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Enhancing power quality in a smart grid using dynamic voltage restorer

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ABSTRACT

Hybrid smart grids which depend on renewable energy have substantial challenges to their reliability and efficiency due to power quality issues. However, the performance and dependability of the system might be impacted by power quality concerns caused by the intermittent nature of renewable energy sources and the presence of nonlinear and unbalanced loads. This study suggests that a hybrid renewable energy-based smart grid can improve power quality by using a dynamic voltage restorer (DVR), a flexible alternating current transmission system device. The goal is to improve voltage stability, reduce voltage spikes and harmonic distortion, and provide a clean power supply. This study's primary contributions are the design and execution of the cascaded H-bridge DVR topology, the development of a modified synchronous reference frame-based controller and a thorough examination of the performance of the integrated DVR system. Total harmonic distortion and voltage regulation are two power quality metrics used to evaluate the effectiveness of the suggested technique in MATLAB simulations.

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1. INTRODUCTION

Power quality (PQ) is gaining importance daily along with the growth of the highly sensitive loads in power networks. The use of distributed renewable power coincides with social growth because of the rising demand for electricity put on by technology and social advancement, the limitations of conventional power development, and the growing relevance of environmental protection in society [1]. However, the addition of additional energy sources to the electrical system has brought about a number of issues. Due to the inability of the associated power consumer's equipment to operate correctly, variations in voltage, current, and voltage frequency occur. This lowers the PQ of the power grid and has an impact on use [2]. Managing PQ has become extremely difficult in the modern smart grid due to the diversity of loads, the requirements for extremely efficient consumption, and the implementation of renewable energy (RE) generation and grid connection technology with the power electronics interfaces [3]. The stability and effectiveness of the grid may be affected by the PQ issues that arise from the integration of various intermittent energy sources, including voltage swells, sags, and high harmonic content [4]. Sensitive commercial and utility end loads on the distribution line are significantly impacted by PQ issues.

The single-phase imbalance voltage sag is a significant PQ issue, along with voltage sag, voltage swell, harmonic distortion, flicker, and spikes. Voltage sag is the PQ issue that affects industrial and commercial users the most often [5], [6]. Voltage sags often result from a number of causes, such as utility network or facility-side problems, reopening the circuit breakers, and the start-up inrush current of big electrical motors. PQ issues may be reduced with the use of different flexible alternating current transmission system (FACTS) devices and control techniques [7]. The FACTS concept was created in the late 1980s to ensure effective use of the resources of the electricity system. The fundamental idea behind FACTS devices was to employ high-voltage power electronics to regulate the voltage and actual and reactive power flow in the transmission system [8], [9]. Dynamic voltage restorer (DVR) [10] is used as a FACTS device to mitigate voltage sags by series-injecting voltage and restoring the reduced supply voltage to its normal level. They may attenuate voltage fluctuations and lower harmonic distortion because of their quick injection or absorption of voltage in response to grid disruptions [11], [12].

A first-generation FACTS device called the static VAR compensator (SVC) may adjust voltage at the necessary bus, enhancing the voltage characteristics of the system [13]. The thyristor-controlled series capacitor (TCSC) represents one of the significant FACTS family members that utilities are increasingly using in long transmission lines in contemporary power systems [14]. A different FACTS device utilized for reactive power compensation and voltage control is the static synchronized compensator (STATCOM) [15]. While DVR and STATCOM both works to improve voltage stability, DVR is particularly good at reducing voltage peaks and valleys brought on by transient disturbances. Comparing the DVR to other FACTS devices like the SVC and STATCOM, there are several clear benefits. While SVC and STATCOM are better suited for steady-state voltage management, DVR's quick and accurate transient reaction allows it to successfully offset voltage sags and swells brought on by unexpected disturbances [16], [17]. DVR is a strong and dependable option for PQ enhancement due to its selective compensation, localized operation, and independent operation, which together give targeted assistance where it is required [18]. DVR is a key tool in hybrid renewable energy (RE)-based smart grids because it may reduce harmonics linked to voltage sags, improving overall PQ [19].

This study's main objective is to provide a unique approach for enhancing PQ in a hybrid smart grid powered by RE sources by integrating a DVR. The study expands on previous studies on PQ improvement methods and smart networks powered by RE [20], [21]. This work intends to improve voltage stability and reduce harmonic content, hence reducing the PQ difficulties in the grid, by using the cascaded H-bridge (CHB) DVR architecture [22] with a controller based on the modified synchronous reference frame (MSRF) theory. This research study has several objectives. In order to increase PQ, it first involves developing and implementing into effect a CHB DVR architecture that allows for accurate and adaptable voltage production. Second, precise regulation and control of the DVR system are now possible because of the development of an MSRF-based controller. Thirdly, the performance of the integrated DVR system will be assessed by comprehensive simulations and analysis, with a focus on PQ parameters including total harmonic distortion (THD) and voltage control [23]. The research conducted has made major improvements to the integration of RE sources into smart grid development. The suggested solution provides a way to dependable and effective grid operation by resolving PQ issues in hybrid RE-based smart grids. The framework of the suggested technique, simulation results, analysis, and discussion will all be covered in the following parts of this research paper. These sections will also highlight the importance of the integrated DVR system in improving the PQ and functionality of the smart grid [24].

2. SYSTEM DESCRIPTION

The goal of this study is to improve the PQ of a smart grid powered by a combination of renewable energy sources. Based on earlier work that used a distributed system to establish a smart grid and improved the inverter voltage and THD employing a genetic algorithm (GA), the proposed system improves on these characteristics. This research aims to improve PQ by adding FACTS devices into the system to reduce voltage fluctuations, harmonics, and power factor changes. To begin with the study, a CHB DVR topology will be designed and implemented. The injected voltage is exactly in-phase and of the same magnitude as the voltage sag during disturbances because to the topology's adaptability and precision in voltage production. Figure 1 presents the proposed smart grid with DVR integration for improving PQ.

2.1. PQ issues in smart grid

PQ problems appear as distorted current and voltage waveforms and/or frequency variations, which may lead to equipment failure or malfunction. In addition, the power systems must provide sinusoidal voltages at the agreed-upon magnitude level and frequency to their clients, ensuring a safe, dependable, and continuous flow of energy. Various sources interchangeably define PQ as supply dependability, current quality, voltage quality, service quality, supply quality, and consumption quality. From the perspectives of effects, causes, and explanations of the PQ phenomenon in power systems. Voltage sags represent the most of these phenomena nearly 31% while voltage transients account for the least 8%. Due to the growing usage of sensitive loads, power electronic devices and photovoltaic systems generate harmonic and asymmetrical voltages that account for 20% and 18% of total voltages, respectively.

A hybrid RE-based layout with a smart grid might have problems with PQ for a number of reasons [25]. Renewable energy sources, like solar and wind, are naturally unpredictable and inconsistent in the amount of electricity they can provide. Variations in wind speed or solar irradiance may cause intermittent power production, which can cause voltage changes and instability in the smart grid. Particularly during sudden changes in the output of renewable energy, these oscillations may create voltage sags or swells. A wide variety of loads, such as nonlinear loads like power electronics and unbalanced loads, are often included in smart grids. Harmonics generated by nonlinear loads alter the voltage waveforms in the power system. Unbalanced loads may also lead to voltage inconsistencies and deviations. These loads' smart grid integration may make PQ problems severe.

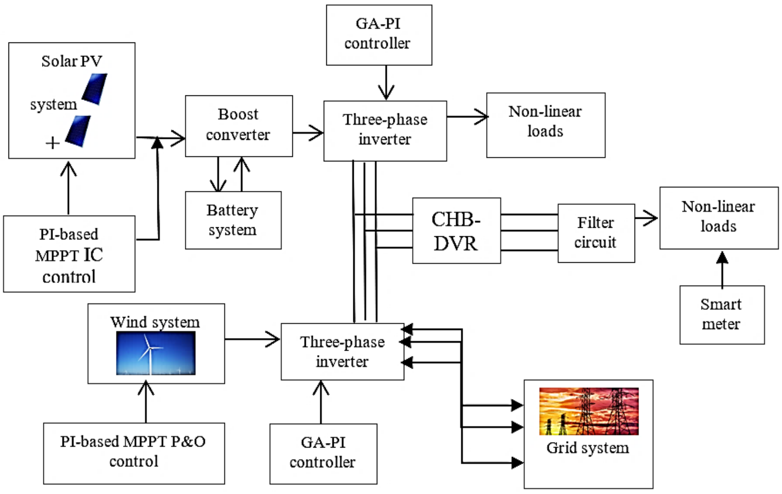

Figure 1. Integration of DVR in smart grid

2.2. Integration of FACTS devices in smart grid

Several countries have conducted research during the last three decades on FACTS devices and how they might be used to improve the PQ in both conventional and modern electrical grids. Developing smart grids along with integrated AC-DC renewable energy systems employ FACTS devices and combined power electronic converters with flexible rapid acting control techniques [26]. They depend on the ideas of i) modulating the impedance and apparent admittance (Y) at the crucial common AC bus and common coupling point; ii) inserting AC components into the electrical network nodes in series or parallel to produce current flows or overloaded voltages; iii) providing a localized reactive or capacitive current to the bus to regulate the flow of reactive power; and iv) controlled switching that modulates or switches the equivalent-driving point impedance (Z) at the interface bus.

The control techniques are based on voltage, power, angle, or reactive power flow regulation utilizing conventional proportional-integral-derivative (PID) controllers, optimum control, and/or multi-objective control performance indices. Increased line usable transmission capacity and regulation of power flow across defined transmission channels are the primary goals of FACTS devices. To enhance the quality of the electricity, FACTS devices can be used. Voltage regulation, reactive power compensation, enhanced power flow management, greater grid stability, and simplified smart grid integration are just few of the many advantages of incorporating FACTS devices into smart grids. Fast and accurate management of grid characteristics is made possible by FACTS devices, which play a significant role in solving the problems of upgrading power systems, incorporating renewable energy, and dealing with dynamic and complicated grid situations. The DVR is one of the FACTS devices that stand out for its capacity to resolve voltage sags and swells, making it an excellent tool for improving PQ and grid resilience.

2.3. Design of CHB DVR

In order to inject regulated voltage into the load voltage bus, a DVR is connected in series with the bus. DVRs are the most cost-effective and easy to set up compared to alternatives like STATCOM and unified power quality conditioner (UPQC). Because it provides the necessary injected voltage and for the most part, DVRs are series-connected compensators, whereas other types of compensators, such as static compensators and UPQCs, are shunt-connected. Therefore, the DVR is the system's regulatory device. The primary function of a DVR is to inject the necessary amount of compensatory voltage in series with the supply in order to stabilize the voltage at the load terminals. DVR coupled in a distribution network are shown in a simplified form in Figure 2.

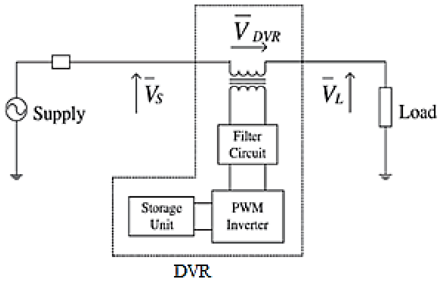

Figure 2. Schematic diagram of DVR

The pre-sag compensation technique continuously monitors the supply voltage in order to spot voltage fluctuations, at which point the differential voltage is generated and injected. In this approach, the pre-sag voltage at the load is maintained. With pre-sag compensation, the voltage on the sensitive load may be brought back to being in phase with the nominal pre-sag voltage and at the same magnitude. This strategy is suggested for non-linear loads that are very sensitive to changes in phase angle. The DVR's rating must be increased for this purpose. In addition, active and reactive power were supplied by the voltage source inverter (VSI) to the DVR in this technique. No active power control occurs during the compensation stage, hence large-scale energy storage is required. The variables after the sag are denoted by the notation $V_{s\text{-}sag}$, $V_{L\text{-}sag}$, $V_{inj,j}$, and $I_{l\text{-}sag}$, whereas the variables before the sag are connected to Vs, VL, and IL, respectively. In addition, during the sag, the phase jump of the supply voltage is denoted by β. The magnitude of the injected voltage between the DVR and the supply are given as (1).

$$V_{inj,j} = \sqrt{\left(V_{s-sag,j}\right)^2 + (V_L)^2 - Cos(\beta_j) * 2.V_L.V_{s-sag,j}} * \sqrt{2} \quad (1)$$

This DVR uses a multilevel CHB converter, which is very modular and produces voltage waveforms in small dv/dt and minimal THD. In addition, because H-bridge cells are connected in series, this converter can be easily expanded to provide various voltages and power levels, and fault-tolerant algorithms are able to operate even when power switches fail because it can synthesize 2n + 1 levels at its AC terminals. The voltage source converter (VSC) has been implemented using a variety of topologies, including two-level, three-level, and multilevel. The following flows may be used to summarize the cascaded structure's primary benefits over other topologies: The multilevel converters (MLC) could analysis the output voltage in fewer steps, they have a lower dv/dt, a lower harmonic content, and less EMI. While eliminating the issues related to direct series and/or parallel connections of power semiconductors used in typical two-level converters, multilevel converters may achieve greater power and voltage ratings. The cascaded converter uses fewer major power components, like valves and diodes, for a specific capacity. When compared to alternative topologies, like flying capacitor and diode clamped topologies, the H-bridge cascaded structure may prevent issues with imbalanced DC link voltage. Without the use of a series injecting transformer, the H-bridge cascaded structure may be directly coupled into distribution systems up to 10 kV level, avoiding issues like voltage drop, harmonics reduction, bulky size, high cost, and issues with saturation and inrush currents related to the transformer magnetization phenomenon. The whole system is adjustable in terms of power capabilities due to the cascaded structure. The H-bridge’s simplified structure is shown in Figure 3.

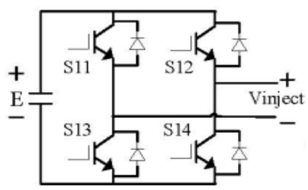

Figure 3. H-bridge structure

In the case of shunt compensation without an energy storage device, such as an active power filter, numerous control algorithms are available to tackle power quality issues in a single phase, but there have been fewer reports in the case of series compensation. Reactive power is effectively supplied by the DVR, while active power is provided by an energy storage device. This injected voltage is influenced by the power factor of the load (PF_L) and the amount of the voltage sag (Vsag). Source voltage Vs, load voltage V_L, and load current I_L are used to demonstrate the system. $Cos\theta_L$ and $Cos\theta_s$ are the load and supply power factors, respectively. The difference between the source and load power, denoted as the injected active power (P_{inj}) in (2), (3), and (4).

$$P_{inj} = I_L V_L \left[Cos\theta_s \frac{V_s}{V_L} + Cos\theta_L\right] \quad (2)$$

$$P_{inj} = PF_L - Cos\theta_s V_s \quad (3)$$

$$P_{inj}^{min} = V_{sag} - (-P_{FL} + 1) \quad (4)$$

2.4. MSRF based controller design

Reactive power and current harmonics. are mostly compensated by using the shunt active filter. For shunt active filters, many control techniques have been developed. In accordance with synchronous reference frame (SRF) theory, the relation transforms the three phase currents in the abc axes into the dq0 rotating reference frame. The AC component of Vd is determined by transforming the measured voltages into a rotating reference frame at constant speed. The inaccuracy in the measured voltages is determined, and the data together with the computed amplitude is sent to the pi controller. This reactive component represents a change in the voltage at the load terminals and is the result of the proportional integral (PI) controller's output. Only Vd DC has to be drawn from the source; the filter is responsible for the rest. The voltages used as filters' references are then converted back to the abc reference axis. Terminal voltage sag and swell are used to determine the voltage phases, which are then phase-shifted either in phase or 180 degrees out of phase with the detected voltages. This is the filter voltage used as an indicator. Rather of injecting voltage at an arbitrary angle, it is always preferable to introduce a component that is either in phase or 180 degrees out of phase. This is exactly the adjustment has been implemented.

The MSRF method is used to extract harmonics for use in creating the reference signals in this study. Based on the synchronous reference frame methodology, this strategy uses a DC bus capacitor to regulate voltage, a stationary/rotating frame to extract harmonic currents, and simplified unit vector generation for synchronization. The MSRF approach is similar to the standard SRF method in some respects, but it differs primarily in how the rotating angles for the d-q reference frame are determined. Although the α-β voltages are utilized in the transformation angle calculation, low pass filters (LPF) are used in the control process to attenuate the voltage harmonics of the input signals. Because of this filter, the approach is less vulnerable to harmonics in the supply voltage. The inverter's necessary pulses are generated by comparing the extracted signal to the current flowing through the compensation circuit or inverter. The MSRF technique involves converting the three-phase supply currents (ia, ib, and ic) to a two-phase (αβ) current in the stationary frame in (5). After the technique has been improved to remove the necessary harmonics components from the distorted load current, the resulting reference current signals may be transformed back to the stationary d-q frame. So, it may calculate i_α and i_β as in (6) and the abc frame current as in (7). Figure 4 shows the MSRF method's block diagram [27].

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}^{-1} \quad (6)$$

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\sqrt{\frac{3}{2}} \end{bmatrix} \quad (7)$$

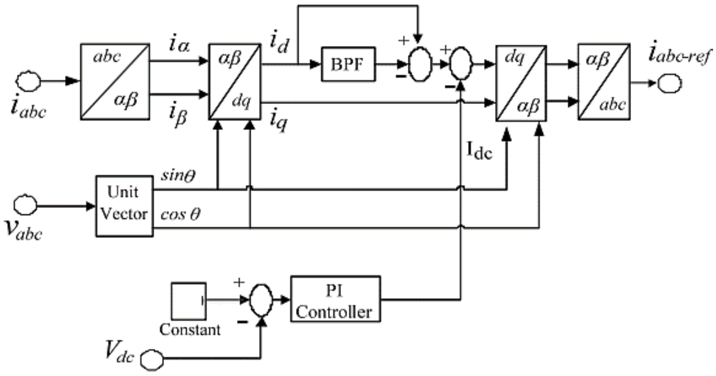

Figure 4. MSRF method's block diagram

3. RESULTS AND DISCUSSION

A comprehensive MATLAB/Simulink simulation model of the hybrid renewable energy-based smart grid was created for the proposed study. Employing a CHB topology and an MSRF-based controller, the DVR was included into the smart grid. The control algorithms were created to respond the voltage sags by adjusting the recording accordingly. Performance metrics for the DVR system were simulated under varying conditions, such as changes in renewable energy output, load, grid voltage, and different power quality indices (such as THD and voltage regulation). Asymmetric cascaded H-bridge (ACHB) DVR structure will be designed and constructed in this study. This design provides exact and precise voltage production, guaranteeing that the injected voltage is in phase with the voltage sag and of the same magnitude. Figure 5 represents the MATLAB simulation diagram of DVR integration in smart grid.

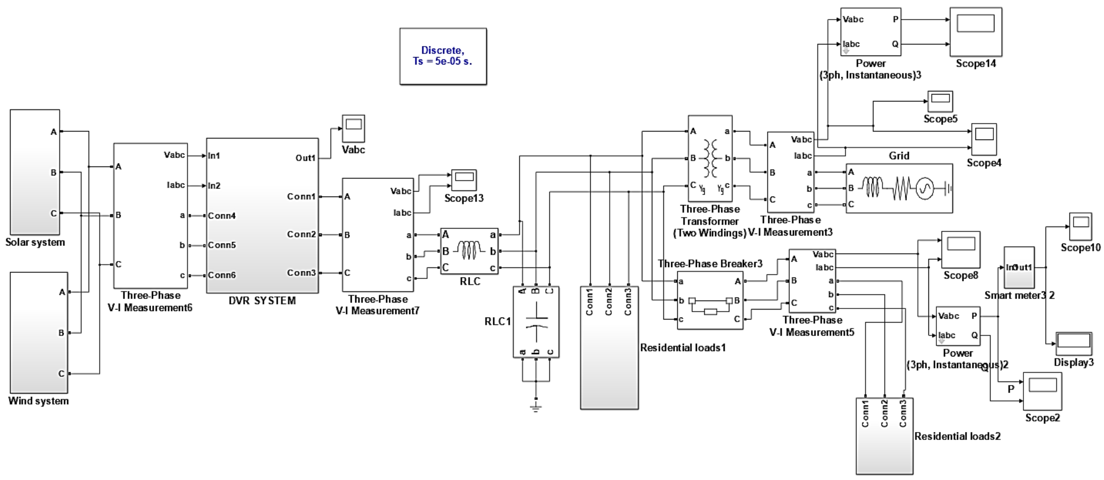

Figure 5. Simulation diagram of CHB DVR in smart grid

Grid voltage will be maintained within acceptable levels during transient occurrences due to the controller's immediate flexibility, which will allow for immediate detection and adjustment for voltage sags. The DVR's ability to selectively compensate for certain loads is an additional manner in which it may prioritize protecting critical components. Because of its selective correction and localized functioning, DVR is a reliable and cost-effective method for enhancing PQ.

The DVR's ability to prevent loss from power fluctuations was evaluated in a variety of conditions. These findings showed that the DVR effectively monitored the grid voltage and injected the necessary voltages to bring it back up to its normal level in a timely manner. This prevented decreases in voltage from affecting essential loads, allowing them to keep running smoothly even while other loads were affected by the disruptions. Figure 6 shows the voltage sag occurs in the distributed network of the smart grid. It shows AC waveform of 230 V and the voltage sag occurs between 0.5 and 0.85. Figure 7 shows the compensated load voltage of the system using CHB-DVR.

Harmonic distortion was much reduced once the DVR was included. Due to the MSRF-based controller's precise regulation of the injected voltages, the DVR was able to successfully correct the harmonic distortions introduced by the non-linear loads. The THD was thereby greatly reduced, improving power quality while providing minimal impact on connected loads. Figure 8 presents the THD value of the compensated load voltage waveform. The THD reductions made by a distributed-STATCOM (D-STATCOM) and a CHB-DVR are shown in the simplified comparison Table 1. With D-STATCOM compensation, the THD is 5.92%. This shows the amount of harmonic distortion that a D-STATCOM is able to fix the system [28]. With CHB-DVR compensation, the THD is much reduced at 3.73%. This illustrates how well the CHB-DVR reduces harmonic distortions, indicating that in load condition, it may be a better option for improving PQ than the D-STATCOM.

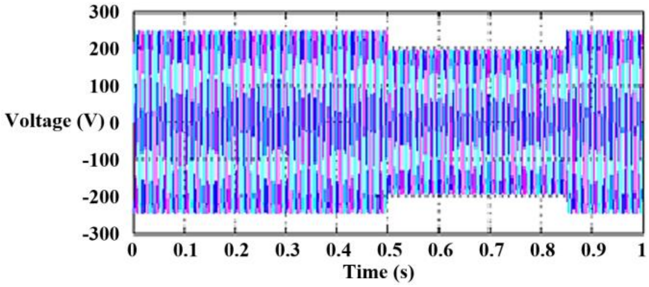

Figure 6. Voltage sag in smart grid

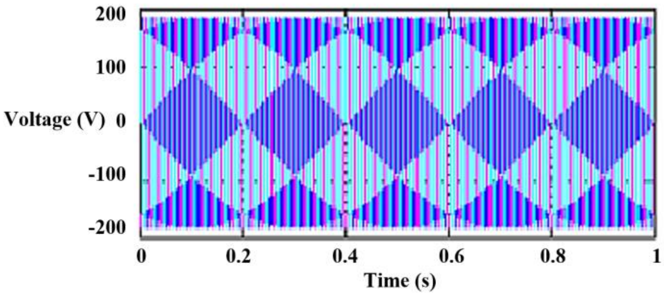

Figure 7. Compensated load voltage with DVR

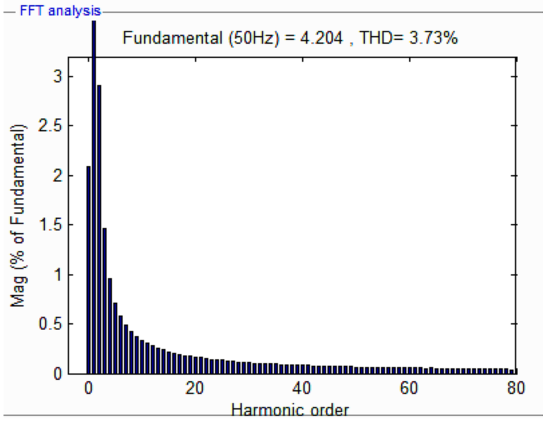

Figure 8. THD analysis of the load voltage

Table 1. Comparative THD analysis

Condition	D-STATCOM compensation	CHB-DVR compensation
THD (%)	5.92	3.73

The key contributions of this study are the CHB-DVR topology and MSRF-based controller for improving PQ in the hybrid smart grid that uses renewable energy. Previously, the smart grid that relied on a combination of renewable energy sources had a THD of 5%. In the present study, the THD was greatly improved and brought down to 3.73% when the DVR was included into the CHB topology and the MSRF-based controller. Overcoming PQ concerns like voltage sags and harmonics required the DVR's quick response time, accurate voltage management, and selective compensating capabilities. With the suggested strategy, the smart grid was able to attain the goals of modern smart grid development and the integration of renewable energy sources by increasing its stability, reliability, and PQ.

4. CONCLUSION

The research described in the paper combined an MSRF-based controller with a CHB-DVR architecture to enhance PQ in a smart grid that is powered by renewable energy sources. PQ concerns like voltage sag and harmonic distortions were shown to be reduced using the suggested strategy, as shown by extensive simulations and analysis. THD was reduced from 5% to 3.73%, demonstrating a significant increase in power reliability. The DVR considerably improved voltage stability and decreased harmonic distortions by injecting or absorbing voltages during disturbances and adjusting for harmonics. DVR performance may benefit from ongoing study of sophisticated control methods and optimization algorithms. PQ management may be improved via the use of methods such as model predictive control (MPC) and control based on artificial intelligence.

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