injected Voltages

In Figure 9, a fault was applied only between phase a and ground, and thus, the DVR detected the fault in phase a and adjusted the voltage to be injected. In the last case, the load voltage was not affected by the phase fault and continued to be supplied according to the situation before the fault.

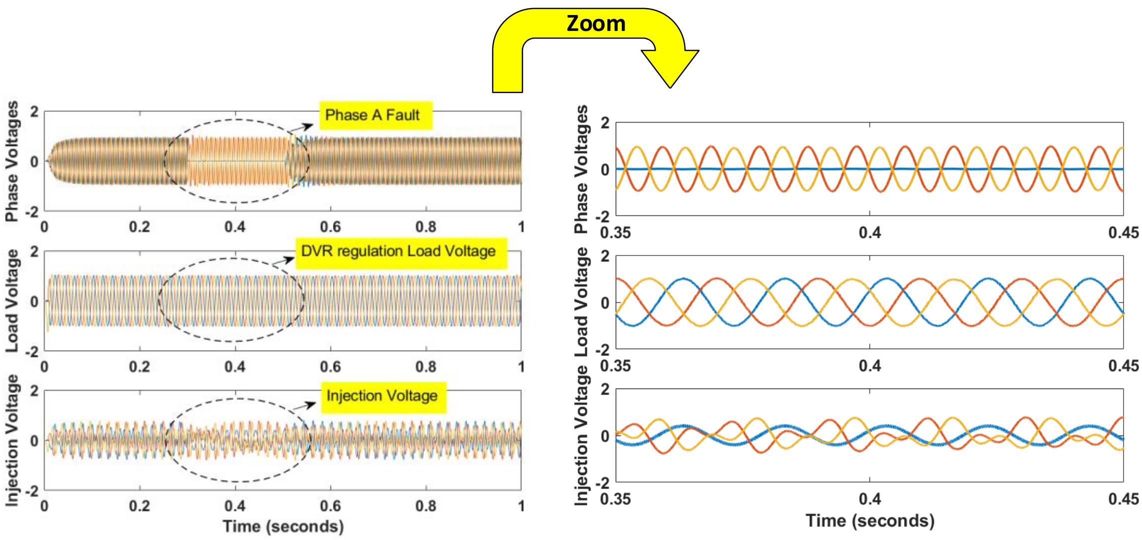


Figure 9. Phase- Ground Fault Basis Voltages

In Figure 10, a fault was applied between all three phases and ground, and the voltages dropped to almost zero for a certain period of time (0.3s- 0.5s). However, the DVR detected the fault between the phases and ground and injected a series voltage and ensured that the load voltage continued to be supplied without changing.

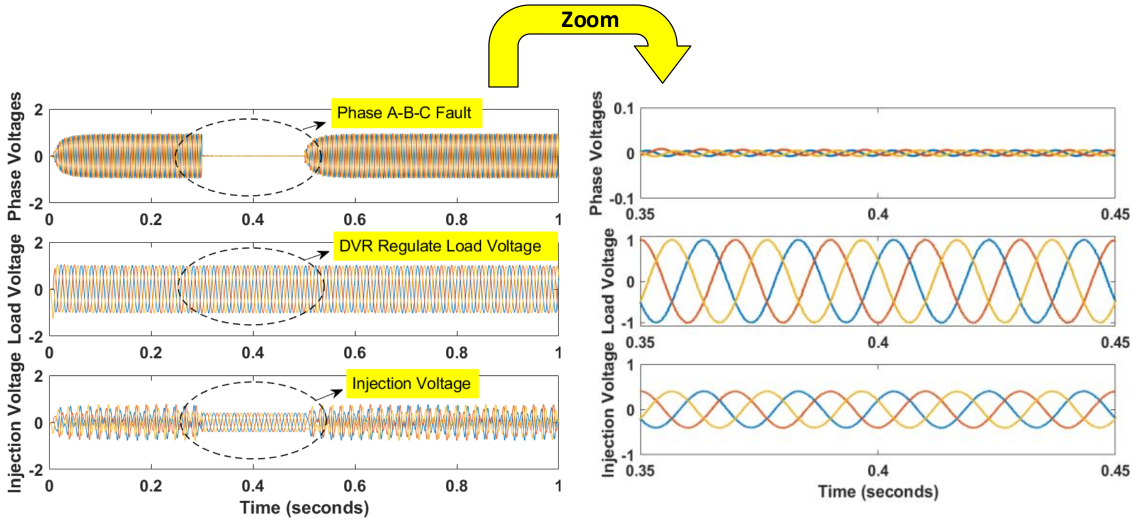


Figure 10. Phase-to-Ground Basis Fault and Its Effect on Load Voltage

In Figure 11, the dynamic and nonlinear load is connected to the system, and the phase load and injected voltages are examined in the cases without DVR and with DVR. In the case without DVR, the effect of the nonlinear load on the source voltage is directly transferred to the load and causes the load to be fed with high harmonic voltage. However, after the DVR is applied to the system, the effect of the nonlinear load is damped, and the series voltage injected into the system ensures that the load continues to be fed with low harmonic voltage.

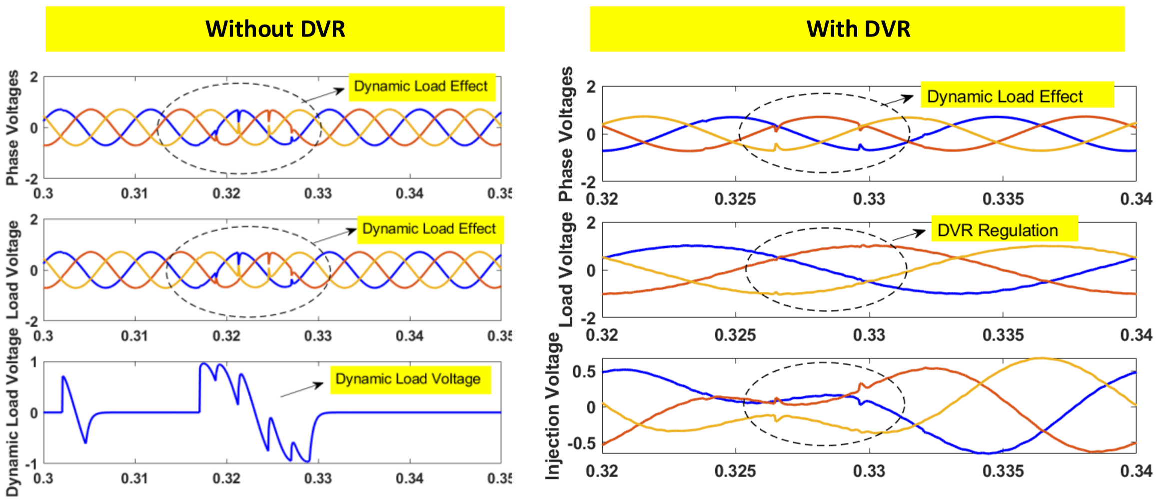
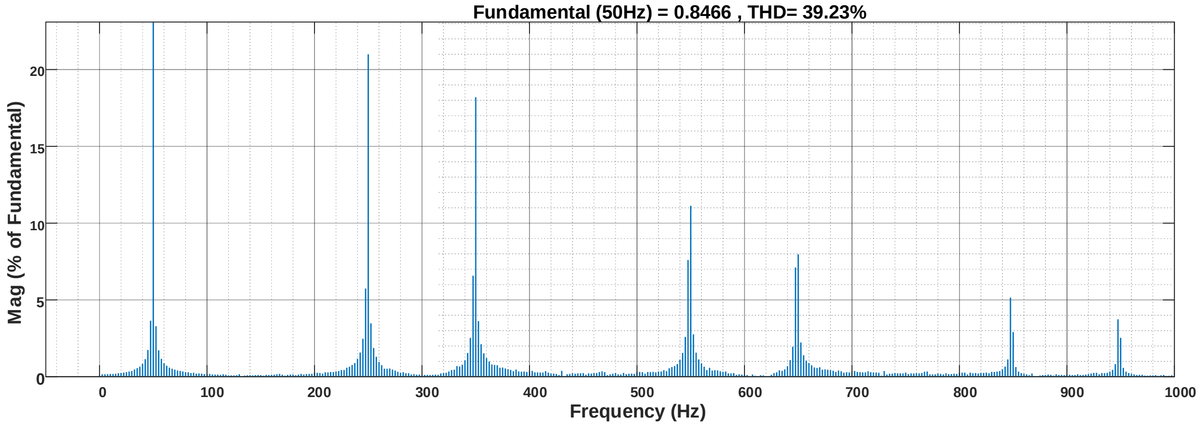
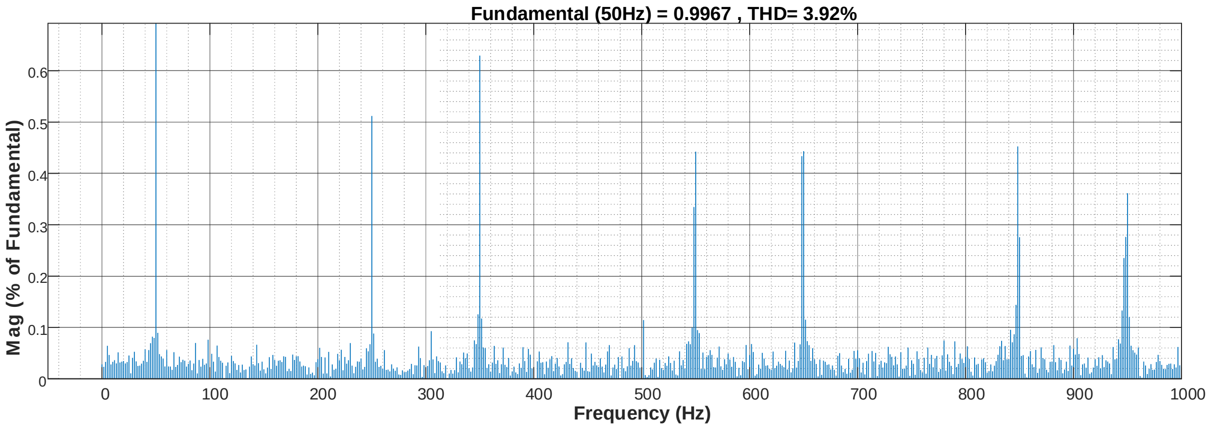


Figure 11. Effect of Dynamic Nonlinear Load on Voltages and DVR

Although the total harmonic distortion (THD) of the load voltage exceeded 39% with the dynamic nonlinear load connected to the system (Figure 12a), it was reduced to 3.92% after the DVR was applied and the compensating voltage was injected (Figure 12b). In Figure 12, "Fundamentals (50 Hz)" denotes the value of the fundamental frequency voltage (refer to Equation 7 and Table 4). Additionally, Table 4 presents the impact of both the dynamic nonlinear load connection and the DVR application on the load voltage THD and other operating parameters.



(a)



(b)

Figure 12. a. Load Voltage THD Without DVR, **b.** Load Voltage THD with DVR

Table 4. DVR Effect on Voltage Harmonics Under Dynamic Load

Operation Parameters	Without DVR	With DVR
Sampling Time (s)	5.10^{-5}	5.10^{-5}
Samples Per Cycle	400	400
Fundamental Frequency Voltage (Per Unit)	0.8466	0.9967
Total Harmonic Distortion (THD)	39.23%	3.92%

In Figure 13, different wind speeds were applied to the wind turbine (14ms-16ms), and the response of the DVR was tested by providing source voltage sags and swells. To prevent the load voltage from being affected by the source voltage fluctuations at different wind speeds, the DVR injected series voltage into the system.

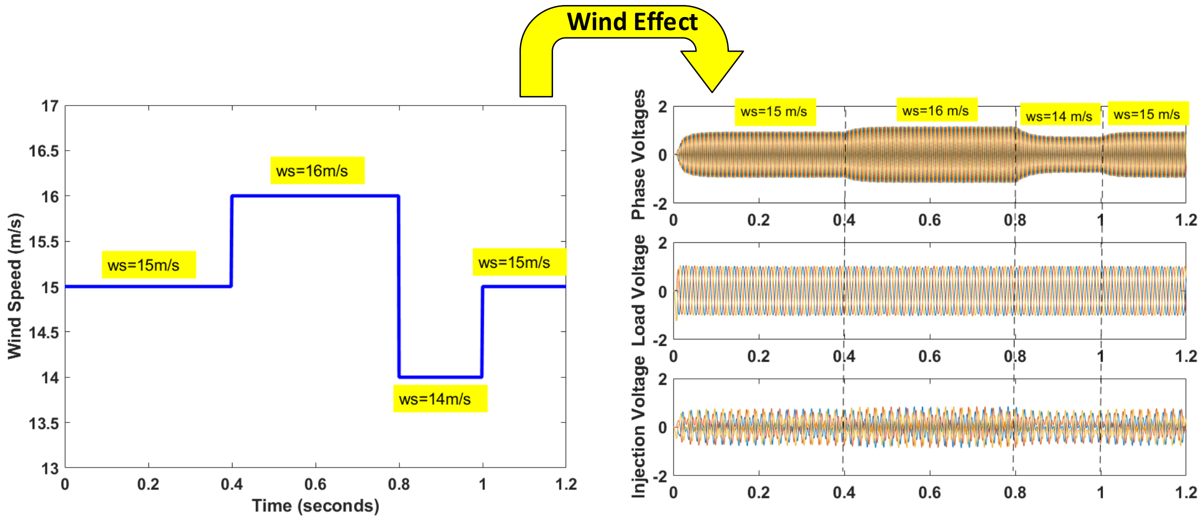


Figure 13. Variable Wind Speeds and Voltage Responses

The harmonic distortion caused by the faults applied between phase and ground (P, means phase, G, means ground) in the load voltage and the THD damping results after DVR application are presented in Table 5.

Table 5. Load Voltage THD With DVR and Without DVR After Phase-to-Ground Fault

Fault Types	Without DVR (THD %)	With DVR (THD %)
P-G	13.53 %	1.56 %
P-P-G	14.41 %	1.59 %
P-P-P-G	13.58 %	1.56 %

CONCLUSION

While stand-alone wind turbine systems provide sustainable energy production, the variable and unpredictable nature of the wind can cause serious problems in terms of power quality. Especially in environments with sensitive loads (such as medical devices, communication systems, and automation systems), sudden voltage fluctuations, harmonics, and frequency deviations can negatively affect sensitive load performance. In this study, a stand-alone wind turbine system is presented with DVR technology to feed sensitive loads (Figure 1). The DVR technology modelled in this study includes phase-locked loop (PLL), a dc-voltage source, and a harmonic filter connected to an inverter for series voltage injection into the power circuit (Figures 4 and 5). The Dynamic Voltage Restorer (DVR) used in the study aims to ensure the safety of sensitive loads by effectively balancing voltage sags, swells, or temporary disturbances that may occur in the independent wind turbine. However, Phase-Locked Loop (PLL) structure is used to precisely monitor the phase angle and frequency of the ac voltage obtained from the wind turbine and to ensure the synchronization of the DVR. The study separately considers the cases of different wind speeds (Figure 13), phase-ground faults (Figures 9 and 10), source and load with different frequencies (Figure 8), including linear and non-linear loads (Figure 11), and ensures the load voltage performs at nominal value even in the specified cases. In addition, under dynamic non-linear load, the DVR ensured compliance with IEEE-519 standards by reducing the load voltage harmonics from 39.23%2 to 3.92% (Figure 12 and Table 4). In addition, the load voltage THD was suppressed under phase-ground fault conditions to ensure the load operates at nominal voltage (Table 5). As a result, the security of sensitive loads and energy continuity in stand-alone wind turbine systems is made possible by advanced power electronic solutions such as DVR and PLL. The integration of these structures not only improves power quality but also ensures that renewable energy systems can be used safely in critical applications. In this study, MATLAB/Simulink program was used for system modeling, analysis, and implementation.

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