Design and Optimization of Dynamic Voltage Restorers for Enhancing Power Quality and Fault Ride through (FRT) in Grid-Integrated Hybrid Energy Systems

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Abstract: The integration of renewable energy sources, such as solar and wind, into modern power grids presents challenges in maintaining power quality and stability, particularly under fault conditions like voltage sags and swells. This research focuses on the design and optimization of Dynamic Voltage Restorers (DVRs) to enhance power quality and Fault Ride through (FRT) capabilities in hybrid solar-wind systems. Using advanced control strategies, including fuzzy logic and adaptive Bee Colony Optimization (ABCO), DVRs mitigate voltage disturbances and optimize the parameters of Proportional-Integral (PI) controllers. The study examines system performance across three scenarios: without DVR, with DVR using fuzzy logic control, and with DVR employing ABCO. Results demonstrate progressive improvements in voltage stability, power quality, and total harmonic distortion (THD) reduction, establishing DVRs as critical components for integrating renewable energy sources into reliable and resilient grid systems.

Keywords: Dynamic Voltage Restorer (DVR), Fault Ride through (FRT), Hybrid Solar-Wind Systems, Adaptive Bee Colony Optimization (ABCO), Power Quality, Total Harmonic Distortion (THD).

I. INTRODUCTION

Approximately 770 million people globally have no access to electricity, and global energy demand is expected to increase by a third by 2035. The primary sources of energy are fossil fuels, accounting for 82% of energy use in 2022; however, these are the sources that contribute heavily to greenhouse gas emissions and global warming. Increasing energy demands are being met and emission reduction targets under the Paris Agreement are being achieved through increasing adoption of RES. In 2022, RES generated 10.2% of the global power. Hybrid energy systems play an important role in modern power grids by integrating renewable sources, such as solar and wind power, with conventional fossil fuels and advanced storage technologies. Hybrid systems are optimized to optimize energy generation, distribution, and consumption to eliminate the issues like intermittency and load fluctuations that have always compromised reliability and sustainability. Hybrid systems combining the complementary characteristics of different types of energy sources ensure both stable and efficient supply of power without compromising environmental sustainability [1] [2].

Hybrid energy systems provide significant benefits in the ability to store excess energy at the point of peak generation and then distribute it at the point of peak demand. Therefore, such a system maximizes grid stability. Battery banks and flywheel-based storage technologies ensure uninterrupted supply even with intermittent conditions. This technology further boosts efficiency because of its operation process based on using the cheapest source and least detrimental form of energy that is available while attempting to reduce both energy and operating losses. Implementing hybrid systems with renewable energy sources greatly minimizes the emission of greenhouse gases in support of global efforts in combating climate change. Besides their contribution toward environmental benefits, hybrid systems also increasingly prove to be versatile. They promote transitions in energy consumption in grid applications for developing regions and ensure essential access to power in remote areas. Hybrid systems have provided the ancillary service of voltage as well as frequency regulation in aid of stabilizing the grids within developed regions. They replace the traditional diesel generators with clean and sustainable alternatives in off-grid locations, thereby nurturing economic and social development [3] [4].

Fault Ride Through (FRT) is an important feature for grid-connected systems, especially with the integration of renewable energy sources such as wind and solar. FRT allows systems to stay connected and operational during short-term faults or disturbances, thereby maintaining grid stability and preventing cascading failures. With increased penetration of renewable energy, grid codes are becoming increasingly stringent, requiring FRT capabilities in energy generation systems. PV power generation systems will have to add backup stability in the system at fault inception. STATCOM, a fixed-speed windmill has enhanced the FRT concept in that there is reactive compensation at fault instances so that its grid can become stable in grid fault situations and control strategies also of Grid Forming type would have emerged today in order to comply with highly stringent grid codes. These mimic the behaviour of synchronous condensers to stabilize the grid during faults, and inverter-based resources may use simplified control mechanisms [5] [6] [7].

The integration of electric vehicles (EVs) into power grids offers significant opportunities but also presents challenges. EV adoption increases evening peak demand, risking grid congestion and outages. Grid upgrades and load management strategies are essential to address this. Vehicle-to-grid (V2G) technology emerges as a solution, allowing bi-directional energy flow where EVs act as mobile storage units, returning unused energy to the grid during high demand, thereby enhancing grid stability and renewable energy integration. Challenges include managing variable charging demand influenced by time, location, and user behaviour, requiring smart grid systems for dynamic adjustments. Expanding charging infrastructure, including public, home, and fast-charging networks, is critical. Voltage and frequency stability may be affected by dense charging loads, necessitating sophisticated management strategies like Demand Response Programs [8] [9] [10].

II. LITERATURE REVIEW

Preethi Sebastian et al. (2024) [11] suggested Dynamic Voltage Restorer (DVR) to improve the FRT capacity of a wind turbine at fixed speed. Both balanced and unbalanced voltage sags are analyzed and simulated for a fixed speed wind turbine employing squirrel cage induction generator (SCIG). Two AI-based controllers, the SVM Regression Model Based Supervised Machine Learning approach and the DNN controller, are used in order to analyze and compare the performance of DVR. The rotor speed can be maintained at rated levels due to the SVM Regression approach, which reduces the torque pulsations to 25%, and 100% voltage sag compensation is obtained during unbalanced voltage sags. It also reduces the Total Harmonic Distortion to 2%

Jiandong Jia et al. (2024) [12] developed a multi-objective optimization model for the regional integrated energy system with the objectives of economic advantages, carbon reduction, and reliability. In analyzing the total benefits of the internal energy stations in the regional integrated energy system, much consideration was on system benefits, inter-station energy sharing, and energy storage. The regional integrated energy system constructed in the study showed higher energy saving, carbon reduction, and independence compared to other integrated energy systems through research findings. The primary energy usage of the proposed system was 16.26 kWh/m2, carbon emissions were 4.33 kg/m2, and the power interaction was 9.99 kWh/m2. Annual total cost for the system is 38.41 CNY/m2. In conclusion, the theoretical support for regional integrated energy systems through the use and promotion of this work is ensured.

D. Jain et al. (2023) [13] examined many strategies of tertiary control for energy management and power flow in a hybrid microgrid system, secondary control for voltage or current error correction, and primary control for current or voltage regulation. This study also looks at the advantages and disadvantages of a number of control structures that operate as decentralized, centralized, and distributed controls. Every microgrid architectural control method's working principle and efficacy have been covered. This study examines specific control aspects, such as coordinated control between several interlinking converter and energy storage systems and mode changeover. System stability is the main concern of microgrid for system engineer thorough knowledge of control strategies is the upmost requirement. Control strategies, rotor angle, voltage and frequency instability in power systems, and techniques for enhancing microgrid stability are thus highlighted in this study.

Nishant Kumar et al. (2023) [14] an auto-tuned MPPT (Maximum-Power-Point tracking) control method and a novel adaptive control strategy for the grid-interfaced photovoltaic (PV) assisted onboard EV (Electric Vehicle) charging infrastructure are presented. The proposed control algorithm is named Multilayer Multi-order Generalized Discrete Integrator based Adaptive Control. The method encompasses damping reduction, noise removal, delay minimization, filtering harmonic components, and an accurate fundamental component estimate feature. In addition, the new technology of MMGDI-AC includes an EV safety management function for safe electric vehicle charging. Furthermore, a "Single-input Adaptive Fuzzy-Logic (SIAFL)" is developed for real-time optimal decision taking. A unique SIAFL tuned P&O (SFPO) MPPT algorithm is presented, which solves the fixed step-change problems of the traditional P&O MPPT technique by utilizing SIAFL with the Perturb and Observe (P&O) algorithm. The major aspects of this work, which uses a double stage single phase topology, are safe EV charging, power management, power quality maintenance, and optimal maximum power extraction from the solar PV array. Both the performance and the capabilities of the created techniques are evaluated under various charging dynamics and grid anomalies. With the use of developed hardware, test results are displayed.

Farah Souayfane et al. (2023) [15] investigated how weather variability affects the best way to design and run renewable energy systems for Saudi Arabian office buildings. A photovoltaic, wind, and battery storage system, along with an additional grid connection, provides the building's electrical needs. By taking into account weather datasets with varying degrees of unpredictability, the optimization method then seeks to determine the ideal capacity of the renewable energy system components in order to achieve a trade-off between life cycle cost and CO_2emissions. According to the findings, taking into consideration all weather variability-especially extreme weather events-raises the cost of investing in a fully renewable energy system because of the additional battery storage (up to 288%). However, ignoring exceptional occurrences throughout the design phase results in a large performance gap that might be made up for with a small change in system cost through grid integration, which raises overall CO_2emissions. Days with high temperatures and clouds are then associated with these extreme weather conditions, which decreases photovoltaic power generation and increases the need for energy from the grid or storage. This study also looks at how power costs affect the layout and functionality of renewable energy installations. Given the issues posed by global weather variability, the paper's conclusions offer valuable suggestions for energy policy.

Table 1 Summary of Key Contributions, Technologies, and Limitations in Energy System Research

Author Name (Citation)	Key Contributions	Technology	Limitations
Preethi Sebastian et al. (2024) [11]	Proposed the use of Dynamic Voltage Restorer (DVR) to improve Fault Ride Through (FRT) capacity in fixed-speed wind turbines. Analyzed and simulated balanced and unbalanced voltage sags. Achieved 100% voltage sag compensation.	Dynamic Voltage Restorer (DVR), SVM Regression Model, DNN Controller	Limited to fixed-speed wind turbines and specific scenarios like unbalanced voltage sags.
Jiandong Jia et al. (2024) [12]	Developed a multi-objective optimization model for regional integrated energy systems, focusing on economic, carbon reduction, and reliability goals. Showed significant energy savings and carbon reductions compared to other systems.	Regional Integrated Energy System	High initial costs; limited scalability without further system optimization and financial incentives.
D. Jain et al. (2023) [13]	Reviewed tertiary, secondary, and primary control strategies for hybrid microgrids. Analyzed decentralized, centralized, and distributed control methods for system stability and efficiency.	Control strategies for microgrid management, including interlinking converters and energy storage systems	Complex implementation of coordinated controls; requires extensive expertise in control strategy for stability and reliability.
Nishant Kumar et al. (2023) [14]	Introduced an adaptive MPPT control method for PV-assisted EV charging infrastructure. Proposed the Multilayer Multi-order Generalized Discrete Integrator and Single-input Adaptive Fuzzy-Logic (SIAFL) algorithms.	Adaptive MPPT, Multilayer Multi-order Generalized Discrete Integrator, SIAFL-based P&O algorithm	Limited to grid-interfaced PV systems; needs validation across different climatic and grid conditions.
Farah Souayfane et al. (2023) [15]	Explored the impact of weather variability on renewable energy system design for Saudi Arabian office buildings. Optimized the system for life cycle cost and CO_2 emissions, considering extreme weather events.	PV, Wind, Battery Storage, Grid Connection	High investment costs due to extreme weather considerations; potential performance gaps without grid integration under extreme conditions.

III. OBJECTIVE

This research work aims to achieve the following key objectives:

- **Simulink Model Development**: Develop a comprehensive SIMULINK model for a grid-integrated hybrid solar-wind system, incorporating a DVR circuit and various loads to evaluate and optimize Fault Ride Through (FRT) capabilities.
- **Behaviour Analysis during Voltage Disturbances**: Investigate the hybrid system's response to voltage disturbances, focusing on the DVR's role in enhancing FRT capabilities under conditions like voltage sags and swells, ensuring stability and reliability.
- **Advanced DVR Control Strategies**: Design and implement sophisticated control strategies for DVR to improve power quality and FRT performance of the hybrid system, leveraging computational methods for enhanced system performance and practical applications.

IV. RESEARCH METHODOLOGY

The integration of renewable energy sources like solar and wind into grid-connected systems, along with advancements in technology and market liberalization, has increased the adoption of distributed generation (DG). However, the variability and intermittency of these energy sources often result in voltage oscillations and power quality issues, impacting grid stability and efficiency. Dynamic Voltage Restorers (DVRs) are essential in hybrid solar-wind systems to mitigate these challenges. DVRs address voltage stability and power quality issues, preventing disruptions, equipment damage, and inefficiencies. They ensure consistent and reliable power delivery, enhancing grid performance and supporting sensitive equipment. By stabilizing energy variations, DVRs improve grid power quality and increase the capacity for renewable energy integration, contributing to a more sustainable and resilient energy infrastructure.

4.1 Hybrid Solar wind (HS_W) Energy system Designing

Dynamic Voltage Restorers (DVRs) play a critical role in addressing voltage deviations caused by disturbances in hybrid solar-wind systems. By maintaining supply voltage within acceptable limits, DVRs protect sensitive equipment and ensure uninterrupted service. They also strengthen the grid's resilience, enabling it to handle the variability of multiple renewable energy sources. In hybrid systems, DVRs smooth voltage fluctuations, optimizing the operation and maximizing the utilization of generated renewable energy. This reduces reliance on fossil fuels, making DVR deployment both economically and environmentally beneficial. The enhanced efficiency and reliability they provide are vital for modern, sustainable energy infrastructure.

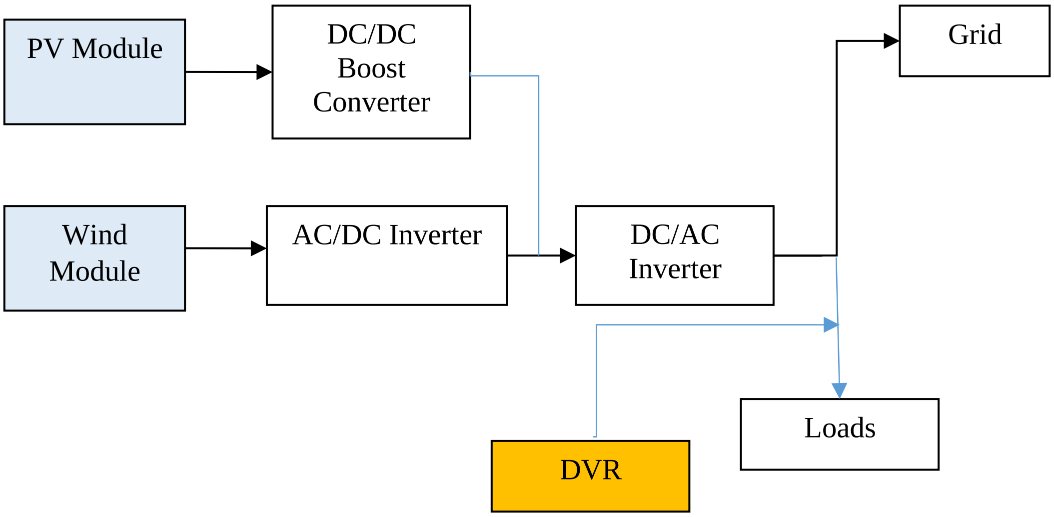

Figure 4.1 Hybrid energy system topology

4.1.1 Solar Energy System Designing in MATLAB

A solar PV array is a collection of interconnected solar panels that convert sunlight into electricity using the photovoltaic effect. Solar panels, composed of semiconductor materials like silicon, generate DC electricity when sunlight dislodges electrons from atoms. Different solar cell technologies, such as monocrystalline, polycrystalline, and thin-film cells, vary in efficiency, cost, and flexibility. Solar panel power output, measured in watts or kilowatts, depends on panel size, cell efficiency, and sunlight exposure. Panels can be connected in series to increase voltage or in parallel to increase current. The Shockley diode equation models the current-voltage relationship of PV cells, accounting for factors like solar irradiance and temperature to predict output.

Table 4.1 PV module parameters defined in the MATLAB

Maximum Power	250.205 Watts
Number of parallel strings	88
Number series modules	45
Open circuit voltage	37.3 Volts
Shot circuit current	8.66 Ampere
Voltage at maximum power point Vamp	30.7
Current at maximum power point Imp	8.15

4.1.2 Wind Energy System Modelling

The model of a wind turbine with a Permanent Magnet Synchronous Generator (PMSG) aims to represent the turbine's components through specific equations. The output aerodynamic power of the wind turbine is expressed as:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \quad (4.1)$$

In the given model, ρ represents air density (commonly 1.225 kg/m³), A denotes the area swept by the rotor blades (in m²), CP stands for the coefficient of power conversion, and v represents wind speed (in m/s).

The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_m R}{v} \quad (4.2)$$

In the model, $\omega_m$represents the rotor angular velocity (in rad/s), and R is the rotor radius (in meters). The mechanical torque output of the wind turbine, denoted as MT, is given as:

$$T_m = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \frac{1}{\omega_m} \quad (4.3)$$

‘The power coefficient is a nonlinear function of the tip speed ratio λ and the blade pitch angle β (in degrees)’.

Then Power output is given by

$$P_{Turbine} = \frac{1}{2}\rho A C_{p_{max}} v^3 \quad (4.4)$$

A standard equation is employed to characterize the power coefficient CP based on the turbine's specific characteristics.

$$(C_p = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \quad (4.5)$$

For every wind speed, there is an optimal point on the wind generator power curve, known as the “Maximum Power Point Tracking (MPPT)” point, where the output power is at its maximum point. Controlling the load of the Wind Energy Conversion System (WECS) results in the turbine rotor operating at variable speeds. This approach ensures that the system extracts maximum power from the wind consistently.

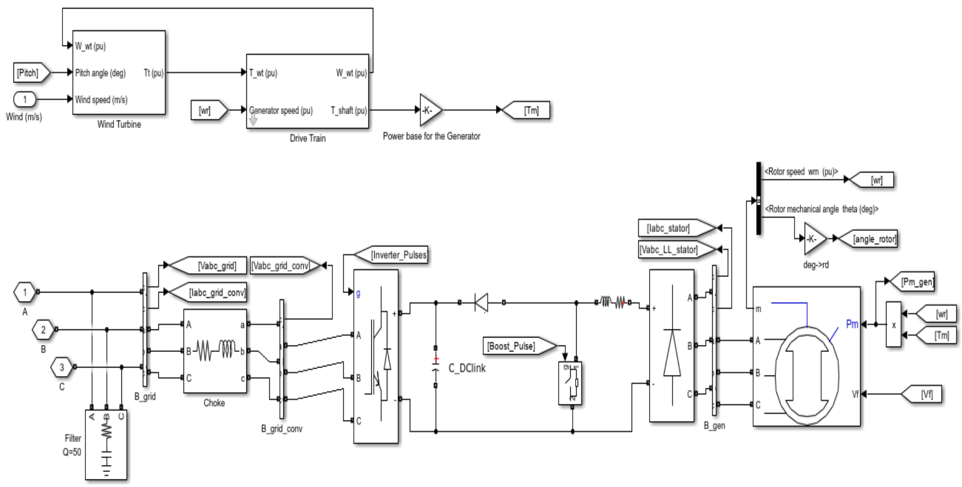

Figure 4.2 designing of wind energy system in SIMULINK

This mechanism uses the variable torque output W_m and tries to optimize the output current and voltage waveform to its maximum value.

4.2 DVR Designing and Control in MATLAB

Dynamic Voltage Restorers (DVRs) have been explored in various configurations, broadly categorized into two groups: AC/DC/AC conversion and DC/AC conversion. The AC/DC/AC approach involves rectification, capacitive storage, and inversion, while the less common DC/AC conversion focuses on inverter operations. The DC/AC method is limited during deep voltage sags (<0.5 PU) due to insufficient reactive power from the capacitor bank and the lack of external charging provisions, reducing its practicality. Enhancements like tap-changing transformers are used to adjust voltage magnitude, and a phase angle regulator (PAR) aligns the generated and current phase angles for smoother operation.

The Dynamic Voltage Restorer (DVR) is used to mitigate voltage quality issues, such as dips or swells, by supplying the missing portion of the supply voltage to protect critical or sensitive loads. It achieves phase advance compensation by injecting a voltage ahead of the line current, which is facilitated by a Quadrature Booster. The injected voltage is introduced into the line through a transformer with a 1:1 turn ratio, ensuring the DVR remains isolated from the power line.

4.2.1 Fuzzy Control system

A FLC in a DVR uses fuzzy set theory to handle imprecise inputs and is, therefore, suitable for dealing with the voltage quality issues in complex power distribution networks. The FLC accepts two primary inputs: the magnitude of the voltage error (the difference between the actual and nominal voltages) and the rate of change of this error. The controller then sends out an output signal based on these inputs that determine the compensation voltage the DVR must inject. Fuzzification comes first, as crisp input values are converted to fuzzy values with membership functions usually triangular, trapezoidal, or Gaussian that classify the inputs into the linguistic variables of Low, Medium, or High. These values are assigned a degree of membership, representing how much belief can be given in each category.

The rule base of the FLC consists of IF-THEN statements that map input segments to output responses. During the inference phase, the controller uses these rules to determine the appropriate output segment based on the degrees of membership of the inputs. The relationship between input and output segments is modelled using fuzzy logic principles. Finally, during the process of defuzzification, a fuzzy output gets translated back to crisp numerical values for the sake of the output of the controller, which controls the DVR's compensation voltage-injecting task so that power supply stability and quality are attained in the course of eliminating any possible sags or swells.

4.2.2 PI adaptive Bee Colony Optimisation for DVR (ABCO_DVR)

The ABCO_DVR algorithm, inspired by honeybee foraging behaviour, optimizes the proportional (K_p) and integral (K_i) gains of PI controllers in DVR systems. It iteratively enhances solutions by exploring and exploiting the search space, with employed bees refining current solutions, onlooker bees focusing on the best candidates, and scout bees searching new regions when improvements stagnate. The algorithm continues until an optimal solution is found, minimizing the objective function and improving the DVR's ability to handle voltage disturbances efficiently.

V. RESULTS AND DISCUSSION

A Dynamic Voltage Restorer (DVR) is essential for maintaining power quality by mitigating voltage sags and swells, particularly in renewable energy systems like hybrid solar-wind setups. This project designs a DVR using artificial intelligence to optimize the PI controller parameters for effective voltage compensation. The study examines the system's performance without DVR, with DVR using fuzzy logic control, and with DVR enhanced by adaptive Bee Colony Optimization (ABCO). Fuzzy logic improves voltage stability by responding dynamically to the uncertainties of renewable energy, while the ABCO approach further optimizes PI parameters for consistent performance during voltage changes. The results show progressive improvements in voltage stability, power quality, and reliability, demonstrating the value of integrating advanced DVR controls for addressing the challenges of renewable energy in power grids.

5.1 Case: 1: Hybrid solar wind (HS_W) energy system with no DVR

The absence of a Distributed Voltage Regulator (DVR) in a hybrid solar and wind energy system makes the system highly susceptible to voltage sags, which can destabilize the grid. When a voltage sag occurs, such as at 0.03 seconds, it directly affects the load side, causing instability and prompting devices to adjust their power intake. These adjustments can amplify disturbances, creating oscillations that may activate protection mechanisms like circuit breakers, further impacting grid stability. Without DVRs, uncontrolled voltage sags can have cascading effects, disrupting critical infrastructure and overall electrical system performance. This highlights the importance of DVRs in renewable energy systems for mitigating voltage fluctuations, enhancing grid stability, and ensuring reliability. Their inclusion is essential to maintaining a resilient and efficient power grid in the face of variable renewable energy sources.

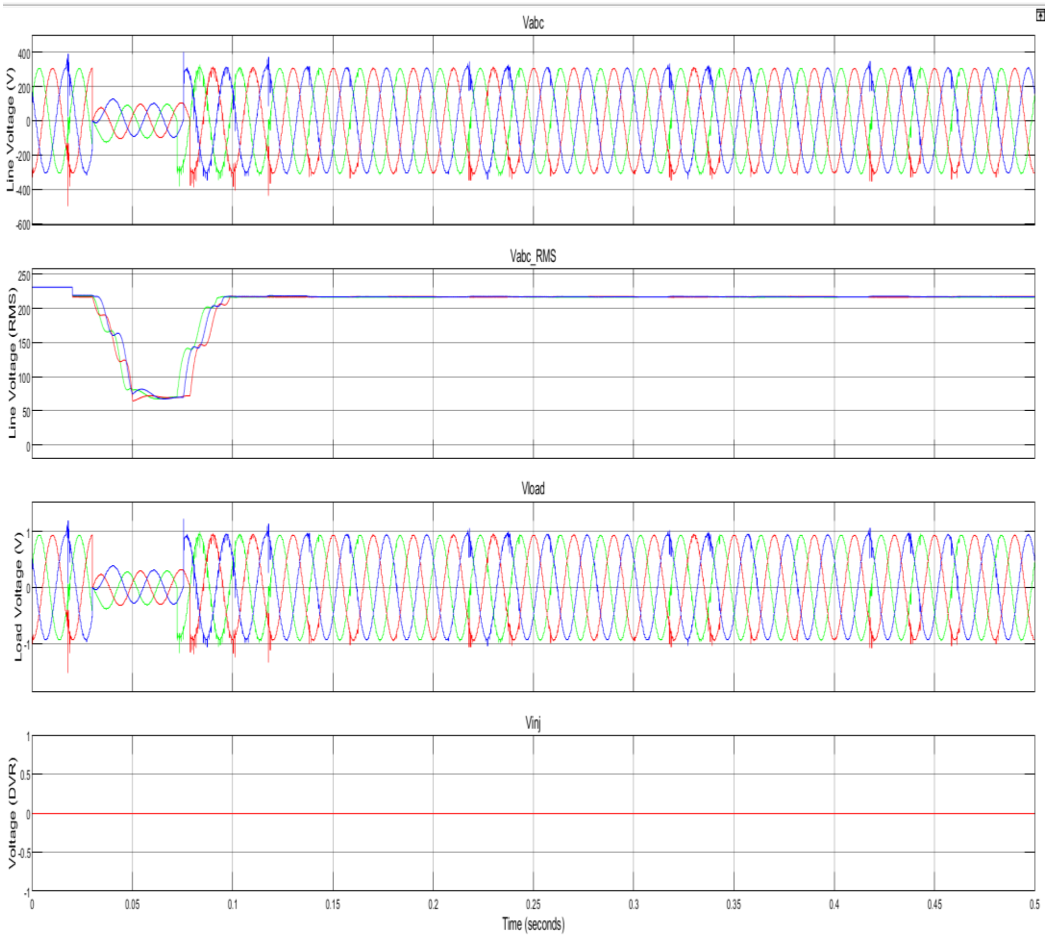

Figure 5.1 Comparative representation of the outcomes in the HS_W system with no DVR control

Figure 5.1 provides a comparative overview of various voltage metrics in the HS_W system without Dynamic Voltage Restorer (DVR) control when a fault occurs at 0.03 seconds. The top plot depicts the three-phase line voltages (Vabc), exhibiting oscillations between approximately -230V to +230V, indicative of symmetrical behaviour across all phases. In the second plot (Vabc RMS), there's a noticeable dip in the root mean square (RMS) voltage around the 0.03-second mark, highlighting a voltage sag. The third plot (Vload) illustrates the load voltage closely resembling the line voltage, maintaining similar amplitude and phase characteristics. Conversely, the fourth plot (Vrij) remains at zero, indicating no injection voltage, a typical scenario in the absence of DVR control.

Case 2: Hybrid Solar Wind (HS_W) Energy System with DVR having Fuzzy Logic Control

In Case 2 of the hybrid solar-wind (HS_W) energy system, the introduction of a Distributed Voltage Regulator (DVR) with fuzzy logic control significantly enhances the system's performance compared to Case 1, where no DVR was present. The DVR actively corrects under-voltages (sags), ensuring that the voltage at the load remains stable and within a specified range. This correction is vital for preventing operational issues that can arise from voltage disturbances, improving the overall reliability and efficiency of the system.

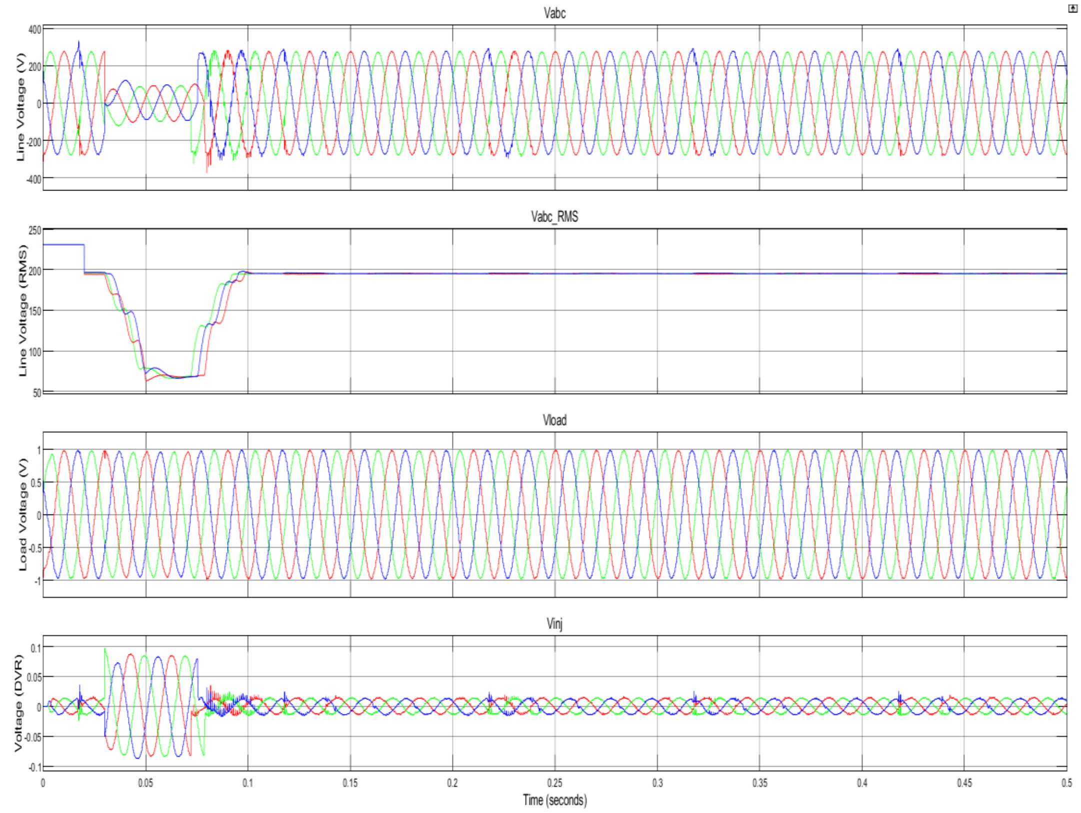

Figure 5.2 Comparative representation of the outcomes in the HS_W system with fuzzy based control for DVR

Figure 5.2 offers a comprehensive comparison of voltage behaviours in the HS_W system with 'fuzzy-based' control for a "Dynamic Voltage Restorer (DVR)". The first plot, Vabc, illustrates the three-phase line voltages fluctuating between -230V and +230V, showing a notable dip around 0.03 seconds. The second plot, Vabc RMS, reveals a significant RMS voltage drop at the same point, dipping below 50V, indicating a voltage sag event that the DVR effectively manages. The third plot, Vload, demonstrates load voltages mirroring line voltages, indicating direct impact from line conditions but showing stability post-disturbance. The fourth plot, Vinj, shows the injected voltage by the DVR. There is a sharp peak in injection at the disturbance point, which indicates that the DVR responds very fast to stabilize the voltage against the sag. These results show the system's improved stability and efficiency with the fuzzy-based DVR control.

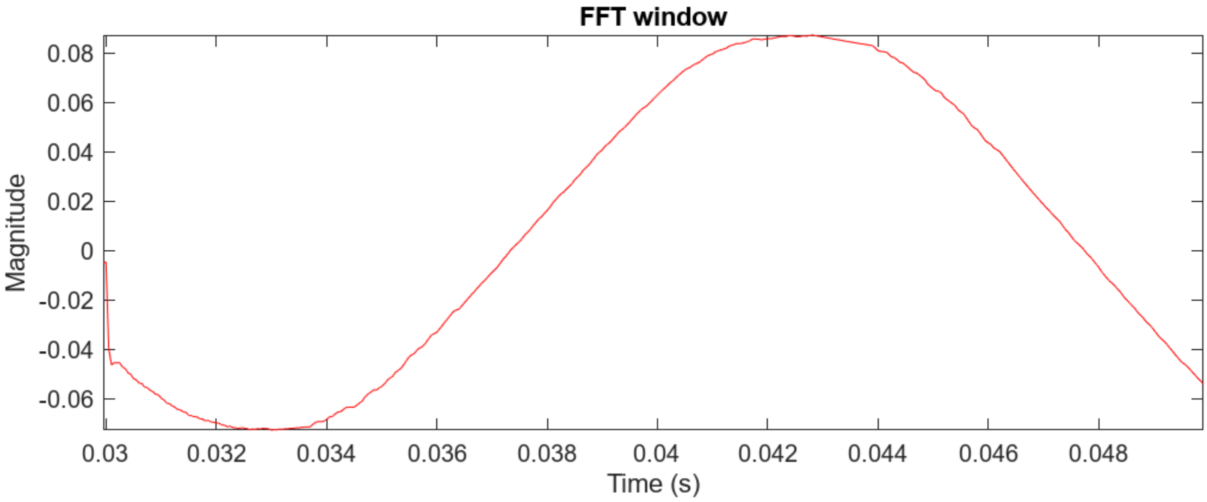

Figure 5.3 FFT analysis of the voltage in phase 1 injected into the line by fuzzy based DVR

Figure 5.3 displays the "Fast Fourier Transform (FFT)" analysis of the 'voltage' in phase 1 injected into the line by a fuzzy-based Dynamic Voltage Restorer (DVR) from 0.03 seconds onwards. This analysis allows for the evaluation of Total Harmonic Distortion (THD %) at this specific time instant.

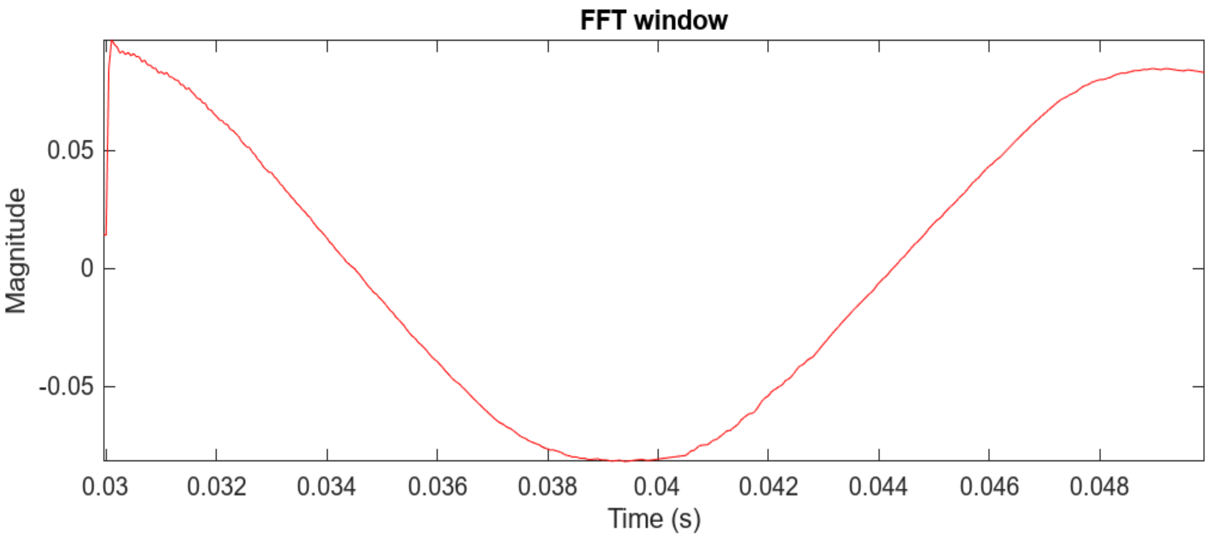

Figure 5.4 FFT analysis of the voltage in phase 2 injected into the line by fuzzy based DVR

According to Figure 5.4, a fuzzy-based Dynamic Voltage Restorer (DVR) injects voltage into phase 2 by using “Fourier Transforms (FFT)”. The analysis covers a timeframe starting from 0.03 seconds, and the Total Harmonic Distortion (THD) percentage is calculated at this specific time instant.

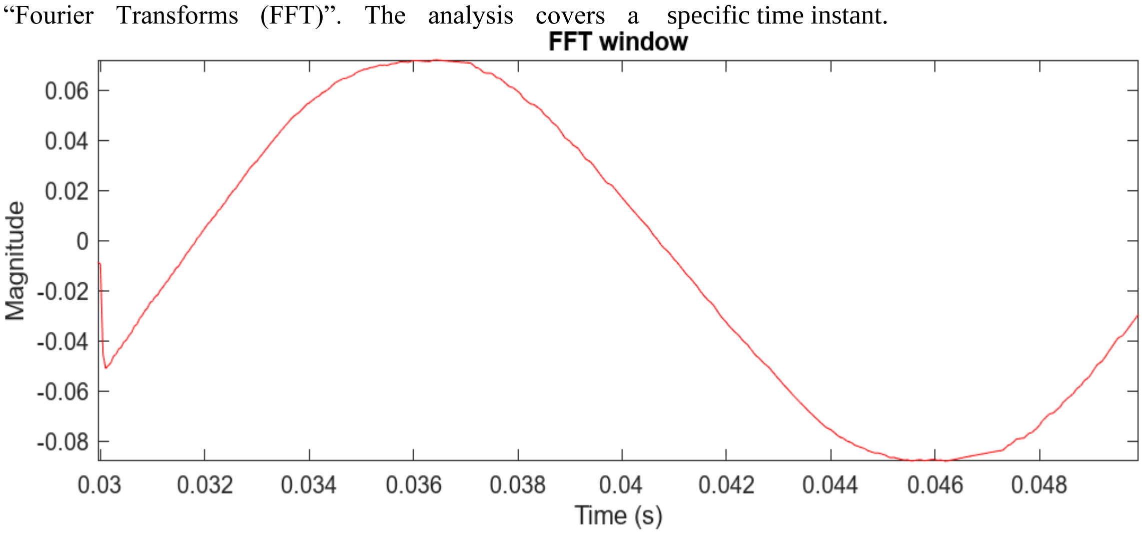

Figure 5.5 FFT analysis of the voltage in phase 3 injected into the line by fuzzy based DVR

Figure 5.5 depicts the “Fast Fourier Transform (FFT)” analysis of the “voltage” in phase 3 injected into the line by a fuzzy-based Dynamic Voltage Restorer (DVR). This analysis is from a certain time interval starting from 0.03 seconds, which gives a high definition on the harmonic content of injected voltage. The ability of decomposing the signal through the voltage FFT helps find the harmonic distortion present within it. Such knowledge may then be used for ensuring injected voltage quality complies with power quality standards.

Case 3: Hybrid Solar Wind Energy System with Proposed PI Adaptive Bee Colony Optimisation for DVR (ABCO_DVR)

Implementing an adaptive PI for Bee Colony Optimization (ABCO_DVR) with DVR in hybrid solar-wind is an innovative technique to regulate the voltage of the renewable energy systems. It enhances the system's stability of the voltage, quality of the power, efficiency, reliability, and adaptability. The adaptive BCO algorithm allows it to tackle complexities arising from the introduction of non-linear loads in a power system that can grossly distort power quality.

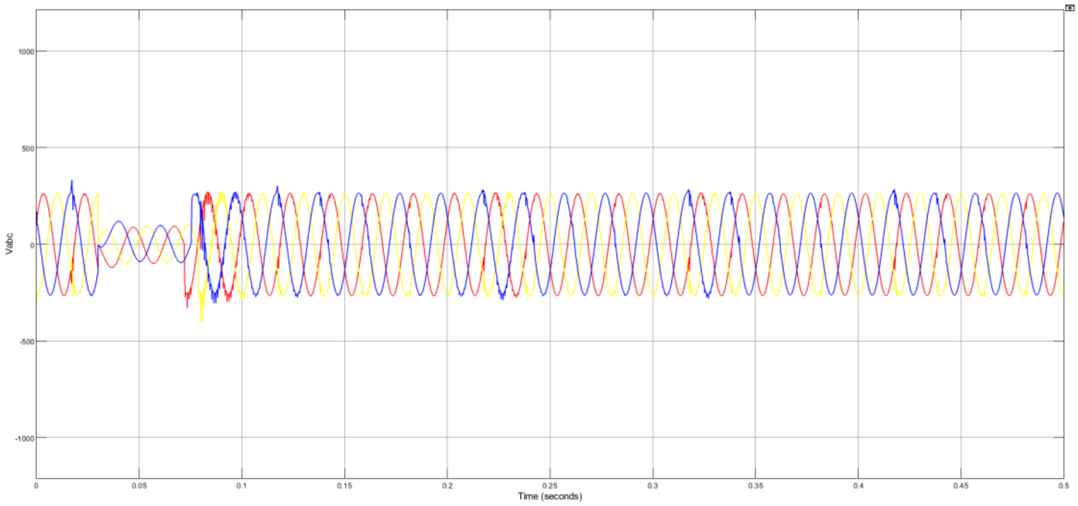

Figure 5.6 Voltage at the bus where voltage dips at 0.03 sec in HS_W system with ABCO_DVR

Figure 5.6 illustrates the voltage at a bus in the HS_W system featuring ABCO_DVR. The plot exhibits three-phase voltage waveforms, indicating a notable voltage dip around 0.03 seconds. This dip occurs due to a fault in the system line, leading to a sharp drop in voltage levels.

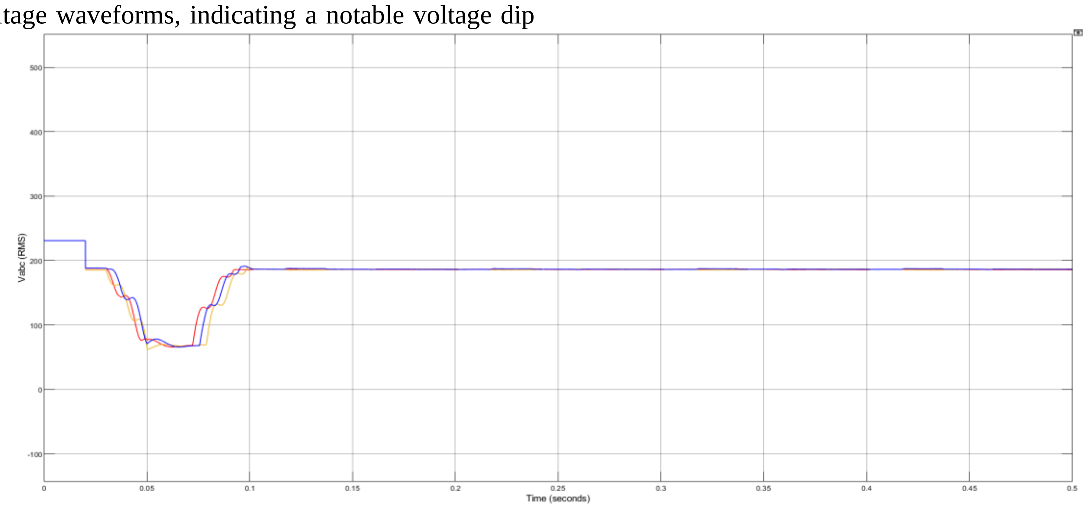

Figure 5.7 Three phase RMS voltage at the bus where voltage dips at 0.03 sec in HS_W system with ABCO_DVR

Figure 5.7 shows the three-phase RMS voltage at a bus in the HS_W system, incorporating a PI adaptive Bee Colony Optimisation for DVR (ABCO_DVR). The graph highlights a substantial voltage dip occurring around 0.03 seconds, where the RMS voltage drops sharply from approximately 230V to below 90V.

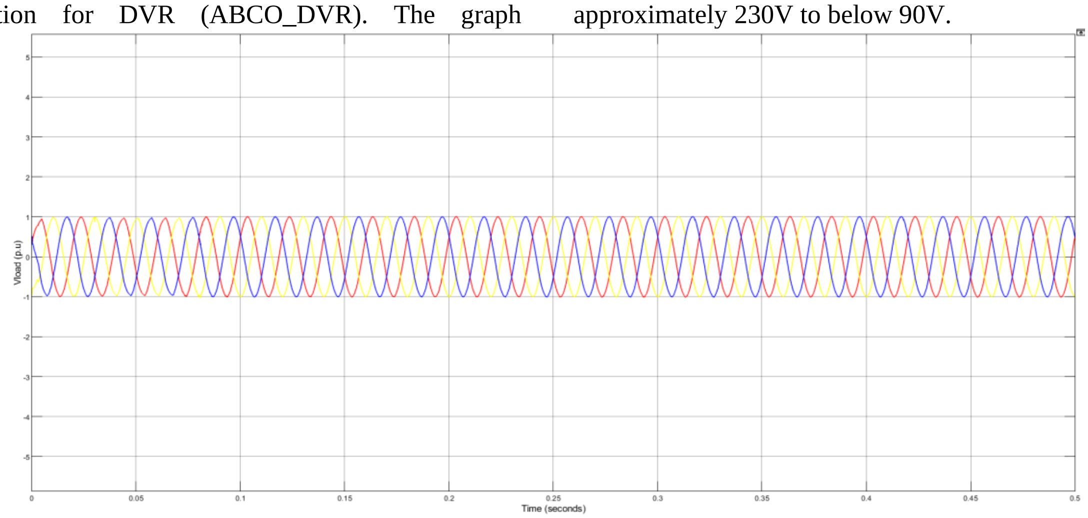

Figure 5.8 Effect on Load voltage in the HS_W system with ABCO_DVR

Figure 5.8 illustrates the impact on load voltage in the HS_W system with PI adaptive Bee Colony Optimisation for DVR (ABCO_DVR). The waveform, shown in three phases, demonstrates stable and consistent voltage oscillations around the zero line, ranging from approximately -1 to +1pu. This stability indicates that the ABCO_DVR system effectively maintains voltage stability across the load, even during potential power disturbances.

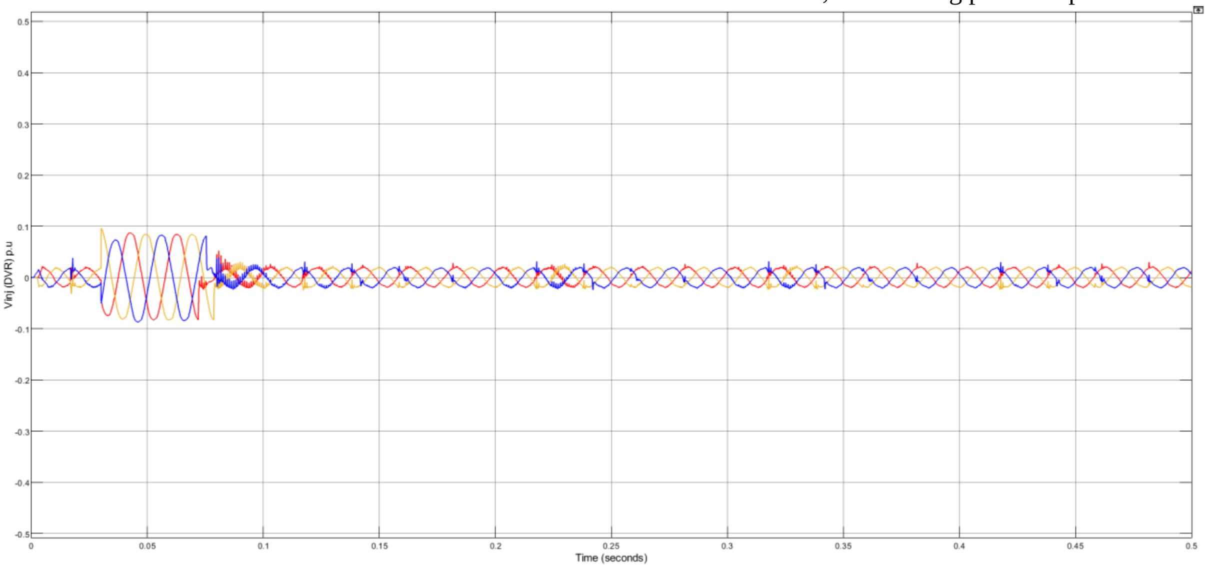

Figure 5.9 Voltage injected into the line by ABCO_DVR for balancing load voltage

Figure 5.9 illustrates the voltage injected into the line by the PI adaptive Bee Colony Optimisation for DVR (ABCO_DVR) to balance the load voltage in the HS_W system. The waveform shows an initial spike in injected voltage, peaking around 0.03 volts, which quickly stabilizes to minimal fluctuations around zero. This rise corresponds to the DVR's response to a voltage disturbance at approximately 0.03 seconds, demonstrating the system's rapid and effective intervention to counteract voltage imbalances.

5.2 Validation

The section focuses on the benefits of using the developed adaptive Bee Colony Optimisation for DVR over a fuzzy logic control system. Data analysis shows that ABCO_DVR has the consistent performance of lower THD in all three phases when compared to the fuzzy logic control. This implies better voltage injected quality into the system. THD reduced implies less stress on the electrical appliances connected to the power system and damage potential, therefore improving efficiency and life expectancy.

Table 5.1 Comparative analysis of the voltage injected by the DVR with two different controls

Injected voltage phase	THD in Hybrid system with fuzzy control for DVR	THD in Proposed system with ABCO_DVR
Phase 1	7.01 %	6.52 %
Phase 2	9.41 %	9.29 %
Phase 3	9.00 %	8.38 %

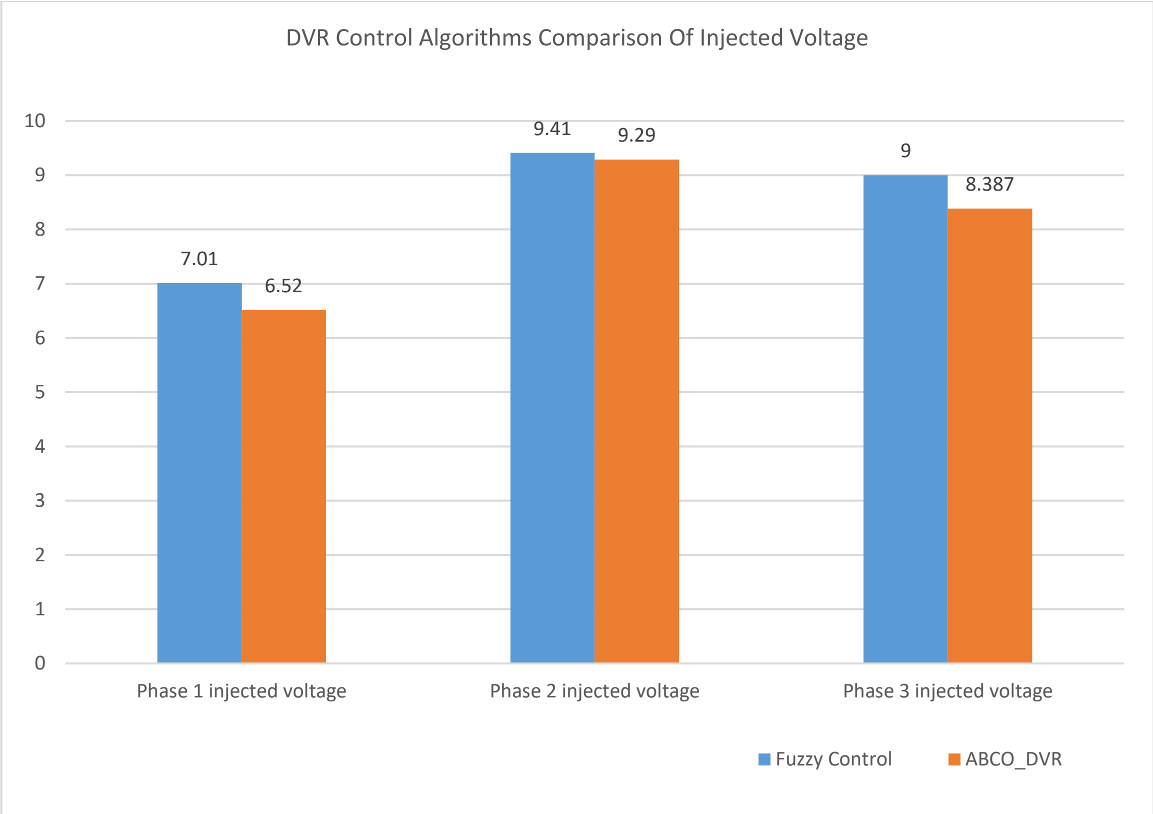

Figure 5.10 DVR Control Algorithms Comparison of THD% in Injected Voltage

Each method shows a considerable improvement in power quality by injecting the compensating voltage to cancel out the disturbances compared with systems without DVR. This successfully demonstrates the effectiveness of the control strategy, especially the PI adaptive Bee Colony Optimization for DVR, or ABCO_DVR in power quality improvement of hybrid solar and wind energy systems. By reducing total harmonic distortion for various phases, ABCO_DVR surpasses its counterpart control with fuzzy logic. Indeed, this system can ensure steady and reliable voltage in renewable energy sources. These conclusions support not only the continuation of the development of the bee colony algorithm in optimising power systems but also offer ways to be followed by advancements in DVR.

VI. CONCLUSION

This research highlights the pivotal role of Dynamic Voltage Restorers (DVRs) in ensuring power quality and stability in hybrid solar-wind energy systems. By comparing control strategies, the study underscores the superior performance of the adaptive Bee Colony Optimization (ABCO) algorithm in tuning DVR PI controller parameters, resulting in better voltage stabilization and lower total harmonic distortion (THD) compared to fuzzy logic control. DVRs not only address voltage sags and swells but also enhance the grid's capacity to integrate variable renewable energy sources effectively. The findings support the adoption of advanced DVR control strategies to overcome the challenges of renewable energy variability, paving the way for sustainable and reliable energy infrastructures.

Conflict of Interest: The corresponding author, on behalf of all authors, confirms that there are no conflicts of interest to disclose.

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