

Efficient Control and Five Level MMC Integration for Power Quality Improvement in DFIG Based Wind Energy System

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Abstract:

Main objectives of the study are to address Power Quality (PQ) problems caused by shifting load demands, including voltage instability and harmonic distortion, which affect system performance and reduce stability. In order to achieve the set goals, the following tasks were accomplished: the design and implementation of a 5-Level Modular Multilevel Converter (MMC) powered by a Double Fed Induction Generator (DFIG)-based wind system, the application of advanced control techniques utilizing D-Q theory and a Hysteresis Current Controller (HCC) for stable current injection, and the incorporation of an LC filter to enhance AC supply quality. The most important results are the reduction of total harmonic distortion (THD) to 1.35%, enhanced voltage stability, and improved overall PQ, validated through MATLAB simulations. The significance of obtained results is the development of a robust and efficient system that addresses PQ issues, offering a substantial improvement over state-of-the-art methods and ensuring high-quality power delivery to grid.

Keywords:

Power Quality (PQ), 5-Level MMC, DFIG-Wind system, DQ- theory, HCC.

1. Introduction

The growth in production of energy using renewable technologies is largely driven, to address environmental issues, specifically global warming [1]. Governments and Organizations are promoting clean energy with wind source playing a crucial role owing to its minimal environmental impact. In wind system, DFIGs [2] are extensively utilized for their ability to perform efficiently at wide range of wind conditions. The DFIG assisted Wind Energy Conversion System (WECS) configuration allows for independent regulation of active and reactive power, making it ideal for integration. Nevertheless, WECS faces power quality problems, including voltage stability, imbalanced reactive power and harmonic distortions [3]. The inherent variability of wind and switching operation of power electronic devices, poses challenge in grid compatibility.

As time progressed, a wide array of converter topologies have been designed by researchers to resolve these challenges. The Voltage Source Converter (VSC) of literature [4], is a simple topology that switches the DC link voltage between positive and negative levels. In addition, significant losses occur, which affects the system efficiency, making it less suitable for power applications [5]. As a consequence, multilevel inverter and converter topologies have been developed. The 3-Level Neutral Point Clamped (NPC) [6, 7] converter is introduced, as an improvement over VSC, minimizing harmonics with generation of 3-Level output, but, complexity arises in balancing neutral point voltage. Another advancement presented in Reference [8, 9] is flying capacitor multilevel converter, which improves the performance by utilizing capacitors and storage elements for generation of multiple voltage steps. This allows for improved reduction in harmonics and offers redundancy, enhancing reliability of system. However, this requires more number of capacitors which increase the system size, and also suffers from complex control and higher losses in capacitors. Overwhelming the limitations, Cascaded H-Bridge inverter [10] has emerged as potential solution for high power applications, owing to its modular structure and excellent performance towards mitigation of harmonics. This topology included multiple H-bridge inverters [11, 12] attached in series, powered using DC source, allowing for nearly sinusoidal output. The design model of CHB converter [13] is highly scalable and fault-tolerant, owing to its operation even

under isolation of individual modules, but requires multiple DC sources. Still, the CHB converter marks a significant leap forward in dealing with power quality issues in wind energy systems. The limitations of these earlier topologies, particularly in terms of harmonic distortion, scalability, and efficiency, paved the way for the development of MMC [14].

MMC technology brings benefits including reduced harmonic distortion and enhanced system efficiency through its modular design. Nevertheless, generation of reference current is essential, to align with the output current with reference value. In Reference [15] Instantaneous Reactive Power Theory (IRPT) is presented which generates reference signals with offset value to zero at cut-off frequencies, but struggles with dynamic responses. Another technique presented in [16] is Short-Time Fourier Transform (SIFT) for generation of reference current, where the signal is segmented for applying Fourier Transform. However, the approach requires significant resource computation, posing limitations for real time applications that demand quick response and processing efficiency. In Reference [17], a harmonic current estimation technique based on the trigonometric orthogonal principle is presented. While effective, it is characterized by high computational demand and slower processing speeds.

In response to the limitations identified, the proposed work contributes with several improvements such as,

- Implementation of 5-Level MMC for efficient conversion of voltage and better suppression of harmonics, resulting in cleaner output.
- Utilizes DFIG based wind source, ensuring system stability with stabilized DC link voltage for MMC system, improving power quality.
- Introduction of HCC, ensuring that the actual current closely matches the desired reference, thus maintaining power quality.

- Combination of DQ theory and MMC, effectively reduces the harmonics and supports in handling non-linear loads.

The proposed combination of a 5-Level MMC powered by a DFIG-based wind system, advanced D-Q theory with HCC control and an LC filter is superior to existing methods because it integrates the strengths of multiple advanced techniques to comprehensively address power quality issues. While traditional converters often suffer from higher switching losses, limited voltage levels and higher harmonic distortion, the 5-Level MMC generates smoother stepped waveforms with reduced harmonics. The use of D-Q theory with HCC ensures precise and dynamic current control, enabling rapid compensation of disturbances and maintaining voltage stability even under fluctuating load conditions. Additionally, the LC filter further suppresses residual harmonics, ensuring near-ideal sinusoidal output. Together, these elements reduce THD, while also improving stability and reliability.

The rest of paper is organized by Section II detailing the description of proposed work, Section III modelling of system, Section IV Results and Discussion and the work is concluded in Section V.

2. Description of Work

The block diagram presented in Fig. 1 illustrates a DFIG assisted wind energy system employing 5-Level MMC for improving power quality. The system connects an 3ϕ AC source at Point of Common Coupling (PCC) where it supplied power to load. In between there is source inductance to smooth the connection between source and load. However, PQ issues arise owing to changes in load. The DFIG system is employed to generate power from wind, which is then converted into DC utilizing PWM rectifier. The PI controller effectively regulates the DC link voltage on comparing V_{dc} with $V_{dc(ref)}$. Therefore, a stabilized DC link voltage is achieved, which is used for the operation of 5-Level MMC.

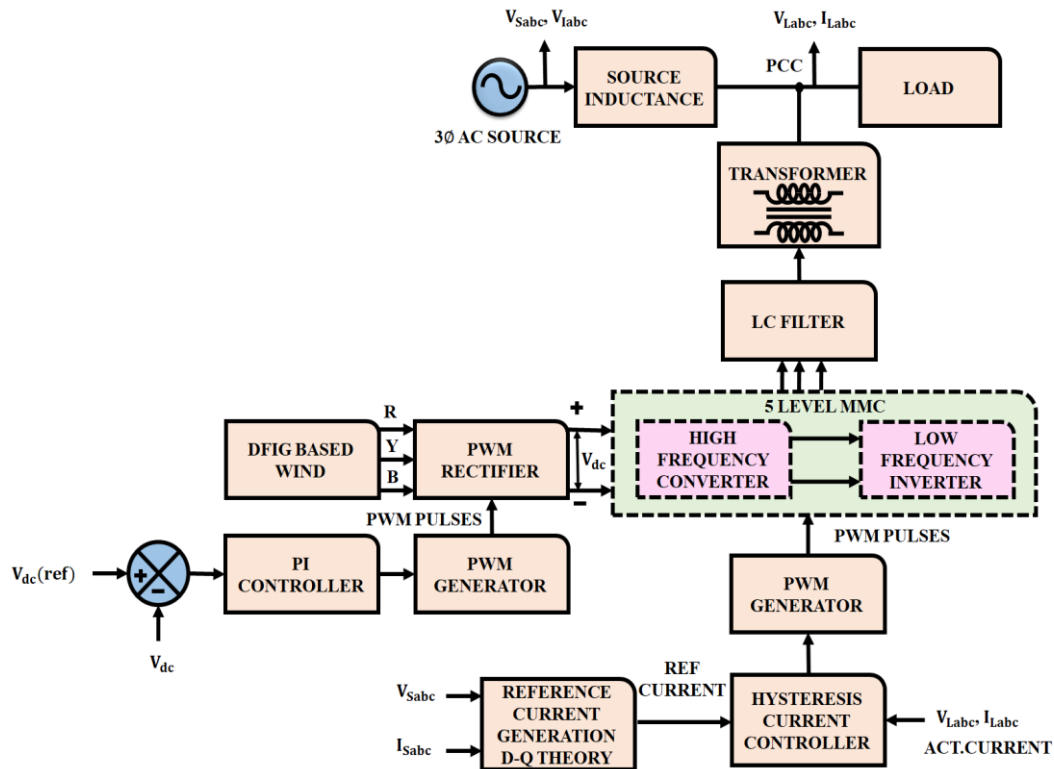


Fig. 1. Proposed MMC Architecture for Power Quality Improvement

In the 5-Level MMC, the high frequency converter is responsible for providing high quality DC output. It is followed by low frequency inverter, which is responsible for conversion of high frequency DC into AC that is synchronized with grid frequency. The inverted output is fed to LC filter, which assist in removal of switching harmonics generated by MMC. The control system uses DQ theory for generation of reference current, that are aligned with the desired voltage and current parameters. This supports in injection of stabilized and balanced power into grid and prevents power quality issues. The HCC employed ensures that the actual current matches with the reference current generated by DQ theory. As a consequence, the system effectively mitigates power quality issues including voltage sags, swells, harmonic distortion and current imbalances leading to overall improvement in power quality.

3. Modelling of Proposed System

3-1- Level Modular Multilevel Converter

The 5-Level MMC is a modular and scalable topology, which is capable of generating multiple levels of voltage by controlling series of submodules (SMs) in each phase. The MMC topology allows for effective conversion of power between AC and DC with minimized losses and harmonic distortions. The topology of 5-Level MMC is illustrated in Fig. 2. The 5-Level MMC is built using multiple submodules connected in series within each converter arm, which allows it to generate a stepped voltage waveform with five distinct levels. Each submodule typically consists of a capacitor and switching devices, enabling precise control of voltage and current. By appropriately switching these submodules on or off, the MMC synthesizes a staircase-like output voltage that closely approximates a sinusoidal waveform, thereby reducing harmonic distortion and minimizing the need for bulky filters.

The switching table of 5-level MMC is listed in Table 1, explaining the performance of submodules in each arm in generation of desired output. Each arm contains multiple SMs, and in the instance of 5-level MMC, two SMs are in each arm. These SMs contribute the stored capacitor voltage to the output at switch ON state or bypassed when switch is OFF.

Table 1. Switching Operation of 5-Level MMC

SM1 (Upper Arm)	SM2 (Upper Arm)	SM3 (Lower Arm)	SM4 (Lower Arm)	V_{out} (Output Voltage)
1	1	0	0	$+V_{dc} / 2$
1	0	0	0	$+V_{dc} / 4$
1	0	1	0	0
0	0	1	0	$-V_{dc} / 4$
0	0	1	1	$-V_{dc} / 2$

In the 5-Level MMC, the switching states of SMs in upper and lower arms define the output voltage level.

Each of SMs can be either switched ON or OFF, by appropriately controlling the SMs in both the arms.

The switching combination for generation of voltage levels are as follows:

- Maximum Positive Voltage:** The upper arms SM_1, SM_2 are in ON state and the lower arm SM_3, SM_4 are in OFF state. At this instance, each SMs adds its capacitor voltage, subsidising to the total arm voltage. Since SM_3, SM_4 are OFF, there is no contribution of voltage. The overall DC voltage from SM_1, SM_2 is applied across the output terminals, resulting in maximum voltage of $+V_{dc} / 2$.
- Mid-Level Positive Voltage:** In this case, only one SM in upper arm contributes its voltage and there is no voltage from lower arm. As a consequence, the output voltage is half of the maximum positive voltage, which is $+V_{dc} / 4$. This level is suitable for generating smoother transitions in output waveform and harmonics reduction.
- Zero Output Voltage:** When one SM in upper arm and lower arm are turned ON, voltage from upper and lower arm cancels each other. The voltage from upper arm $+V_{dc} / 4$ and from lower arm $-V_{dc} / 4$, results in net output of zero volts. This balanced switching state creates neutral or zero voltage point in the waveform.
- Mid-Level Negative Voltage:** Here, both SM_1, SM_2 are bypassed, with no voltage support. On SM in lower arm is turned ON, and the capacitor voltage produces a negative voltage of $-V_{dc} / 4$, resulting in mid-level negative output voltage.
- Maximum Negative Voltage:** In this case, the upper arm SM_1, SM_2 is in OFF and lower arm SM_3, SM_4 is turned ON. The ON state of lower arm contributes the full capacitor voltage to output. The upper arm SM_1, SM_2 is bypassed, so there is not voltage contribution. As a consequence, the voltage from lower arm generates the maximum negative voltage $-V_{dc} / 2$.

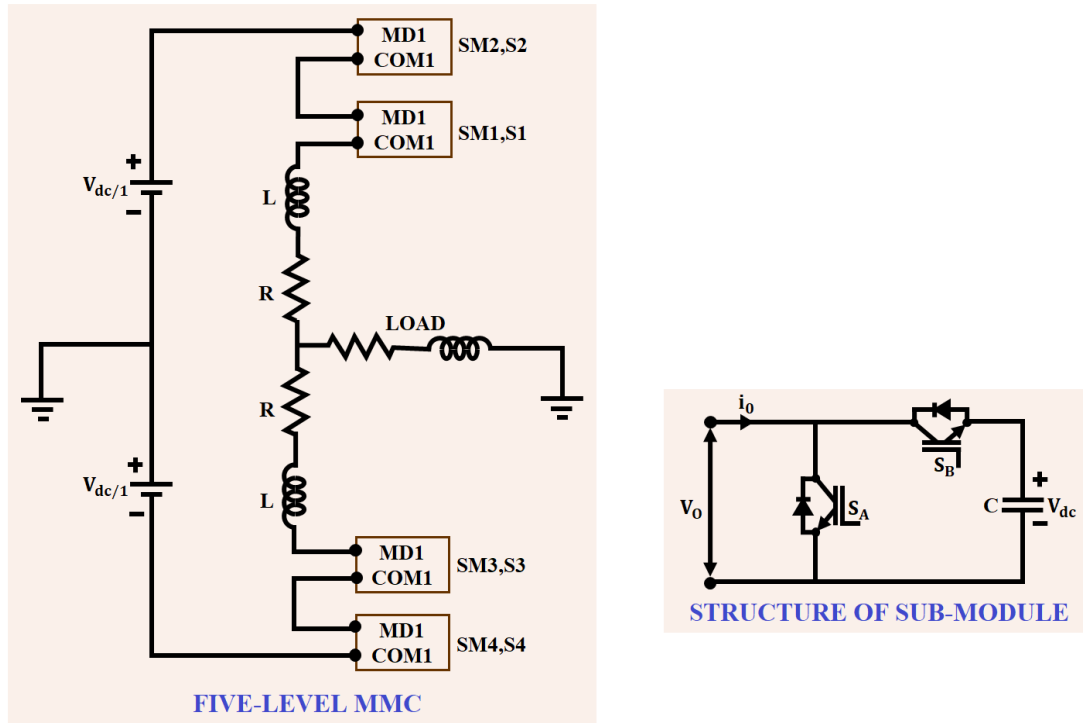


Fig. 2. Five-Level MMC System

This combination of switching states allows the MMC to produce stepped waveform with 5 distinct voltage levels $+V_{dc}/2, +V_{dc}/4, 0, -V_{dc}/4, -V_{dc}/2$. By alternating between these levels, the MMC produce more sinusoidal AC output, with improved power quality, reduced harmonics and reduces the need of large filters. The switching states are controlled, and allows MMC to generate smoother output and making it ideal for high power applications.

3-2- DFIG Driven WECS

In this work to power the MMC, the DFIG based WECS is adopted shown in Fig. 3, owing to its performance towards varying wind speeds. The wind turbine is accountable for capturing kinetic energy and converting it into mechanical energy. The generated AC output is first processed by a PWM rectifier, which converts it into a regulated DC voltage. This DC link is then fed into a MMC, which produces a high-quality stepped AC output with reduced harmonics for grid integration. To maintain stable DC

voltage, a PI controller continuously compares the actual DC voltage with the reference value and adjusts control signals accordingly. The generated power from wind turbine is expressed as,

$$P_a = \frac{1}{2} \rho S C_p (\lambda, \beta) V^3 \quad (1)$$

Where area circulated by wind turbine is noted as S , air density as ρ , wind speed is signified as V and power conversion efficiency as C_p . The aerodynamic torque expression is given by

$$T_a = \frac{P_a}{\Omega_t} = \frac{1}{2\Omega_t} \rho S C_p (\lambda, \beta) V^3 \quad (2)$$

Here, turbine speed is indicated by Ω_t . The DFIG is a wound rotor induction generator which contributes in generation of power.

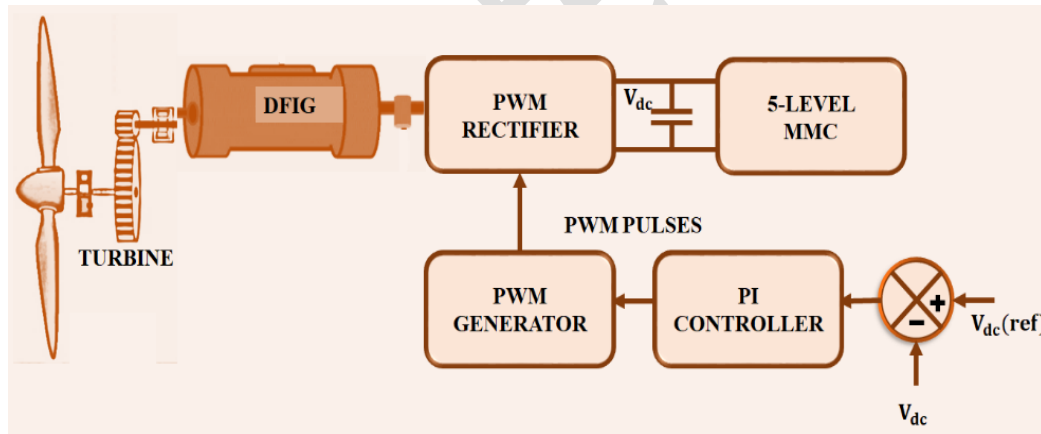


Fig. 3. Architecture of DFIG Driven WECS

The voltage expression for DFIG in dq frame is expressed as

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt} \phi_{ds} - \omega_s \phi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt} \phi_{qs} + \omega_s \phi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt} \phi_{dr} - (\omega_s - \omega_r) \phi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt} \phi_{qr} - (\omega_s - \omega_r) \phi_{ds} \end{cases} \quad (3)$$

$$\begin{cases} \phi_{ds} = L_s I_{ds} + M I_{dr} \\ \phi_{qs} = L_s I_{qs} + M I_{qr} \\ \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (4)$$

Where rotor and stator indices is represented as r and s , resistance is denoted by R , flux as, synchronous reference frame as d and q . In addition, the electrical frequency is signified a ω_s , with V and I expressing voltage and current. The inductance is related as L and mutual inductance as M . The governing mechanical expression for DFIG is stated as

$$J \frac{d\Omega}{dt} = T_a - T_{em} - f\Omega \quad (5)$$

Where speed of DFIG is indicated as Ω , total inertia of turbine as J , damping coefficient as f and electromagnetic torque as T_{em} expressed by

$$T_{em} = p \frac{M}{L_s} (\phi_{qs} I_{dr} - \phi_{ds} I_{qr}) \quad (6)$$

Here number of pole pair is written by p . The expression indicating active and reactive power at stator side is expressed by,

$$\begin{cases} P_s = \frac{3}{2}(V_{ds}I_{ds} + V_{qs}I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs}I_{ds} - V_{ds}I_{qs}) \end{cases} \quad (7)$$

The integration of DFIG-WECS with MMC necessitates controller to manage complex interactions within the system. In this work PI controller is utilized for optimizing the flow of power, maintaining stability of voltage and for ensuring efficiency and reliability of wind system.

3-3- Hysteresis Current Control

HCC in Fig. 4 is a commonly utilized non-line control strategy in power system for control of inverter. The HCC is the hysteresis bandwidth, defining the range within which the current is allowed to vary. The controller operated by maintaining the actual current within the predefined bandwidth around reference current. The HCC technique continuously, compares the actual i_{actual} and reference current i_{ref} and generates error Δi_e . If actual current exceeds the upper or lower limits of this band, the inverter switches states to correct it. A narrower bandwidth results in higher current tracking accuracy but increases switching frequency, leading to more switching losses and Electromagnetic Interference (EMI). In contrast, a wider bandwidth lowers switching frequency and losses but reduces current tracking accuracy.

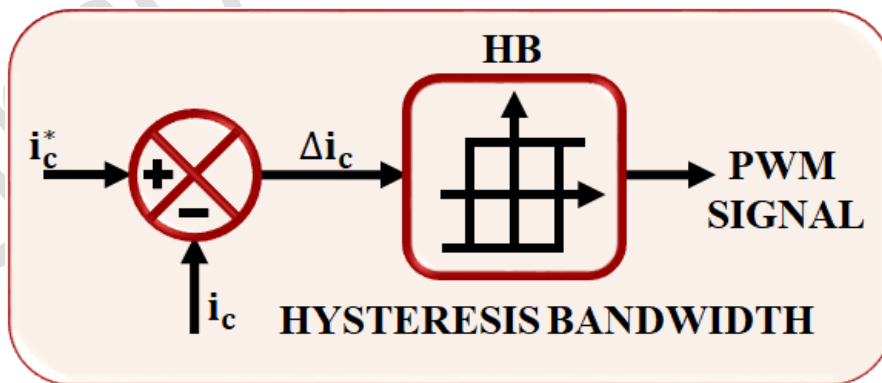


Fig. 4. Hysteresis Current Control

This eliminates the effect on tracking performance compared to triangular wave comparison and does not necessitate a fixed triangular carrier. Initially, the instantaneous deviation (Δi_c) is evaluated by taking the difference between actual current (i_c) from the compensation current command signal (i_c^*) . This deviation is then fed into hysteresis comparator, where the bandwidth is set to $(2\Delta i_c)$. The actual current is controlled within the range of $i_c^* + \Delta i_c$ and $i_c^* - \Delta i_c$ to follow the command current closely. In case of hysteresis band is too wide, the switching frequency of inverter decreases, causing low switching losses. However, this also ranks with larger tracking error, initiating the compensation current to contain more high-frequency harmonics. In converse, a narrow hysteresis bandwidth improves the tracking accuracy but increases switching frequency, resulting in higher switching losses. Therefore, the switching frequency range is chosen as a compromise between these factors. This corrective output is then sent to PWM generator, which is used to modulate the MMC's switching actions and control the current flow precisely.

3-4- Generation of Reference Current by DQ Theory

In the proposed work MMC integrated with DFIG-WECS, generating reference current using dq theory. This enables the decoupling of active and reactive power control, essential for managing power quality and system stability.

The voltage and current from a 3ϕ system is converted into a stationary reference frame $\alpha\beta$ using Clarke's transformation.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (8)$$

Where x defines voltage or current. Next Park's transformation is applied for transforming these signals into dq reference frame.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (9)$$

Where ωt specifies angle of rotation and this transformation results in DC components for balanced, sinusoidal system. For converting the system again into $\alpha\beta$ frame into dq frame, the following expression is used

$$\begin{bmatrix} x_\alpha^* \\ x_\beta^* \end{bmatrix} = \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} \quad (10)$$

At last the signals are converted back into original 3ϕ system as given by the expression

$$\begin{bmatrix} x_a^* \\ x_b^* \\ x_c^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_\alpha^* \\ x_\beta^* \end{bmatrix} \quad (11)$$

This conversion allows the control system to inject the optimal compensating current back into the system. Thereby accurate current compensation takes place, even when the supply voltage is distorted or unbalanced.

4. Results and Discussion

Table 2 details the specification of proposed work. Moreover, the detailed results of simulations, illustrating the performance of proposed system in effectively controlling power flow, maintaining voltage and current quality, and enhancing the switch to balance efficiency is also discussed. In the system modeling, the WECS is designed using a DFIG coupled with a 5-level MMC, simulated in MATLAB/Simulink. The DFIG parameters include a nominal power rating of 10 kW, frequency of 50 Hz

and detailed machine constants such as stator and rotor resistances, inductances, magnetizing inductance, inertia constant and friction factor to ensure realistic dynamic behavior. The MMC converter is configured with an input voltage of 600 V, sub-module capacitance of 10 mF and switching frequency of 10 Hz to generate a high-quality multilevel output waveform. Simulation scenarios include variations in wind speed, which directly affect turbine torque, rotor speed and pitch angle of the DFIG, allowing assessment of system response under fluctuating input conditions. Performance is evaluated in terms of output voltage and current waveforms, harmonic distortion, voltage stability and current regulation.

Table 2. Design Component Parameter

Parameter	Ratings
DFIG	
Pairs of Poles	3
Friction Factor	0.01F(pu)
No. of Turbines	4
Inertia Constant	0.685Hs
Magnetizing Inductance	2.9mH
Rotor Inductance	0.16mH(pu)
Rotor Resistance	0.016 Ω (pu)
Stator Resistance	0.023 Ω (pu)
Stator Inductance	0.18mH (pu)
Nominal Power	10kW
Frequency	50Hz
MMC converter	
Input voltage	600v
Frequency	50Hz
Capacitance voltage per sub module	10mF
Switching frequency	10 Hz

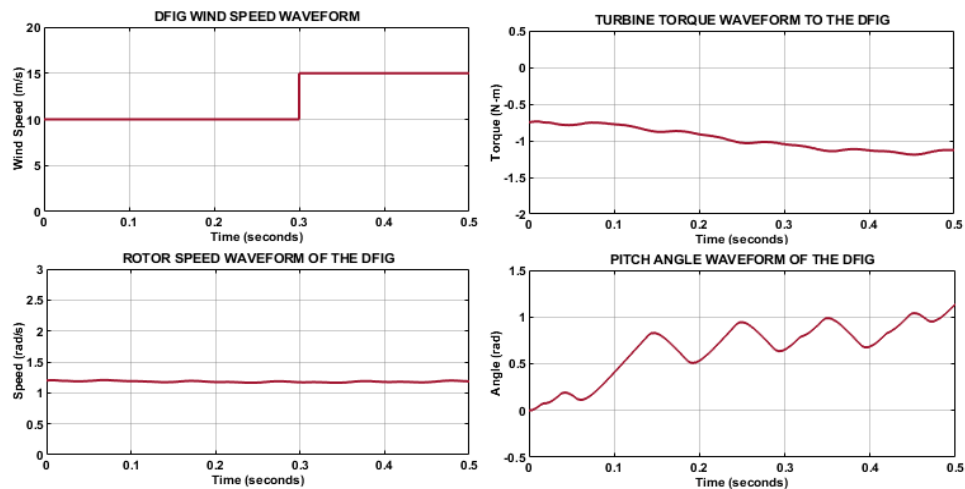


Fig. 5. Dynamic Response of DFIG in Wind System

The waveform in Fig. 5 demonstrates the performance of DFIG system in a wind energy setup, highlighting critical parameters over time. The wind speed waveform, shows step change in wind speed occurring at 0.3s, indicating a variation in input wind conditions. This change impacts the turbine's performance. The turbine torque reacts to wind speed variations by exhibiting a dynamic decline, stabilizing after fluctuations at initial stage. The rotor speed waveform of DFIG adjusts to maintain stability despite changes in input torque and wind speed. Finally, the pitch angle waveform shows dynamic increases and oscillations to regular output power and ensures system stability under varying wind speeds.

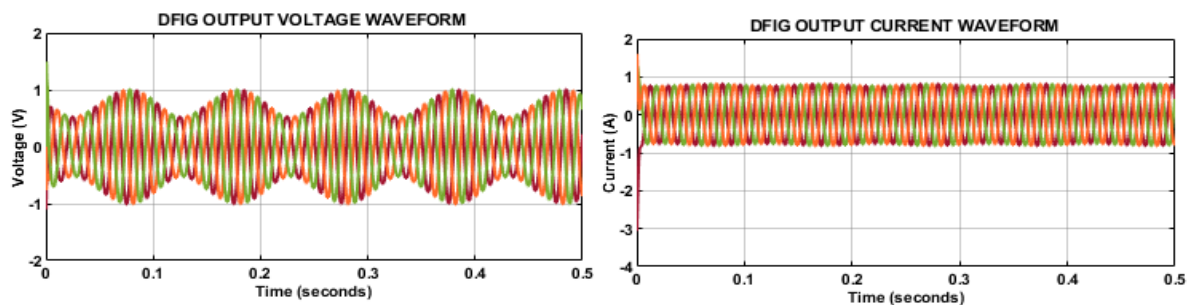


Fig. 6. Voltage and Current Output of DFIG System

The output characteristics of DFIG system is illustrated in Fig. 6. It is seen that the DFIG output voltage waveform, fluctuates sinusoidally, indicating generation of AC voltage, with variations in amplitude owing to system dynamics. The DFIG output current waveform exhibits sinusoidal characteristics, but with stable amplitude, representing steady delivery of current under controlled operation.

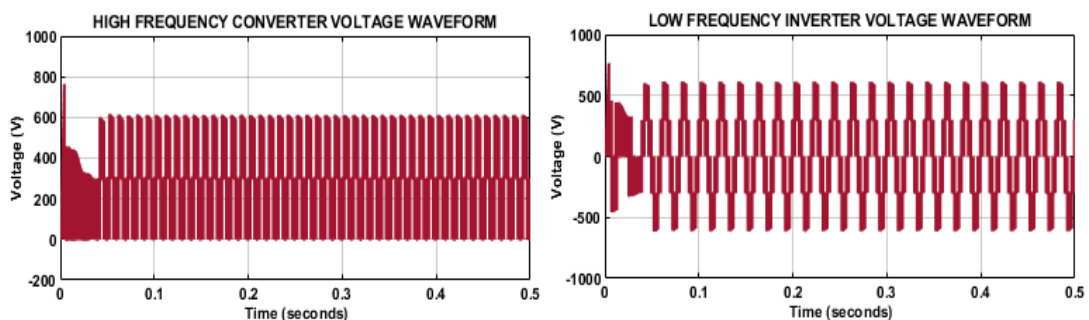


Fig. 7. Five Level MMC Waveform

The voltage characteristics of high frequency and low frequency converter is illustrated in Fig. 7. IT is seen from the high frequency converter waveform that, rapid switching characteristics with steady voltage level of 600V is accomplished after initial oscillations. Whereas, the low frequency converter exhibits the same sinusoidal output with variations at the initial level, after continuing at 600V representing the low-frequency voltage conversion essential for interfacing with grid.

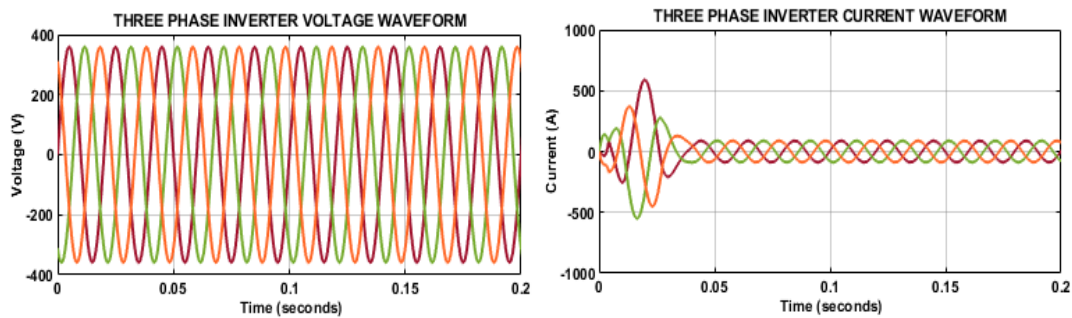


Fig. 8. Inverter Characteristics Waveform

This waveform in Fig. 8 depicts the voltage and current characteristics of three-phase inverter utilized in the proposed DFIG-based wind energy system. The three-phase inverter voltage waveform, demonstrates sinusoidal voltages for each phase with a stable amplitude, ensuring effective power delivery to load. While the current waveform, initially exhibits a transient response followed by steady sinusoidal currents for each phase, demonstrating the inverter's capability to stabilize and synchronize current output with the system.

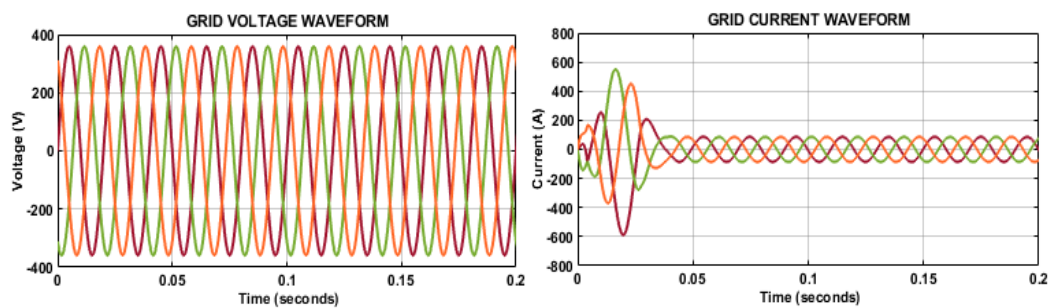


Fig. 9. Grid voltage and Current Waveform

This voltage and current waveforms observed at the grid interface in the proposed DFIG-based wind energy system is illustrated in Fig. 9. The grid voltage waveform, represents consistent amplitude and frequency, indicating proper synchronization with grid standards. Whereas the grid current waveform,

initially shows variations the three-phase sinusoidal voltage of 330V with before settling at 50A into steady sinusoidal currents for each phase.

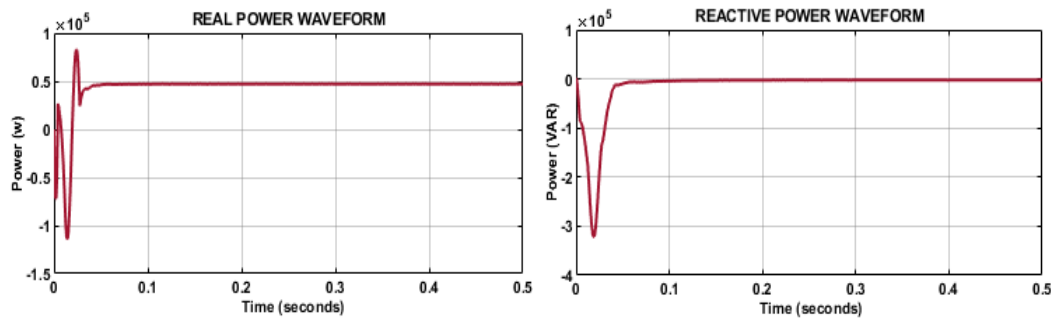


Fig. 10. Real and Reactive Power Waveform

The real and reactive power characteristics of proposed DFIG-based wind energy system is demonstrated in Fig. 10. The real power waveform, which starts with an initial transient response and quickly stabilizes to deliver steady positive real power, reflecting effective energy transfer to the grid. The reactive power waveform, beginning with a negative transient before settling near zero, indicating successful reactive power compensation and improved power factor control. Fig. 11 showcases the THD waveform, which is at 1.35%, referring to minimized harmonic distortions. The harmonic spectrum illustrates that the proposed system successfully maintains the fundamental component at 50 Hz with a magnitude of 8.51, while suppressing most higher-order harmonics to negligible levels, yielding a very low THD of 1.35%. The small residual harmonics observed at multiples of the fundamental frequency are well within acceptable IEEE 519 standards, ensuring minimal waveform distortion. This low distortion level directly generates smoother voltage and current waveforms leading to reduced losses in converters, transformers and transmission lines. Furthermore, the reduced harmonic stress enhances the longevity of connected equipment, prevents overheating and ensures stable grid synchronization. Overall, the precise THD reduction confirms that the system achieves high-quality power output, making it highly reliable for grid-connected wind energy applications.

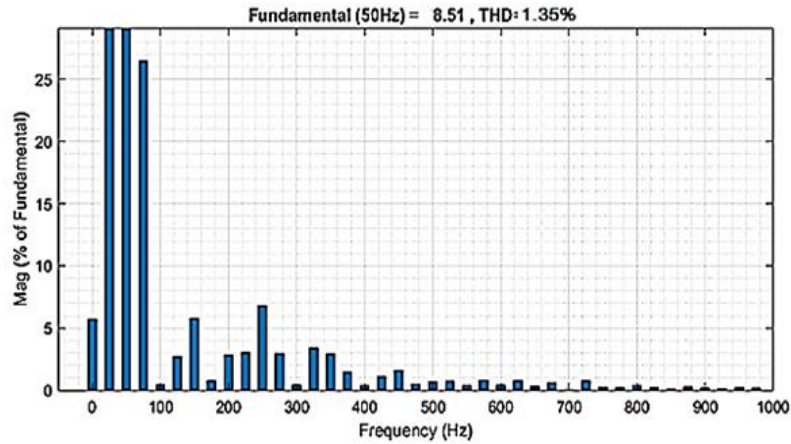


Fig. 11. THD Waveform

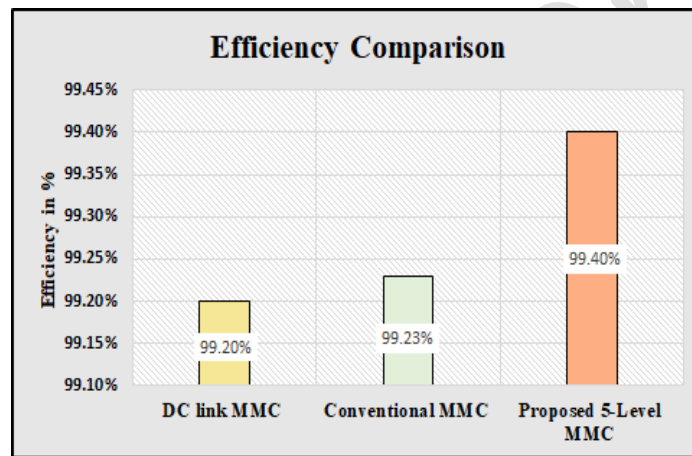


Fig. 12. Efficiency Comparison

Fig. 12 represents the efficiency comparison to analyse the performance efficacy of the 5 level MMC with various conventional converters. From the above chart it is understandable that, 5-level MMC attained quite higher efficiency of 99.40%, when compared to DC link MMC [18] and conventional MMC [19] that obtained 99.2% and 99.23% respectively, indicating enhanced converter performance is attained using 5-Level MMC within the proposed model.

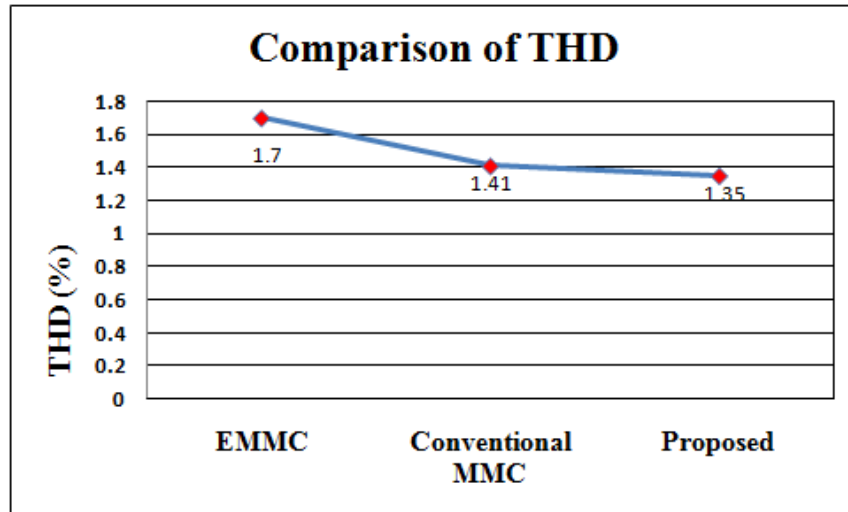


Fig. 13. THD Comparison

The THD comparison graph is shown in Fig. 13, in which THD attained by EMMC [20] and conventional MMC [21] is compared with proposed 5-Level MMC and from the comparative evaluation it is notable that, proposed MMC showcases reduced THD of 1.35% than [20] and [21] which obtained slightly higher THD of 1.7% and 1.41 %, referring to the presence of moderate or little harmonic distortions.

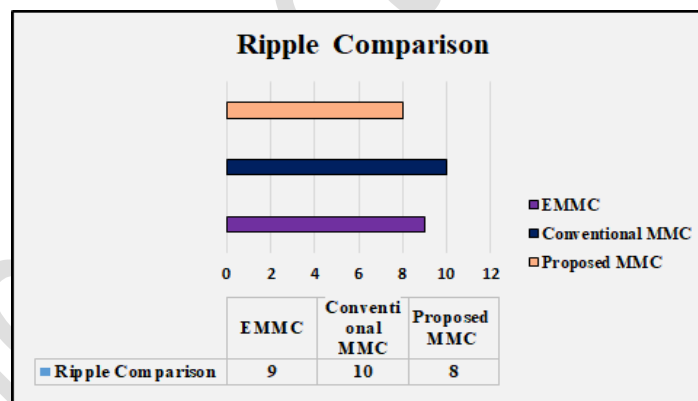


Fig. 14. Ripple Comparison

Fig. 14 demonstrates comparison of ripples attained by the proposed converter with [20] and [21], The above chart showcases that, ripple produced by the 5-Level MMC is 8, while the ripple produced by [20] and [21] is comparatively higher, indicating fluctuations , due to this reason the output power quality is

also minimized. Therefore, utilization of 5-level MMC produces reduced ripples, hence ensuring reduced fluctuations with increased output power quality.

Table 3. THD comparison with existing methods

Methods	THD (%)
Kumar et al. [22]	7.89
Ramirez et al. [23]	1.71
Zheng et al. [24]	5.5
Jin et al. [25]	2.46
Jiang et al. [26]	1.36
Proposed	1.35

Table 3 presents a comparative analysis of THD achieved by the proposed system against several existing methods. The results clearly highlight that the proposed control strategy achieves the lowest THD of 1.35%, which is an improvement over other works. This marginal yet significant reduction in THD reflects the effectiveness of combining MMC topology, D-Q theory and hysteresis control, ensuring enhanced power quality and stable grid integration. The results demonstrate that the proposed system not only competes with but outperforms state-of-the-art approaches, establishing its efficiency in mitigating harmonics and ensuring high-quality power delivery.

5. Conclusion

This paper concludes a novel solution for enhancing the power quality challenges that are raised due to load fluctuations, voltage instability and harmonic distortions by integrating 5-Level MMC with DFIG based WECS. The incorporation of proposed converter in DFIG effectively improves the power quality by reducing harmonics thus, improving the voltage stability. In addition to this, the deployment of D-Q theory and HCC achieves optimum control, assuring smooth and consistent power supply to the grid. Furthermore, the utilization of LC filter effectively removes any unwanted interferences, hence attaining sinusoidal waveforms with limited distortions. The proposed system efficacy is validated through MATLAB/Simulink, depicts that, proposed model depicts minimized THD of 1.35%, ensuring efficient and reliable power supply, with improved output power quality. Overall, the system assures highly stable and effective power supply with reduced fluctuations, consecutively increasing the power electronic

technology for RES. However, the simulation-based validation, though effective, may not fully capture real-world uncertainties such as grid disturbances, parameter variations, or non-ideal switching behavior, which can impact system reliability. Future research can focus on developing real-time hardware-in-the-loop (HIL) testing and experimental validation for bridging the gap between simulation and practical implementation.

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