Integrated Dstatcom with Wecs for Harmonic Mitigation and Power Quality Enhancement in Electrical Distribution Networks

Subhashini K[1], Vidhya Saraswathi Satish[2]
[1]*Associate Professor, Department of Electronics and Communication Engineering Sri Sairam Engineering College Chennai, India*
[2]*ME -Embedded Systems and Technologies, Department of Electronics and Communication Engineering Sri Sairam Engineering College Chennai, India*

***Abstract*—The integration of renewable energy sources, particularly Wind energy conversion systems (WECS), into the existing power grid is transforming the energy landscape by reducing our reliance on conventional fossil fuels. However, this transition is not without its challenges, particularly concerning the power quality and reliability of the grid. This project proposes an integration of a Distribution Static Synchronous Compensator (DSTATCOM) into the Wind Energy Conversion System (WECS) to mitigate harmonic distortions. The DSTATCOM actively monitors the system for harmonic distortions caused by the non-linear load. The DSTATCOM, situated at the point of coupling, plays a dual role in mitigating harmonics from both the non-linear load and the introduced wind turbine system. Adjust compensating currents to address harmonics generated by the combined effect of the non-linear load and the wind turbine system. Bi- Directional Battery Converter enables the storage of excess energy generated by the WECS system and facilitates the release of stored energy back into the load when required. The DSTATCOM, in conjunction with a Proportional-Integral (PI) controller, rectifies the wind system, effectively reducing harmonics. The PI controller plays a crucial role in maintaining a constant DC link capacitance, addressing harmonics, voltage stability issues in the wind system, ultimately contributing to enhanced electrical power quality. Simultaneously, the system optimizes the utilization of renewable energy sources, ensuring sustainable and environmentally friendly power generation. At last this project is implemented and results are verified in Matlab simulation 2021a.**

***Index Terms*—PI controller, Distribution Static Synchronous Compensator, Wind Energy Conversion System, Matlab simulation 2021a.**

I. INTRODUCTION

GRID codes and standards impose stringent requirements on the harmonic emissions of wind power plants (WPPs).

Conventionally, passive power filters are used to limit voltage harmonics at the point of interconnection (POI) of WPP, yet they tend to be overloaded when the harmonic distortions from WPP vary in a wide range, and their power losses and costs need to be optimized. To tackle these challenges, the static synchronous compensator (STATCOM) that is used with the WPP is exploited to actively mitigate harmonics. The active filtering function of STATCOM provides a flexible approach to mitigating the variation of harmonic distortions in the WPP. Several methods have thus been developed for STATCOMs to mitigate the harmonic voltages at the POI of WPP. A simple approach is to operate STATCOM as a harmonic current source to actively counteract the harmonic current generated by the WPP. Yet, the effectiveness of the method is influenced by the varying WPP impedance and the grid impedance seen from the POI. To address this problem, the resistive active power filtering (R-APF) control is used with the STATCOM. The idea of R-APF control is to make STATCOM behave as a harmonic resistance (R) to actively dampen harmonic voltage at the POI of WPP. However, the STATCOM is typically deployed with a step-up transformer to the POI of WPP.In recent years, renewable energy (RE) sources have captured global interests among academic institutions, industries, and governments due to their numerous advantages for improving energy reliability, efficiency, and minimizing carbon emission. RE resources like

wind energy and solar photovoltaic (PV) are extensively used for generation of power at the grid level due to their capability of minimum impact on the environment, sustainability, zero fuel cost, minimum operation cost of the plant, and pollution-free electricity generation. The solar PV energy has merits over the wind energy, such as its quiet operation and capability to be harvested easily in the residential areas. It has main disadvantages of non-availability during night hours and variable output with the time of day. Grid integration of RE sources into the utility grid leads to issues of technical and economic nature in PQ field, reliability, harmonics, voltage stability, control, and protection. Large scale integration of RE sources to the utility grid also affects frequency control and allocation of reserves. Integration of PV into the grid causes problems related to operation due to intermittent behavior of these sources. It affects the frequency/load control, unbalancing of voltage levels, unbalance ing of current levels and load following in the utility network. It further leads to the PQ problems like poor power factor, voltage disturbance, flicker and harmonic distortions. Nowadays, custom power electronic technology-based devices like dynamic voltage restorer (DVR), DSTATCOM, and unified power quality conditioner (UPQC) are widely utilized for improving PQ in RE sources-based hybrid grid. DSTATCOM is capable of controlling the voltage at the point of common coupling (PCC) with grid in flexible manner, which helps in PQ improvement. If a battery energy storage system (BESS) is designed to be incorporated in parallel to DC bus capacitor, then DSTATCOM gains the capability of exchanging both active and reactive powers with grid. Above discussed power variations are mitigated by variation of amplitude and phase angle of converter voltage relative to the terminal voltage of the line. This helps for improving the dynamic performance of systems by voltage regulation and frequency control. BESS also enhances the capacity of DSTATCOM which achieve load balancing, compensation of reactive power, and elimination of harmonic currents. They proposed a design of hybrid grid incorporating wind energy, solar energy, loads, BESS and conventional generator for minimizing the effects of grid disturbances. Minimization of power generation variability due to the variable nature of RE sources is achieved using DSTATCOM. Implementation of DSTATCOM for improving PQ for individual applications like solar PV generation, wind generation, water pumping system, load compensation, and residential low voltage network, has been reported in the literature. However, few studies are available focused on the use of DSTATCOM for addressing improvement of PQ for grid integrated PV plant Implementation of DSTATCOM controlled by adaptive neural network supported control method for suppression of harmonics, balancing of load, and regulation of voltage in isolated distributed generation system has been presented. Shahnia, has described the use of DSTATCOM for the circulation of excess power in the medium and low voltage DN interfaced with the 1-phase renewable power generation system. Mahela, presented a method for improving the quality of power using DSTATCOM incorporated with BESS in hybrid utility grid RE penetration using simulation studies. The aforementioned literature review clearly indicates the research gap that needs to be properly addressed for future smart grids with the high level of penetration of solar PV plants.

If there is no high-voltage (HV) sensor used at the POI of WPP, a series L-Rcircuit at the harmonic frequencies is resulted by the R-

APF-controlled STATCOM, where the L is the leakage inductance of the step-up transformer, and it tends to degrade the harmonic damping effect. To further mitigate the impact of the transformer's leakage inductance, a negative- inductance (−L) control at the harmonic frequencies is added into the R-APF control. It is shown in that a more effective harmonic voltage damping can be attained with the −L-R-APF control. Yet, in the aforementioned control schemes, the inner-loop selective harmonic current/voltage control is commonly used.

The recent studies show that the phase lag of the inner control loop can introduce negative resistances in the vicinity of controlled harmonic frequencies. These negative resistances can jeopardize the stability-robustness of the harmonic control. The corresponding instability issues have been reported and, which show that the negative resistance may induce under-damped resonance in grid-connected converter interfaced with LCL filter. For enhancing the stability-robustness of harmonic current control, the impedance-passivity concept is employed to shape the output admittance with a non-negative real part. Then the stability of harmonic current control can be guaranteed provided that the grid impedance is passive. However, those

works are concerned with the harmonic current rejection of grid connected converters. They cannot be readily used with the −LR-APF. As discussed later in this paper, the synthesis of −L at the selected harmonic frequencies can increase the order of the system, complicating the analytical impedance-passivity-based design.

II.LITERATURE SURVEY

A study titled "Controller Design of DFIG Based Wind Turbine by Using Evolutionary Soft Computational Techniques" by O. P. Bharti, R. K. Saket, and S. K. Nagar [1] examines the implementation of Doubly Fed Induction Generator (DFIG)-based wind turbines. The study focuses on the application of evolutionary soft computational techniques such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) to optimize the controller design for better dynamic performance. The results indicate that soft computing techniques help in achieving improved transient response and stability in WECS under varying wind conditions.

The paper "Power Quality Issues and Their Mitigation Techniques in Grid Tied Solar Photovoltaic Systems-A Review"[2] by A. N. Deshmukh and V. K. Chandrakar provides an extensive review of power quality problems in renewable energy systems, particularly solar photovoltaic (PV) systems. Despite its focus on solar power, the study provides valuable insights into voltage fluctuations, harmonic distortions, and reactive power compensation, which are also relevant for wind energy systems. The study suggests that integrating DSTATCOM with a renewable energy system significantly improves power quality by compensating for reactive power fluctuations.

In "Modeling and Control of a DFIG-Based Wind Turbine During a Grid Voltage Drop", authors A. B. Lajimi, S. A. Gholamian, and M. Shahabi [3] propose a robust control mechanism for wind turbines operating under sudden grid voltage drops, also known as Low Voltage Ride Through (LVRT) conditions. The study highlights the importance of reactive power compensation using STATCOM technology, demonstrating how voltage stability can be maintained even in the presence of transient faults. This study emphasizes the need for adaptive control strategies to ensure grid reliability while integrating largescale wind farms.

The study "Security Enhancement of Hybrid Source in the Grid with STATCOM" by M. M. N. Akhtar and V. K.

Chandrakar[4] investigates the role of STATCOM in maintaining grid security when hybrid renewable energy sources, including wind and solar, are integrated into the distribution network. The paper explores various cyber-physical threats and emphasizes how STATCOM-based controllers enhance grid resilience by providing real-time voltage support, reducing oscillations, and compensating for harmonics.

In "ANN Based DC Link Control of STATCOM in Wind Integrated Distribution System for Power Quality Conditioning", S. K. Rani and S. Prabakaran [5] propose the use of Artificial Neural Networks (ANN) for controlling the DC link voltage in a STATCOM-integrated wind energy system. The study demonstrates that ANN-based control algorithms can significantly improve harmonic suppression, voltage stability, and power factor correction. Unlike traditional Proportional-Integral (PI) controllers, ANN-based controllers exhibit faster response times and better adaptability under fluctuating wind conditions.

A paper titled "A New Reactive Current Reference Algorithm for the STATCOM System Based on Cascaded Multilevel Inverters" by L. K. Haw, M. S. A. Dahidah, and H. A. F. Almurib[6] introduces a novel reactive current reference algorithm for improving the dynamic performance of STATCOM systems. The study demonstrates how cascaded multilevel inverters enhance the power quality of wind-integrated systems by efficiently compensating for harmonic distortions. The algorithm optimizes reactive current injection, leading to improved voltage stability and reduced grid disturbances.

In "Impact of PSS and STATCOM Devices to the Dynamic Performance of a Multi-Machine Power System", G. Shahgholian, E. Mardani, and A. Fattollahi[7] explore the combined effects of Power System Stabilizers (PSS) and STATCOM devices on the dynamic performance of large-scale power systems. The study highlights that when STATCOM is used alongside PSS, it significantly improves voltage stability, damping of low-frequency oscillations, and overall system robustness. The findings are crucial for designing wind-integrated power systems that require effective stabilization mechanisms to mitigate voltage and frequency fluctuations.

The research "AC Voltage Sag/Swell Compensator Based on
Three-Phase Hybrid Transformer With Buck-Boost MatrixReactance Chopper" by J. Kaniewski, Z. Fedyczak, and G. Benysek[8] presents a hybrid compensator design for addressing voltage sag and swell issues in renewable energy systems. The study proposes a three-phase hybrid transformer combined with a buck-boost matrix-reactance chopper, which enhances the stability of power supply to sensitive industrial loads. The results indicate that such compensators, when combined with DSTATCOM technology, can significantly improve grid reliability in wind-integrated networks.

In "Harmonic Domain Modelling of Space Vector Based STATCOM", D. M. Holey and V. K. Chandrakar analyse [9] the effectiveness of harmonic domain modeling techniques in STATCOM systems. The study employs Space Vector Modulation (SVM) to enhance harmonic compensation capabilities, reducing the impact of non-linear loads in windintegrated grids. The research concludes that advanced modulation techniques like SVM can greatly enhance the performance of STATCOM in filtering harmonic distortions and improving overall power quality.

The paper "Off-Grid Hybrid Solar Power Conditioning Unit for Critical and Non-Critical Loads" by M. Chaudhari, K. Babu, S. W. Khubalkar, and P. Daigavane[10] discusses a hybrid power conditioning unit designed for off-grid applications. While primarily focused on solar energy, the study provides insights into energy storage management, grid synchronization, and load balancing, which are applicable to wind energy systems as well. The findings suggest that incorporating bidirectional battery converters into wind energy storage systems can improve energy efficiency and ensure uninterrupted power supply during grid disturbances.

III. RELATED WORKS

The increasing integration of Wind Power Plants (WPPs) into electrical grids has led to growing concerns about power quality issues, particularly harmonic distortions. Various compensation devices and control strategies have been proposed to address these challenges, with the Static Synchronous Compensator (STATCOM) emerging as an effective solution for mitigating harmonics and stabilizing voltage fluctuations at the Point of Interconnection (POI). This section presents an overview of recent advancements in STATCOM-based harmonic mitigation techniques and control strategies.

One of the key challenges in harmonic mitigation is the impact of the leakage inductance of step-up transformers, which degrades the damping effect of harmonics in WPPs. To counteract this issue, researchers have proposed Negative-Inductance (−L) Control in combination with Resistive-Active Power Filter (RAPF) Control. This approach has been shown to enhance harmonic damping by effectively neutralizing the transformer's leakage inductance. However, the implementation of negative inductance introduces complexities in system modeling, particularly in achieving impedance-passivity-based designs, which are crucial for system stability and robustness.

Another critical aspect of harmonic mitigation is inner-loop selective harmonic current and voltage control, commonly employed in STATCOM systems. Studies indicate that while these control loops are effective in mitigating harmonics, they can also introduce negative resistances at certain harmonic frequencies, which may destabilize the system. This phenomenon has been observed in grid-connected converters with LCL filters, where negative resistance effects lead to under-damped resonance conditions. To address this issue, an impedance-passivity approach has been developed to ensure that the system's output admittance remains stable, provided that the grid impedance exhibits passive characteristics. While this technique improves stability, it is primarily focused on harmonic rejection in conventional grid-connected converters and is not directly applicable to −L-R-APF-based STATCOMs.

Several studies have also explored the use of multi-band BandPass Filters (BPFs) in harmonic compensation. These filters can selectively attenuate specific harmonic components, improving the effectiveness of STATCOM-based mitigation strategies. However, designing analytically feasible impedance-passivity models for multi-band BPFs remains a challenge, limiting their practical implementation. Furthermore, frequency scan verification methods have been employed to validate the effectiveness of impedance-passivity designs. While these methods provide valuable insights into harmonic behavior under controlled conditions, they may not comprehensively

capture system responses under dynamic operating scenarios.

Recent advancements in adaptive control algorithms for STATCOM have also contributed to improved harmonic mitigation. Traditional STATCOMs primarily focus on reactive power compensation to maintain voltage stability. However, when STATCOMs are utilized for harmonic suppression, their active and reactive power references must be dynamically adjusted to prevent interference with harmonic control functions. To achieve this, researchers have developed adaptive STATCOM control algorithms that continuously monitor harmonic distortions and optimize power references in real time. These algorithms significantly enhance harmonic suppression efficiency, especially in weak-grid conditions where conventional STATCOM strategies struggle to maintain performance.

The integration of Artificial Intelligence (AI) and Machine Learning (ML) into STATCOM control systems has also shown promising results in addressing harmonic distortions. AI-driven predictive models leverage historical grid data to anticipate harmonic fluctuations and adjust compensation strategies accordingly. This intelligent control approach provides a more adaptive and self-optimizing solution compared to conventional PI-based controllers. However, the computational complexity and real-time processing demands of AI-based STATCOM controllers pose challenges for large-scale implementations.

Another key consideration in STATCOM-based harmonic mitigation is the impact of grid strength on harmonic control effectiveness. Studies have shown that harmonic voltage distortions are significantly lower in strong grid conditions, whereas weak grids suffer from resonance effects, particularly with harmonic orders such as 5th, 7th, 11th, and 13th. To address this issue, researchers are developing hybrid control strategies that integrate STATCOM with other power quality improvement devices, such as Active Power Filters (APFs) and hybrid filters, to achieve more comprehensive harmonic mitigation in weak-grid conditions.

In summary, extensive research has been conducted on improving STATCOM-based harmonic mitigation in WPPs. While approaches such as −L-R-APF control, impedance-passivitybased stability enhancements, adaptive control algorithms, and AI-driven predictive models have demonstrated promising results, several challenges remain. The complexity of system design, negative resistance effects, analytical infeasibility of multi-band BPFs, and real-time computational requirements must be addressed for optimal STATCOM implementation. Future research should focus on simplified and robust control structures that ensure harmonic mitigation while maintaining system stability and adaptability to diverse grid conditions. Additionally, hybrid AI-driven STATCOM controllers could offer a more intelligent and efficient approach for enhancing power quality in renewable energy-integrated power systems.

IV PROPOSED SYSTEM

The increasing penetration of Wind Energy Conversion Systems (WECS) in modern power grids has led to significant challenges in power quality, stability, and harmonic distortions. Due to the intermittent nature of wind energy, integrating non-linear loads into the system can further exacerbate harmonic distortions, voltage fluctuations, and power quality issues.To address these challenges, this project proposes the integration of a Distribution Static Synchronous Compensator (DSTATCOM) in the WECS, along with a Proportional-Integral (PI) controller and a bi-directional battery converter, to ensure improved harmonic mitigation and enhanced voltage stability.

The proposed system incorporates a DSTATCOM at the point of common coupling (PCC) to counteract harmonic distortions introduced by both the non-linear loads and the wind turbine system.The PI controller is employed to regulate the DC-link voltage, ensuring the DSTATCOM operates efficiently to maintain grid stability.Additionally, a bi-directional battery converter is integrated into the DC-link, enabling the system to store excess energy and discharge it when needed to balance the grid.

The collaborative functioning of these components significantly improves power quality and voltage stability in the three-phase fourwire electrical distribution system.

Components and Functionality

1. Distribution Static Synchronous Compensator (DSTATCOM)

The DSTATCOM plays a crucial role in mitigating harmonic distortions caused by non-linear loads and the wind turbine system.It operates by monitoring harmonic distortions in real-time within the electrical

distribution system.The DSTATCOM injects compensating currents to counteract harmonic currents and maintain a sinusoidal waveform.It also provides reactive power compensation, which helps in voltage regulation and improving overall power quality.Additionally, the DSTATCOM addresses voltage sags and swells, ensuring a stable voltage profile at the point of common coupling (PCC).By implementing DSTATCOM, the system ensures that both the non-linear loads and the wind turbine system do not introduce excessive distortions into the grid, thereby enhancing the power quality of the electrical distribution system.

2. Proportional-Integral (PI) Controller

To optimize the DSTATCOM's performance, a PI controller is employed, which is responsible for regulating the DC-link voltage within the DSTATCOM to ensure steady operation.The PI controller ensures a constant capacitance value, allowing the DSTATCOM to inject accurate compensating currents.It minimizes voltage fluctuations, harmonics, and maintains stability under dynamic grid conditions.The PI controller dynamically adjusts the compensating current levels based on real-time harmonic analysis, enabling the DSTATCOM to effectively counteract power quality issues.

3. Bi-Directional Battery Converter

A bi-directional battery converter is introduced in the DC-link to provide energy storage and supply capabilities.The converter stores excess energy generated by the wind turbine during periods of high wind speeds.It discharges stored energy when wind speeds drop or demand increases, ensuring continuous power supply.Additionally, the converter provides additional voltage support to stabilize grid fluctuations and reduce power intermittency.The integration of the battery storage system enhances grid stability, allowing for a smoother transition between energy generation and consumption while reducing voltage fluctuations.

Operational Mechanism

1. Harmonic Identification & Mitigation

The DSTATCOM continuously monitors the power system for harmonic distortions caused by both non-linear loads and the wind turbine system.Once distortions are detected, the DSTATCOM injects compensating currents in real-time to counteract them, ensuring a stable grid waveform. 2. Voltage Regulation & Stability Enhancement

The PI controller plays a key role in ensuring that the DC-link voltage remains constant, allowing the DSTATCOM to operate efficiently.By regulating compensating currents, the PI controller helps maintain voltage stability, thereby reducing issues such as voltage sags, swells, and harmonic fluctuations.

3. Energy Storage & Supply via Bi-Directional Battery Converter

When the wind turbine generates excess power, the battery converter stores the surplus energy in the DC-link.During periods of low wind speeds or increased demand, the stored energy is released back into the system, maintaining a consistent power supply and preventing voltage instability.

4. Coordinated Operation of DSTATCOM & Battery Converter

By leveraging both DSTATCOM and battery storage, the proposed system effectively compensates for harmonics introduced by wind energy conversion and non-linear loads.It enhances power quality by ensuring stable voltage and frequency levels.The system improves energy utilization by storing and discharging energy as needed.

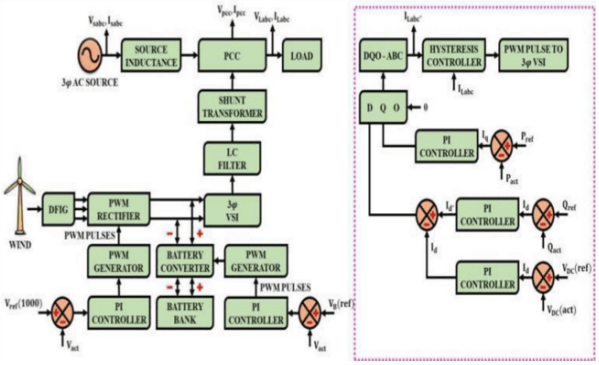


Figure 1. System Architecture

V.MODULE DESCRIPTION

The wind power system contains wind turbine that exchanges wind's kinetic energy as rotating motion, then turbine speed is equated to the generator speed by using gear box, a generator that changes mechanical energy into electrical energy, the rectifier that transforms ac voltage into dc, manageable dc-dc converter is used to suggest the maximum power point

The airs kinetic energy is transferred by wind turbines (i.e. wind power) as mechanical power which are utilized to operate the machine else generator directly.

The shape of blades, pitch angle, speed of rotation, and rotor radius are used to associate the power from the blades of the turbine. Generated power is represented as,

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \theta) R^2 V^3$$

In which, P_m– Power taken through wind turbine; ρ–Air density;
θ –Pitch angle; R–blade radius; V– Wind speed;

WIND POWER SYSTEM

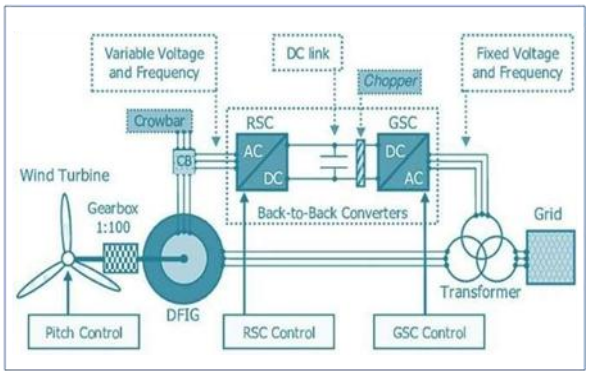


Figure 2. WECS With DFIG

And λ is the ratio of tip-speed and it is dnoted as,

$$\lambda = \frac{nR}{V}$$

In which R is rotor speed

In which, R is rotor speed; C_p is expressed with function of tip speed ratio

$$C_p = \frac{1}{2}\left(\frac{116}{\lambda_1} - 0.4\beta - 5\right) e^{\left(\frac{-16.5}{\lambda_1}\right)}$$

The wind turbine shaft is automatically fixed with the generator rotor shaft, thus the developed mechanical power through wind turbine (through kinetic energy towards mechanical energy transformation) that transferred towards rotor shaft and the construction of rotor contains rotor winding (both field else armature). By this, the roaming conductor is obtained at stationary magnetic field else stationary conductor at roaming magnetic field. However, the principle of generator is used to generate the electric voltage.

5.2.1 DOUBLE FED INDUCTION GENERATOR

The induction motor is considered as the induction generator when the motor runs at negative slip. However, this generator is not self-exciting and it is excited with the frequency that is fixed though the stator requires the exciter. Because of this reason the machine is provided with two supplies then this can be said as the doubly fed induction generator and this is suitable for producing wind power.

It is essential to recognize about machines dynamic model, to understand and design the wind turbine generator scheme with the vector control design. Electrical machine model that is sufficient for control system design rather contain entirely dynamic effects that are important and rising throughout steady state, transient operations. By this the machine is supplied with the varied generation of voltage and current. In this section, the model that instantly valid with varied current and voltage and the machine is frequently described with both ABC reference frame, numerous altered reference frames of DQO.

5.2.2 DFIG Model depicted in ABC reference frame

The wound rotor induction machine (IM) that measured by symmetrical two poles then three-phase windings for ease. The cross-sectional vision for machine below reflection, in which the slotting effect is neglected is illustrated at figure 3.

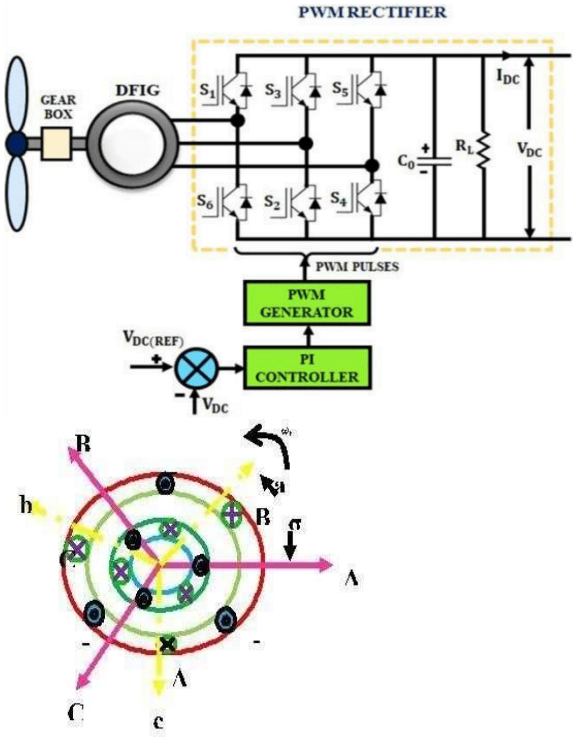


Figure 3 Cross-sectional view of wound rotor IM

The display of stator phase is given through 120 electrical degrees after one another; thus, the rotor phase too moved with 120 electrical degrees after one another. Magnetic axes angle is among stator phase winding, A, then rotor phase winding, a, is σ. Rotor speed can be represented as $wr = d\sigma/dt$yet direction of it is given with counter-clockwise direction.

The ABC model is developed by the following assumptions: The DFIG stator and rotor phases are distributed symmetrically, in this the resistances, magnetizing, leakage inductances are equal in entire three phase. The created magneto motive force is dispersed sinusoidal over DFIG stator circumference. Consequently, harmonic components are absent. The circumference of the mind-air-gap is constant with reluctant airgap, and it is said as the constant.The mutual inductances saturation is ignored.The skin effect at stator, rotor phase winding conductors is ignored. Time at which the frequency of the current is increased, skin effect initially improves the leakage flux presences at DFIG, thus the resistances are increased and leakage inductances are reduced.Core losses are ignored, then the power losses over stator, rotor phase resistances be measured. Crosssaturation effect, i.e., connection among two perpendicular axes, is ignored.

5.2.3 PWM Rectifier

The primary function of a PWM (Pulse Width Modulation) rectifier is to convert the variable-frequency alternating current (AC) generated by a wind turbine into direct current (DC). This conversion allows for improved control and compatibility with the electrical grid. PWM rectifiers provide precise control, enabling a stable DC voltage level even when wind speeds vary, thus contributing to a reliable and consistent power supply.

PWM rectifiers offer fast dynamic response capabilities by rapidly adjusting their output voltage and current in response to variations in wind power.

The PWM voltage source rectifier is commonly used in AC motor drives to obtain a stable DC voltage. On the grid side, the converter functions similarly to a PWM rectifier. The model of a three-phase PWM voltage source rectifier is initially developed in the direct ABC reference frame and is later converted into the DQO synchronous reference frame to facilitate controller design.

5.2.4 Three-Phase Model in ABC Reference Frame The converter circuit of a three-phase PWM voltage source rectifier, shown in Figure 7, consists of six IGBTs with body diodes, AC-side resistances and inductances, a DC-link capacitor, and a load resistance.

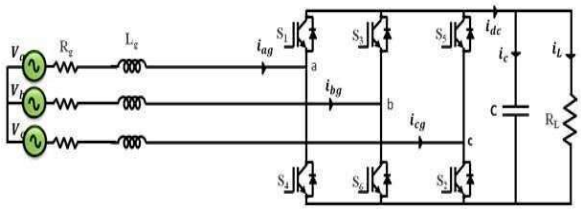


Figure 4. *Voltage Source Rectifier*

The model considers three-phase voltage sources at the input, connected through resistances and inductances to the rectifier circuit. The DC-link capacitor stores energy, and the load resistor determines power dissipation.

Switching functions for each phase define the state of the upper and lower switches, which determine the voltage applied to the load and the current flowing through the circuit. The model uses Kirchhoff's law to describe the behavior of the current in each phase. It also accounts for voltage drops across resistive and inductive elements and the effect of the switching logic on the output voltages.

The system assumes a balanced three-phase network, where the sum of phase voltages and phase currents is zero. This simplification helps in reducing the mathematical complexity of the model. The current flowing into the DC-link capacitor is influenced by the switching states and the load conditions. A power balance equation relates the AC side input power to the DC-side output.

The overall model of the three-phase PWM rectifier provides insight into how voltage and current behave under different switching conditions and forms the basis for control system development.

5.2.5 DSTATCOM and Its Components

A Distribution Static Compensator (DSTATCOM) is a shuntconnected power electronic device used at the distribution level to provide reactive power compensation and improve power quality. It is typically installed near the load and consists of several key components: a DC capacitor, a three-phase inverter (often based on IGBTs or thyristors), an AC filter, a coupling transformer, and control logic.

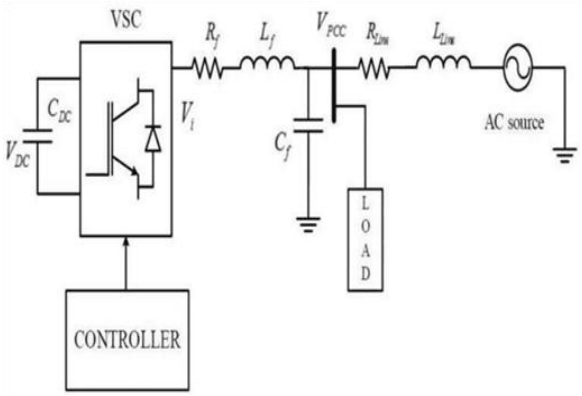


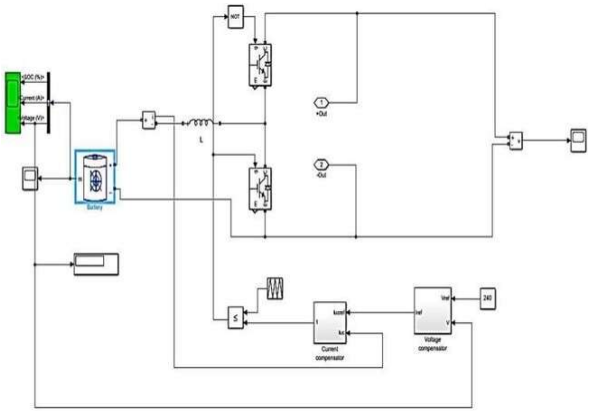
Figure 5. *Basic Building Blocks of a DSTATCOM*

The inverter converts the DC voltage from the capacitor into a controllable three-phase AC voltage. By adjusting this output voltage, the DSTATCOM can either inject or absorb reactive power. When the inverter output voltage exceeds the grid voltage, it supplies reactive power (capacitive mode). Conversely, when the grid voltage exceeds the inverter output voltage, the DSTATCOM absorbs reactive power (inductive mode). If both voltages are equal, the system is in a floating condition with no
power exchange.
The control of reactive power is achieved by managing the phase angle between the inverter output and the system voltage. Modern DSTATCOM devices use advanced controllers, such as
Proportional (P), Proportional-Integral (PI), and hysteresis current controllers, to dynamically adjust voltage and current to meet system demands.

5.2.5. Modelling of DSTATCOM

In a DSTATCOM, the inverter plays a central role in regulating voltage and controlling power flow. The direction and magnitude of reactive power exchange depend on the difference between the inverter's output voltage and the grid voltage. If the inverter voltage is higher, reactive power flows from the DSTATCOM to the grid. If it is lower, the flow is reversed.
During operation, the DSTATCOM adjusts the output of the voltage source converter to maintain system stability and support voltage during dynamic changes in load or fault conditions. Multi-level converters may be used to enhance power handling capacity and reduce harmonic distortion.

Capacitor banks attached to the DC link store energy and help regulate the DC voltage. They ensure consistent performance



even when power demand fluctuates or during transient events. Pulse Width Modulation (PWM) techniques are used to control the inverter switches, allowing fine-tuned control of output voltage and current.

5.2.6 Benefits of Capacitor Banks

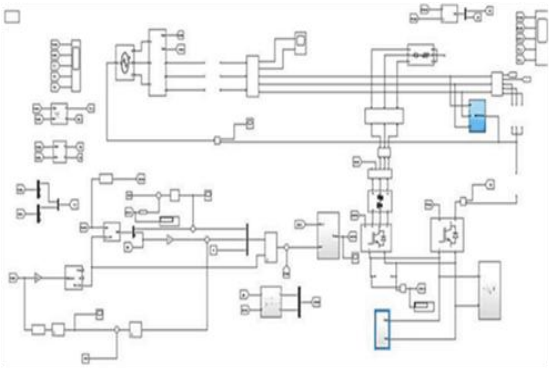


Figure 6. Overall Simulation

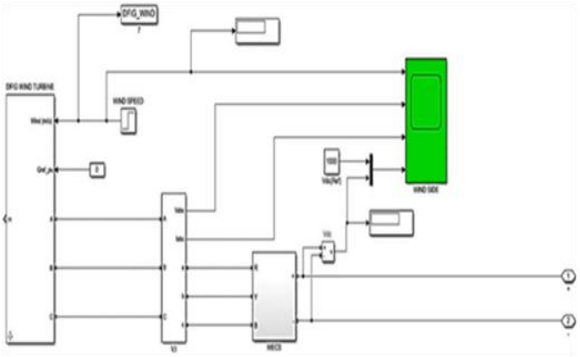


Figure 6. (A) Overall Simulation

Capacitor banks are widely used in electrical power systems to provide reactive power compensation, improve voltage profiles, and enhance system stability. Their main benefits include improved power factor, reduced transmission losses, increased system capacity,

and decreased operational costs. Capacitor banks can be installed in various forms, such as shunt or series configurations, depending on the application. They are available with internal or external protection mechanisms, and may be fused or unfused depending on system requirements. These banks support voltage levels at transmission buses or enduser points and are especially useful during low-voltage or highload conditions. They are typically switched ON or OFF automatically by controllers based on voltage level or reactive power demand.

Proper sizing and location of capacitor banks are critical to avoid overvoltage or overheating. Unbalance protection is provided to safeguard the system, and fast-discharge devices are used to quickly discharge the capacitors for rapid reconnection, ensuring continuous and stable power delivery in industrial and commercial applications.

VI. RESULTS & DISCUSSION

The proposed method are more effective in resolving PQ problems such voltage swell and sag. MATLAB platform is used verify the performance of proposed system. The attained outcomes are show that the proposed system has superiority to minimize the PQ issues with improved power factor.

Figure 7. Overall Simulation

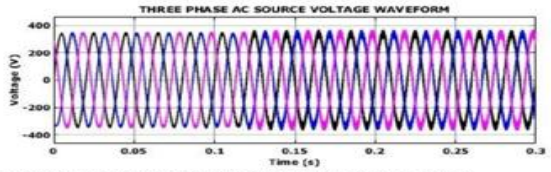


Figure 8. Source Voltage and Source Current Waveform

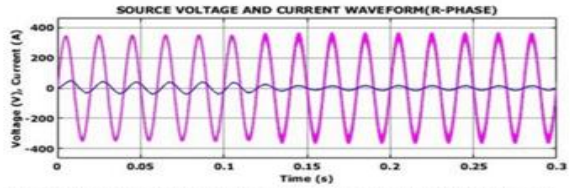


Figure 9. Source Voltage and Source Current in Phase Waveform

The Figure 15 demonstrates the V-I waveform of the PI controller. The figure 14 represent the input source voltage and current waveformof 3ϕ inverter. It is observed that the DSTATCOM can reduce voltage variance, balance load current harmonics, and meet reactive power requirements.

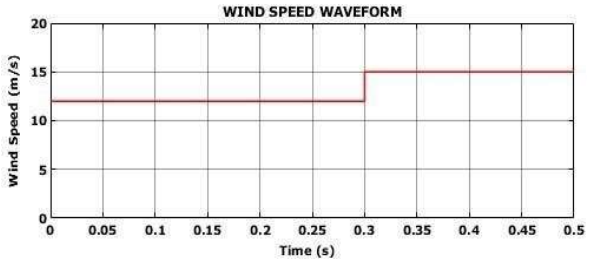


Figure 10. Wind Speed Waveform

The response of the change in wind speed is reflected in the generator. The figure 16 depict the disturbance in their magnitude

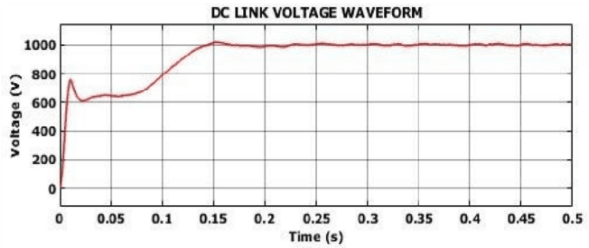
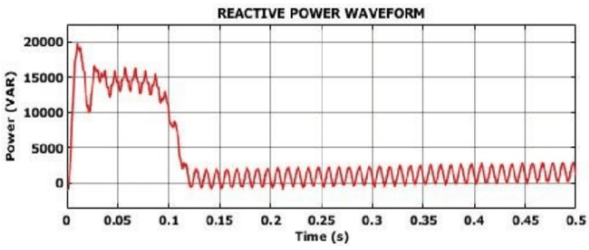


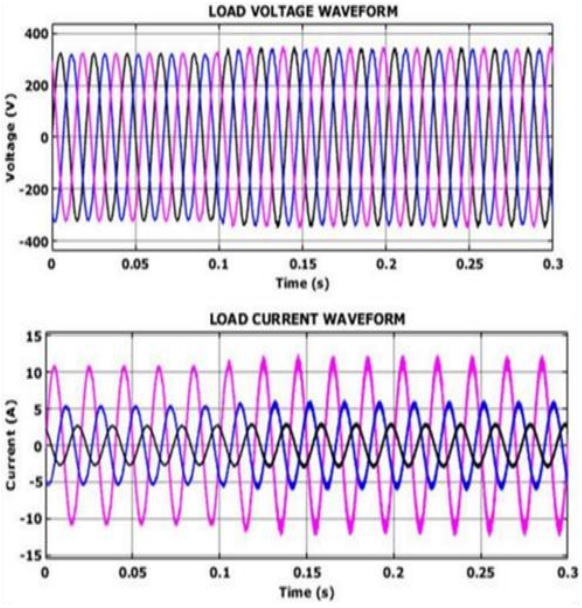
Figure 12. DC Link Voltage Waveform

The DC link exhibits an output voltage $1000V$ as shown in Figure 12 which is further maintained in the DC link.
Figure 13. Waveforms for Load Voltage and Load Current.

The figure 13. represent the load voltage and current waveform under voltage sag condition. It is observed that the distribution networks efficiently use D-STATCOM in conjunction with PI to improve power quality.

To generate the gate pulses required for the three-phase H-Bridge inverter, DQ theory has been utilized. By utilizing PI, Hysteresis PWM controller can provide gate pulses at its best output.





for the speed change occurred at 0.3 sec

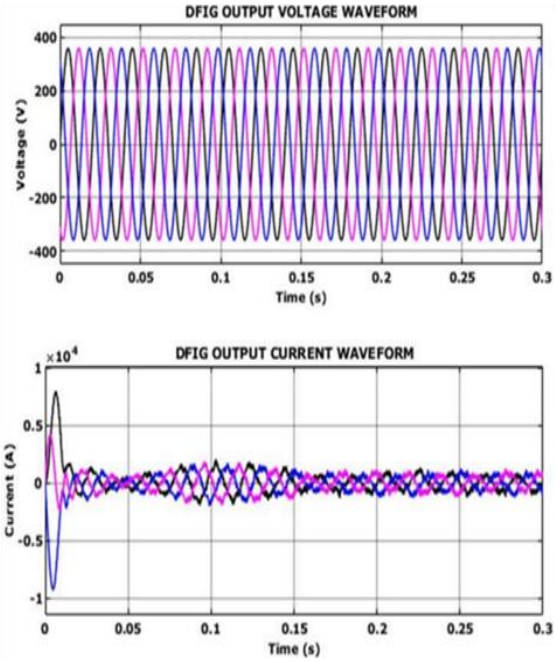


Figure 11. (A) DFIG output voltage waveform, (B) DFIG output current waveform

The waveforms for DFIG Output voltage and current waveforms are mentioned in Figure 17 (A) & (B). The output voltage from DFIG shows initial variations till 0.1_S and further a constant voltage of $1000V$ is maintained.

Figure 14. Real and Reactive Power Waveform

The figure 14. illustrates real and reactive power waveforms of the PI controller.

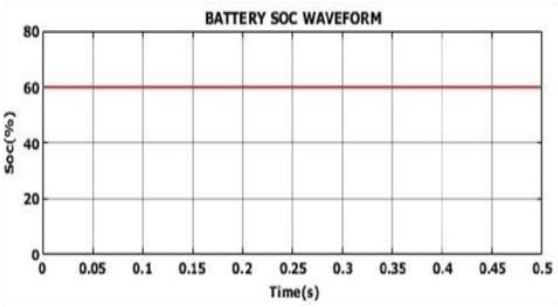


Figure 15. Battery SOC Waveform

The figure 21 represents the battery SOC waveform that battery is incorporated in DSTATCOM system as an energy storage system and also it shows that SOC is maintained at 60%.

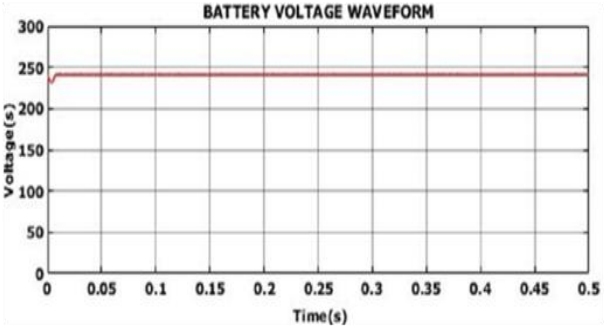


Figure 16. Battery Voltage Waveform

The figure 16 represents the battery voltage waveform that battery is incorporated in DSTATCOM system as an energy storage system

By controlling the bidirectional power flow, the PI controller ensures that the DC link capacitance remains stable, contributing to improved electrical power quality.

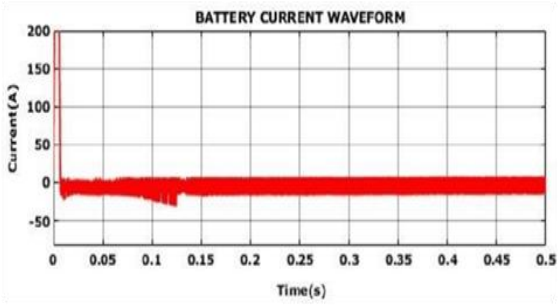


Figure 17. Battery Current Waveform

The figure 17. represents the battery voltage waveform that battery is incorporated in DSTATCOM system as an energy storage system

The bidirectional battery converter, controlled by the PI controller, works in conjunction with the DSTATCOM. The combined operation addresses harmonic distortions in the electrical distribution system, providing a comprehensive solution for power quality enhancement.

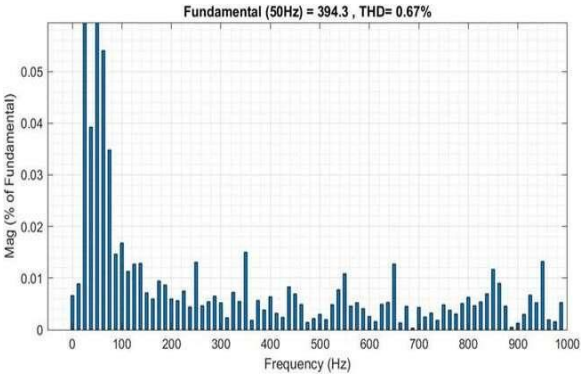


Figure 18. THD waveform for Load voltage

The figure 18. represent the THD waveform for grid VOLTAGE that shows due to the effective compensation of PQ disturbances, the power factor is maintained as unity. Thereby a lower THD value of 0.67% is obtained using the proposed technique.

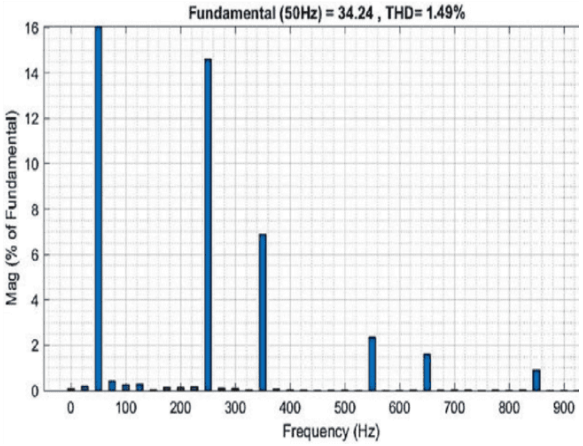


Figure 19. THD waveform for Load current

The figure 19. represent the THD waveform for load current that shows due to the effective compensation of PQ disturbances, the power factor is maintained as unity. Thereby a lower THD value of 1.49% is obtained using the proposed technique

VII.CONCLUSION

The integration of DSTATCOM, PI controller, and a bidirectional battery converter in a Wind Energy Conversion System (WECS) presents a comprehensive solution for mitigating harmonic distortions, voltage instability, and power quality issues. By incorporating DSTATCOM at the point of common coupling (PCC), the system effectively reduces harmonic distortions from both non-linear loads and the wind turbine system, ensuring a stable and high-quality power supply.The PI controller plays a crucial role in maintaining DClink voltage stability, allowing the DSTATCOM to inject accurate compensating currents for harmonic suppression and voltage regulation. Additionally, the bi-directional battery converter enhances the system's reliability by storing excess energy during peak wind conditions and supplying power during low wind conditions, ensuring continuous energy availability and improving overall grid performance.The proposed system effectively addresses major challenges associated with renewable energy integration, such as voltage fluctuations, power intermittency, and harmonic distortions. By ensuring smooth and stable operation, the system enhances the efficiency and reliability of wind power generation, making it a viable and sustainable solution for modern power grids.

Overall, the combination of DSTATCOM, PI controller, and battery storage in the WECS significantly enhances power quality, grid stability, and energy efficiency, making wind energy a more dependable and practical alternative for future power systems. This approach contributes to the broader goal of achieving sustainable energy solutions while maintaining a resilient and robust power grid infrastructure.

REFERENCES

[1] H. Akagi, "New trends in active filters for power conditioning," IEEE Transactions on Industry Applications, vol. 32, no. 6, pp. 1312-1322, Nov.-Dec. 1996.

[2] A. Ghosh and G. Ledwich, Power Quality Enhancement Using Custom Power Devices, Springer, 2002.

[3] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of power converters in AC microgrids," IEEE Transactions on Power

Electronics, vol. 27, no. 11, pp. 4734-4749, Nov. 2012.

[4] S. S. Murthy, B. Singh, P. Jain, and J. B. Dixit, "Grid integration issues of wind energy conversion systems: A review," IEEE Transactions on Industrial Electronics, vol. 64, no. 10, pp. 8357-8373, Oct. 2017.

[5] S. K. Khadem, M. Basu, and M. F. Conlon, "Power quality in grid connected renewable energy systems: Role of custom power devices," International Journal of Electrical Power & Energy Systems, vol. 39, no. 1, pp. 45-53, Jul. 2012.

[6] P. Verma, A. Singh, and B. Singh, "A comprehensive review on DSTATCOM configurations," IEEE Transactions on Power Electronics, vol. 36, no. 8, pp. 8655-8671, Aug. 2021.

[7] M. G. Molina and P. E. Mercado, "Control design and simulation of DSTATCOM with energy storage for power quality improvements," IEEE Transactions on Power Delivery, vol. 25, no. 2, pp. 1112-1122, Apr. 2010.

[8] T. T. Lie and W. Shu, "Battery energy storage system to stabilize wind farms and improve power quality," IEEE Power Engineering Review, vol. 21, no. 5, pp. 39-42, May 2001.

[9] R. A. Mastromauro, M. Liserre, and A. Dell'Aquila, "Control issues in single-stage photovoltaic systems: MPPT, current and voltage control," IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 3112-3121, Jul. 2008.

[10] B. Singh, P. Jayaprakash, and D. P. Kothari, "A Tconnected transformer and three-leg VSC based DSTATCOM for power quality improvement," IEEE Transactions on Power Electronics, vol. 23, no. 6, pp. 2710-2718, Nov. 2008.