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An Intelligent Mechanism for Enhancing Power Quality in Grid-Tied DFIG Based Wind Energy System Using Simplified Vector-Controlled Statcom

[1,2]Sreenivasulu Meda, [3]Bishnu Prasad Muni, [4]Kolli Ramesh Reddy

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Abstract: Recent years have witnessed substantial growth in harnessing wind energy for power generation, and this trend is anticipated to persist. However, the inherent intermittency of environmental conditions, coupled with the integration of wind power systems into the electrical-grid, poses challenges to power quality. These challenges encompass voltage fluctuations, power factor variations, and insufficient voltage regulation. The injection of wind-generated power into grid significantly impacts the overall efficacy of the distribution system. The Static Compensator (STATCOM) emerges as a promising solution to handle these challenges. This article introduces a simplified vector control method to enhance Power Quality (PQ) in grid-connected wind power plants by integrating a STATCOM. The proposed STATCOM is connected in parallel to a typical 25kV, 30km transmission line coupled to a 2MW Doubly Fed Induction Generator (DFIG). The central principle of this approach revolves around meeting the reactive power demands of both the load and the DFIG. The effectiveness of this proposed technique is assessed through simulations using MATLAB/Simulink software. The simulation outcomes offer valuable insights into the potential of this approach to alleviate PQ issues and enhance the operational efficiency of grid-connected wind energy systems.

Keywords: *Battery Energy Storage System (BESS), Doubly Fed Induction Generator (DFIG), Power Quality, Reactive Power, Static Compensator (STATCOM)*

1. Introduction

Due to the simultaneous growth of population and industrialization, the demand for power has surged recently, placing power generation on the brink of a significant challenge. The sources for generating electricity encompass both renewable and nonrenewable options. However, an ongoing reliance on nonrenewable sources for power generation has led to amplified global warming, air pollution, fossil fuel depletion, and rising costs. Consequently, transitioning towards renewable energy sources (RES) has become imperative for shaping the future energy landscape. Among various renewable sources, the wind energy generation system has emerged as a cost-effective and reliable option for producing electricity. The strategic deployment of wind turbines, synchronized with the grid, facilitates the seamless integration of renewables, thereby alleviating the environmental impact associated with power generation [1-3]. This inclination towards wind generation has seen remarkable growth, with individual wind turbine units capable of generating up to 5 MW. Wind power has gained prominence as a widely adopted renewable source in the power system domain. Projections indicate that the world's energy demand will reach 1791242 GW by 2030. To address this, the Indian government has set a goal to enhance its renewable energy capacity. By 2025, they plan to expand their wind energy capacity from 25 GW to 75 GW. However, a crucial issue lies in transmitting this generated power from remote locations to the consumption points [2].

Nevertheless, connecting wind turbines to the grid introduces an array of power quality issues, encompassing voltage disturbances, harmonic currents, fluctuations on frequency and power factor concerns [4]. Diverse techniques have been devised to tackle these power quality challenges within wind turbine power plants. One of the most effective remedies involves leveraging power electronics based Flexible Alternating Current Transmission System (FACTS) devices, renowned for their efficacy in enhancing power quality [5]. In cases where grid faults affect the wind farm based system, FACTS devices emerge as the optimal solution for preserving stability of larger power system. This is attributed to the capacity of FACTS devices to govern the circuit breaker of the wind turbine generator, ensuring its re-closure during normal operation after grid disruptions.

The consumption of reactive power plays a pivotal role in magnetizing wind turbine induction generators. To address the compensation of reactive power, FACTS

[1]*Research scholar, JNTUH, Hyderabad*
[2]*EEE Department, Vasavi College of Engineering, Hyderabad, India*
[3]*EEE Department, Vasavi College of Engineering, Hyderabad, India*
[4]*EEE Department, G. Narayanamma Institute of Technology and Science, Hyderabad, India*

devices have been harnessed that supply required reactive power and thus contributing to voltage stability during grid disturbances and adverse weather conditions impacting wind turbine output. Furthermore, FACTS devices offer vital support in terms of supplying reactive power to stabilize network voltage and enhance the system power factor [6-7]. Concerted research endeavours have been directed towards enhancing power quality in wind energy-based distribution systems. Lei and Shen [5] combined a STATCOM with a hybrid battery comprising LiFePO4 lithium and a supercapacitor to bolster power quality. This approach was applied WECS having squirrel cage rotor, and thereby effectively mitigating wind turbine fluctuations. Amen and Djamel [8] introduced the concept of employing a unified power flow controller (UPFC), recognized as most intricate and adaptable device within FACTS realm. UPFC serves the purpose of regulating power flow in both transmission and distribution networks. The application of UPFC, as discussed in References [9] and [9], entails a higher cost compared to other FACTS devices.

Another significant contribution is from She and Huang [10], harnessed the capabilities of the STATCOM for reactive power compensation within the required distribution system. However, this study highlighted STATCOM's limitation in efficiently compensating for active power without the integration of a battery energy storage system. DFIG stands out as a highly dependable option for electricity generation. Furthermore, multiple control methodologies, including field-oriented control (FOC) with conventional proportional-integral (PI) controllers, have been developed for DFIG in existing literature [11-12].

This research focuses on addressing the challenges that arise during the integration of wind turbines into the grid, along with subsequent power quality concerns. Some researchers have put forth the idea of adopting the Unified Power Flow Controller (UPFC) as a solution, while others have suggested the implementation of the Static VAR Compensator (SVC) to ameliorate quality of power. In essence, UPFC is primarily used to manage reactive power compensation in transmission lines handling voltages of higher levels. However, its feasibility for low voltage distribution systems is hindered by the substantial costs associated with it. Therefore, incorporating UPFC into distribution networks isn't a practical strategy for enhancing power quality [12].

SVC, as the pioneering device in FACTS family, has a historical role in enhancing power quality. Nonetheless, its popularity has waned due to its comparatively slow switching technology. Consequently, the utilization of SVC in contemporary applications has seen a decline.

The DFIG integration to the grid also causes disturbances, i.e. The primary established control strategies for DFIG encompass vector control (VC), involving the separate regulation of rotor currents using PI controllers, along with the Direct Torque or Direct Power Controlling methods [13,14]. The latter two approaches leverage hysteresis comparators to manage active and reactive powers for direct power whereas torque and flux direct torque. However, these techniques face power quality issues. These issues propagate into the grid and connected loads. Hence there is a necessity to have a suitable compensator for power quality and grid stability. Therefore, in this paper, a simplified Space Vector PWM (SVPWM) based STATCOM has been developed to control the reactive power, frequency variations and oscillations at the PCC of the transmission feeder during the operation with DFIG-based Wind Energy Conversion System (WECS) and grid simultaneously. The novelty of this research work is design of the simplified SVPWM based STATCOM connected at the transmission feeder where the DFIG based WECS and Grid is connected. The proposed STATCOM not only compensates the grid and WECS disturbances but also drive the load during the interruption of grid or WECS supply.

2. System Configuration

Figure 1 depicts the block diagram of the test system employed in this article. Grid modelling comprises a 25 kV, 500MVA, 50 Hz supply swing bus point, which supplies a 25kV distribution network. DFIG and BESS are connected to grid by 20MVA, 13.8kV/25kV transformer. The loads are connected to the 25kV line which comprises of both linear and nonlinear loads.

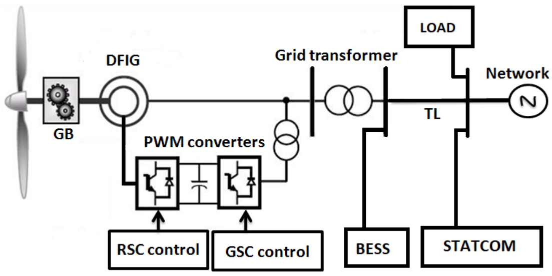


Fig. 1. Block diagram of System Configuration

The nominal-Π line configuration represents the 25kV line extending thirty kilometers. Additionally, the system has a DFIG based WECS. These wind turbines are equipped with a protection system that monitors various electrical parameters. Wind speed experiences a gradual rise from 8 meters per second to 14 meters per second at the 16-second mark, establishing a stable state. It is noteworthy that all examinations in this study are conducted post the system's attainment of a steady state, specifically after 16 seconds.

During normal operational conditions, the converter connected at the grid side of DFIG maintains DC link voltage at approximately 1200 V. To compensate for reactive power in the system, a shunt connected STATCOM is coupled in employed. The whole system is modeled and simulated in MATALB/Simulink environment.

A. DFIG Based WECS

This research delves into the application of DFIG in a wind farms. DFIG is acknowledged as an induction generator with wound rotor, where stator winding of the generator is grid connected operating at a consistent frequency. There is also a converter connected to the rotor that administers power in rotor winding. These two converters constitute a back-to-back configuration and are termed as rotor-side converter (RSC) and grid-side converter (GSC) . RSC autonomously controls stator reactive and active power, while GSC ensures a constant DC link voltage at DC link.

The DFIG enables power generation, particularly in scenarios where wind speeds oscillate between sub-synchronous as well as super-synchronous speeds, resulting in increased energy production. DFIG wind turbines have gained popularity, especially in extensive wind farms, due to their capability to deliver power within a consistent range of voltage and frequency, even as the rotor speed varies. Contemporary preference leans towards unity power factor operation as it offers rewards for active power generation. Reactive power generation is typically considered when there are suitable financial incentives, although the DFIG can independently control overall system power factor by adjusting its active as well as reactive power outputs.

However, the DFIG encounters challenges under grid faults. Its stator is directly connected to grid, leading to the possibility of unwanted currents that are high in magnitude and these are induced in windings of rotor during grid faults. In such cases, the safety system might block RSC. Furthermore, low terminal voltage during faults can lead to elevated DC-link capacitor voltages due to an imbalance in active power between RSC and GSC. Consequently, utilities often disconnect the DFIG promptly to safeguard its operation. To mitigate the impact of disturbances on grid side, such as 3-phase faults, abrupt load changes, and voltage fluctuations, reactive power compensation becomes essential. This is because DFIG-based wind farms might be unable to provide sufficient voltage support and reactive power, primarily due to their limited power capacity, for instance, in the case of a 9 MW capacity [15-16]. DFIG specifications are summarized in Table I.

Table I DFIG Parameters

Parameter	**Value**
Synchronism	1500 rev/min .
Rated power	2 MW.
Rated Stator voltage	690 V_{rms}.
Rated Stator current	1760 A_{rms}.
Rated Torque	12.7k-Nm.
Grid frequency (f_s)	50 Hz.
pairs poles(P)	2.
Rated rotor voltage	2070V_{rms}.
Stator resistance(R_s)	2.6 mΩ.
Stator Leakage inductance(L_{sl})	87 µH
Magnetizing inductance(L_m)	2.5 mH.
Rotor resistance ($R_{r'}$)	26.1 mΩ.
Rotor leakage inductance(L_{rl})	783µH.

Rotor resistance (R_r)ref to stator	2.9mΩ .
Rotor leakage inductance(L_{rl})ref to stator	87μH.
Stator inductance	2.587 mH
Rotor inductance	2.587 mH.

B. STATCOM

The STATCOM is classified as a component within the FACTS category. Its composition includes a Voltage Source Converter (VSC), a DC energy storage unit, and a coupling transformer that links to distribution circuit via another coupling transformer. This converter role is to transform the DC voltage stored in capacitor into 3-ϕ AC voltages. By modulating the converter voltage amplitude concerning the line bus voltage, VSC can generate or absorb required reactive power. This manipulation facilitates the controlled flow of current between STATCOM and distribution system. This capability empowers STATCOM to counteract voltage variations such as sag, swell, transient disturbance, as well as to support voltage regulation.

Precisely determining the rating of the STATCOM involves several factors, primarily guided by the reactive power requirement of the system for recovering from and enduring typical faults or disturbances while minimizing the likelihood of losing synchronization with grid. Ultimately, the financial analysis of the system has a key role in the ultimate determination of the STATCOM rating.

In this article, a simplified SVPWM based STATCOM has been modelled and developed, deemed adequate for safeguarding the wind farm against potential synchronization loss with the grid during various temporary disturbances.

3. Simplified SVPWM based STATCOM

The Voltage SVPWM technique is one among the efficient modulations for triggering Voltage Source Inverter (VSI) effectively [17-19]. In this article a simplified SVPWM developed to create triggering signals that align with the three-phase reference voltages, which are computed based on the load current. The illustrated approach for controlling STATCOM using the SVPWM method can be observed in Figure 2.

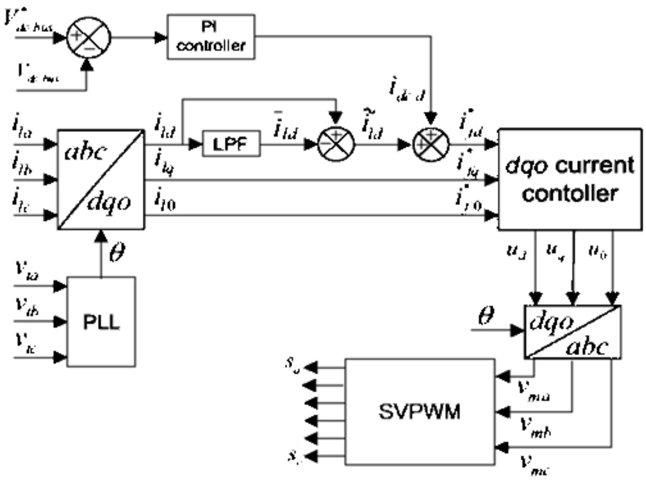


Fig. 2 Proposed simplified SVPWM control for STATCOM

The successful synthesis of voltage space vectors holds paramount importance within the SVPWM control methodology. The traditional approach employs the CLARKE transformation to convert reference voltages into d-q coordinates, facilitating the creation of reference vectors. By strategically selecting basic vectors with specific time durations, reference vectors will be computed. In this process, the sectors containing the reference vectors will be computed based on their respective phase angles and duration of basic vectors is established by computing both the phase angles and magnitudes of the reference vectors. These computations involve extensive irrational numbers as well as trigonometric functions, leading to a substantial computational load. This, in turn, could result in notable calculation inaccuracies, thereby compromising the overall performance of the STATCOM

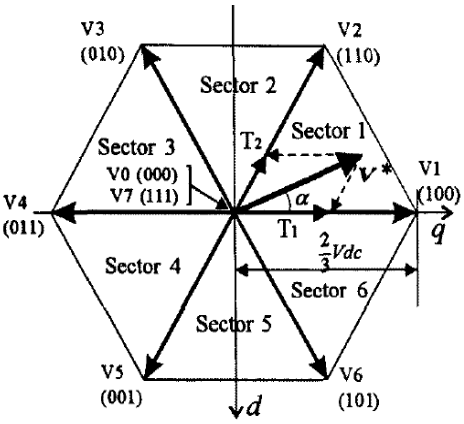


Fig. 3. VSI switching states Vectors

To tackle this challenge, a different strategy for SVPWM is proposed, building upon the effective voltage vector concept present in traditional SVPWM, yet introducing a fresh perspective. This method allows for the reconstruction of genuine gating times without the necessity of segmenting and recombining tasks. By employing the principles of d-q theory, reference voltages of all phases are obtained through the utilization of SRF (Synchronous Reference Frame) voltages. The diagram depicted in Figure 3 visually illustrates switching states of the SVPWM-based VSI. The six non-null states, which are denoted as active states, are mathematically expounded as space vectors in the ensuing manner.

$$\vec{V}_g = \frac{2}{3} V_{dc} e^{j(g-1)\frac{\pi}{3}} (g = 1......6) \quad (1)$$

To directly establish the switching times accurately from phase voltages, stationary d-q frame reference voltages used in the equation addressing effective times are being transformed into phase voltages using the following sequential procedure.

$$\begin{pmatrix} V_{as}^* \\ V_{bs}^* \\ V_{cs}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} V_q^* \\ V_d^* \end{pmatrix} \quad (2)$$

$$T_1 = \frac{\sqrt{3}.T_s}{V_{dc}} \left[\frac{\sqrt{3}}{2}.V_q^{s*} + \frac{1}{2}.V_d^{s*} \right]$$

Simplifying the equation (3) we get

$$= \frac{T_s}{V_{dc}} \left[V_{qs}^* + \frac{1}{2}.V_q^{s*} + \frac{\sqrt{3}}{2}.V_d^{s*} \right]$$

$$= \frac{T_s}{V_{dc}} V_{as}^* - \frac{T_s}{V_{dc}} V_{bs}^* = T_{as} - T_{bs}$$

$$T_2 = \frac{\sqrt{3}.T_s}{V_{dc}} \left[0.V_q^{s*} + 1.V_d^{s*} \right]$$

$$= \frac{T_s}{V_{dc}} \left[\left(-\frac{1}{2}.V_q^{s*} - \frac{\sqrt{3}}{2}.V_d^{s*} \right) - \left(-\frac{1}{2}.V_q^{s*} + \frac{\sqrt{3}}{2}.V_d^{s*} \right) \right]$$

(7)

$$= \frac{T_s}{V_{dc}} V_{bs}^* - \frac{T_s}{V_{dc}} V_{cs}^* = T_{bs} - T_{cs}$$

As outlined in the preceding equations, the effective time spans T_1 and T_2 are determined based on the gaps between timing durations T_{as}, T_{bs}, and T_{cs}, associated with their respective phase voltages. Similarly, when addressing remaining sectors, effective time spans are interchanged with phase voltage timings using aforementioned approach. This observation highlights that the effective time span, as established in traditional SVPWM, essentially signifies the distinction between two-time points allocated to corresponding phase voltage. Thus, irrespective of sector alignment of reference vector, time assignments designated to each phase voltage can be depicted as follows. In this article, these assignments are referred to as 'virtual timings' for phase voltages.

$$T_{as} = \frac{T_s}{V_{dc}}.V_{as}^* \quad (3)$$

$$T_{bs} = \frac{T_s}{V_{dc}}.V_{bs}^* \quad \left\{ \begin{array}{l} V_{as}^* + V_{bs}^* + V_{cs}^* = 0 \\ \therefore T_{as} + T_{bs} + T_{cs} = 0 \end{array} \right\}$$

$$T_{cs} = \frac{T_s}{V_{dc}}.V_{cs}^* \quad (4)$$

It's worth noting that the intervals between the 'imaginary timings' possess significance individually, and specific 'imaginary timings' could hold negative values contingent on the phase reference voltage. The computed pattern of imaginary switching pulses originates from equation (9). The effective duration, Teff, is precisely the timespan between Tmax and Tmin, encompassing the period during which the STATCOM receives the effective voltage. It's important to highlight that a solitary degree of freedom is present, affording the flexibility to position the effective time anywhere within a provided sampling interval.

An additional key observation is that the tangible switching pattern, can be conveniently generated by executing a shifting operation on 'imaginary timings' within time domain while retaining effective time. This procedure is portrayed in Figure 5. A zero-voltage instance in time is introduced to the theoretical phase voltage timings, symmetrically positioned at the initiation and conclusion of a single sampling period. This arrangement ensures the precise placement of the effective time at midpoint of sampling interval.

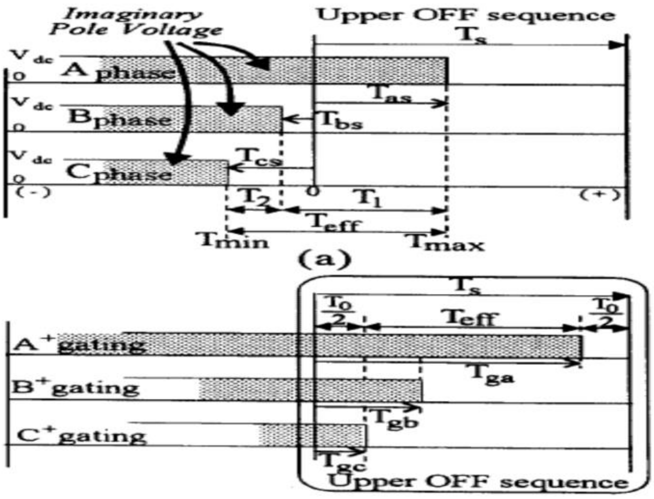


Fig. 4. Pattern of gate pulses for the proposed method (a) Imaginary switching pattern. (b) Actual switching pulse pattern for inverter.

Therefore, the actual switching times for STACOM arm can be derived as follows.

$$T_{ga} = T_{as} + T_{offset}$$
$$T_{gb} = T_{bs} + T_{offset}$$
$$T_{ga} = T_{cs} + T_{offset} \quad (10)$$

$$\begin{cases} T_{eff} = T_{\max} - T_{\min} \\ T_0 = T_s - T_{eff} \end{cases} \quad (11)$$

and,T_{min}+T_{offset}=T_0/2

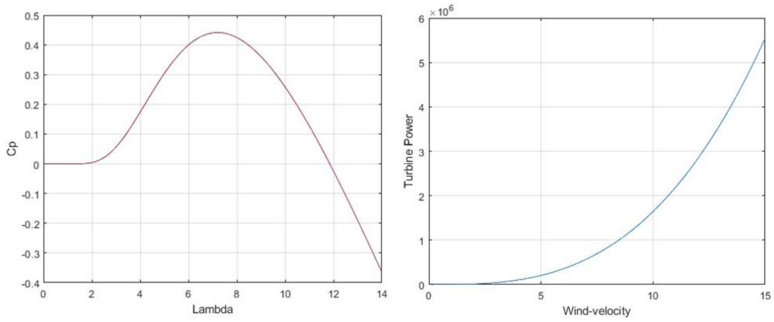
Therefore $T_{offset} = T_0/2 - T_{min}$

Consequently, the precise gating durations can be easily computed using equations (9), (10), and (11). The entire process of determining gating durations, as elucidated above, pertains to switching sequence during 'OFF'.

Nevertheless, during the 'ON' switching sequence case, actual switch times need to be adjusted by deducting the sampling time. This adaptation ensures the development of a symmetrical switching pulse spanning two sampling intervals. By introducing the concept of an effective time vector, actual switch times can now be directly deduced from SRF voltage. The execution of this innovative SVPWM approach demands only a straightforward 3-element segmenting algorithm. As a result, the computational burden for implementing proposed PWM technique can be significantly diminished compared to conventional SVPWM technique.

4. Simulation Results

The single line diagram shown in the Fig.1 is modelled and simulated in MATLAB/Simulink environment. The DFIG turbine responses are simulated and the results are illustrated in Fig. 5.



(a) Lambda vs C_p (b) Wind velocity vs P_t

***Fig. 5** Turbine Response*

The DFIG voltage and the currents using SVPWM control at the feeding point are shown in Fig.6. The variations are due the fluctuations of DFIG during the starting operation.

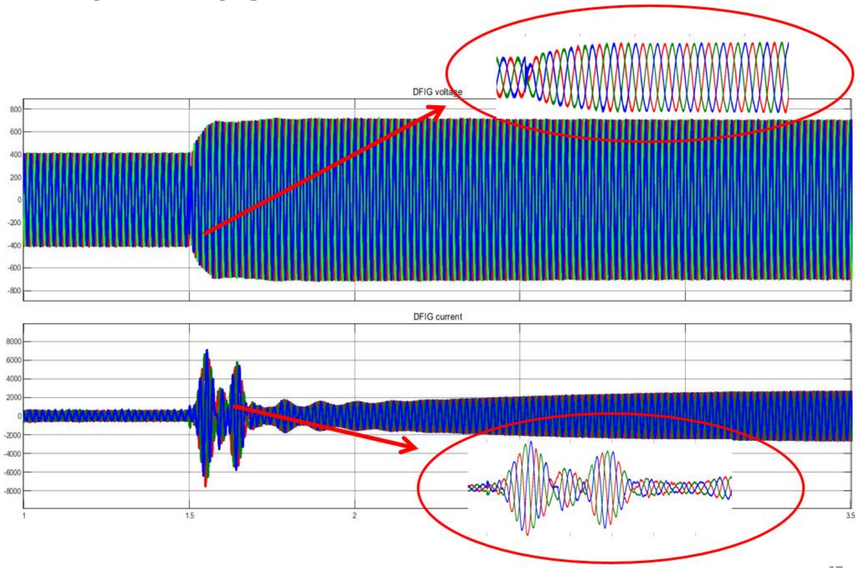


Fig. 6. DIFG output voltages and currents

The DFIG generated voltages have been injected to the 25kV grid through 13.8/25kV step-up transformer and the 25kV grid side voltages are depicted in Fig. 7.

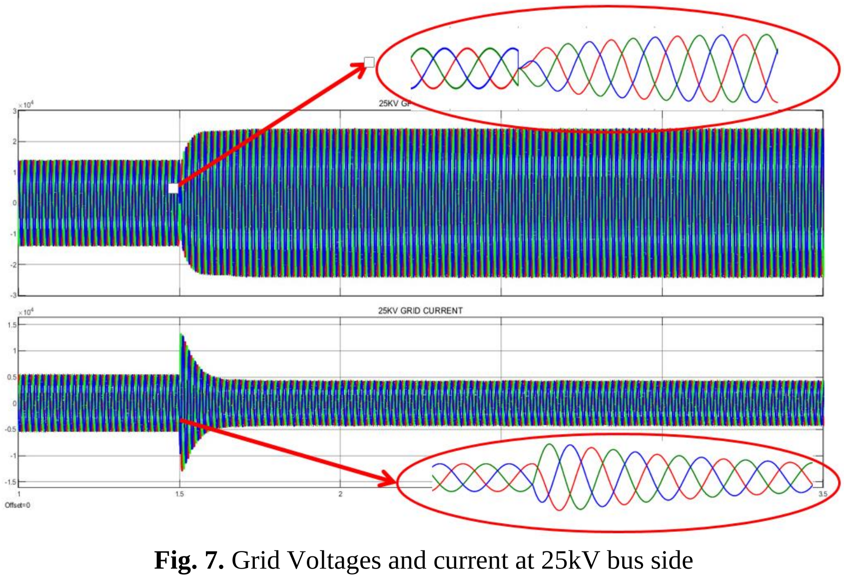


Fig. 7. Grid Voltages and current at 25kV bus side

The integration of the DFIG to the 25kV grid will reduce the grid consumption of the loads. However there is an issue of reactive power. The active and reactive power profiles at the 25kV grid have been illustrated in Fig. 8.

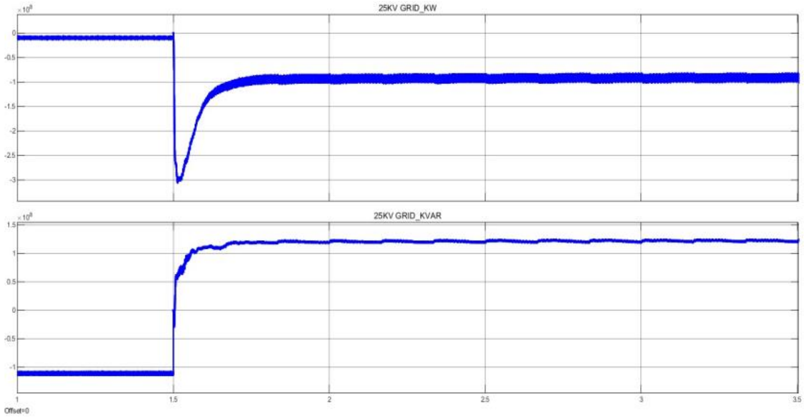


Fig. 8. Grid side Active and reactive power profiles

The load side voltages and currents are depicted in Fig. 9. and the active and reactive power profiles are shown in Fig. 10.

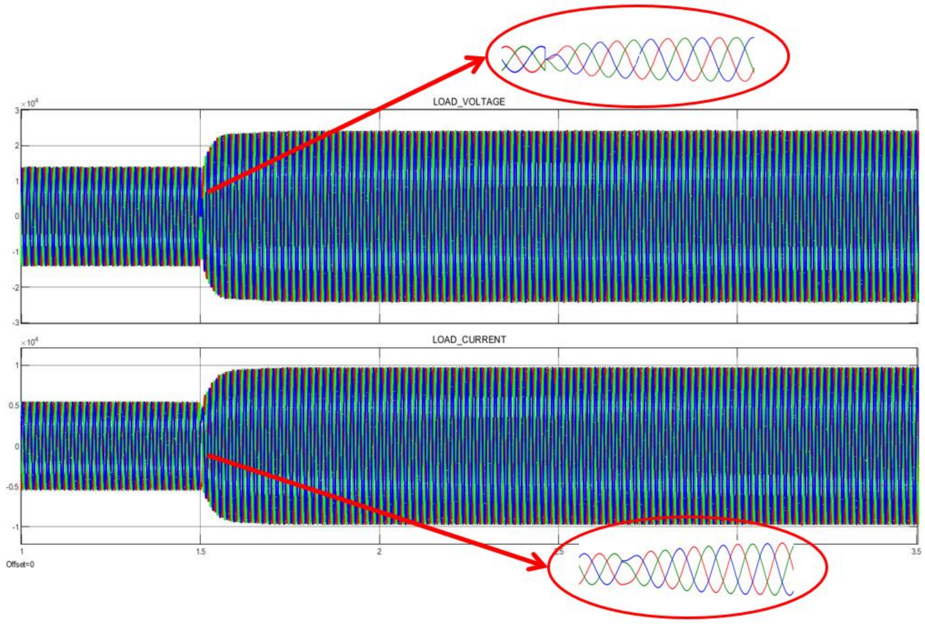


Fig. 9. Load side voltages and currents

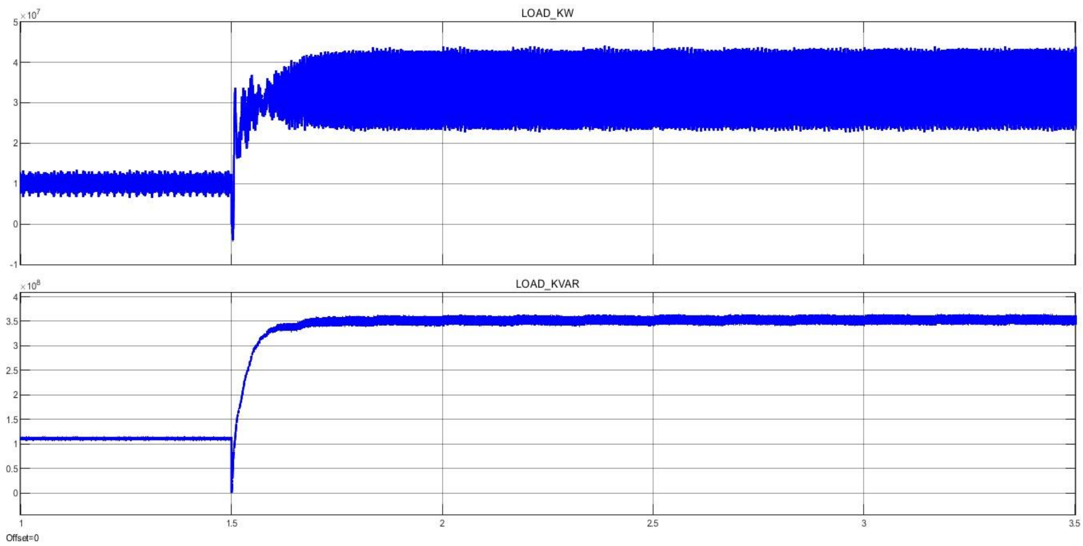


Fig. 10. Active and reactive profile at load

The frequency response at 25kV grid point and the DFIG injection point are illustrated in Fig. 11. The STATCOM has been turned on after 1.5 secs and the load frequency is maintained within the acceptable limits.

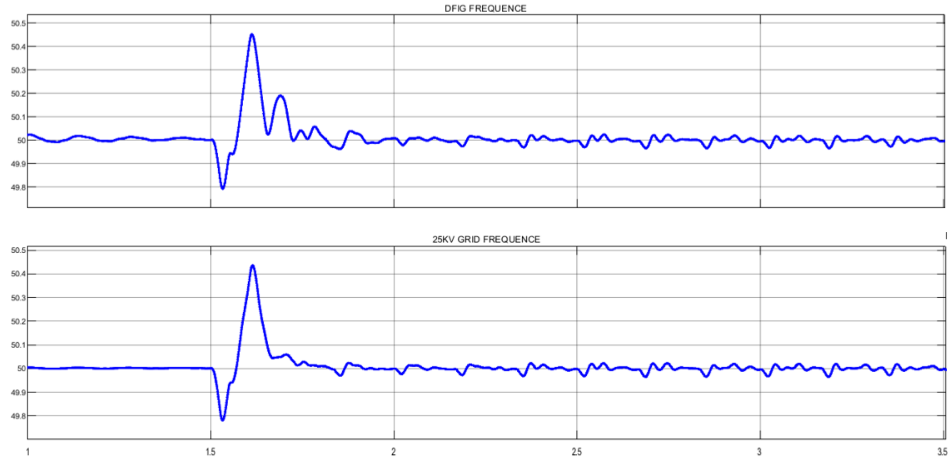


Fig. 11. Frequency Responses

The Battery Energy storage system responses are depicted in Fig. 12.

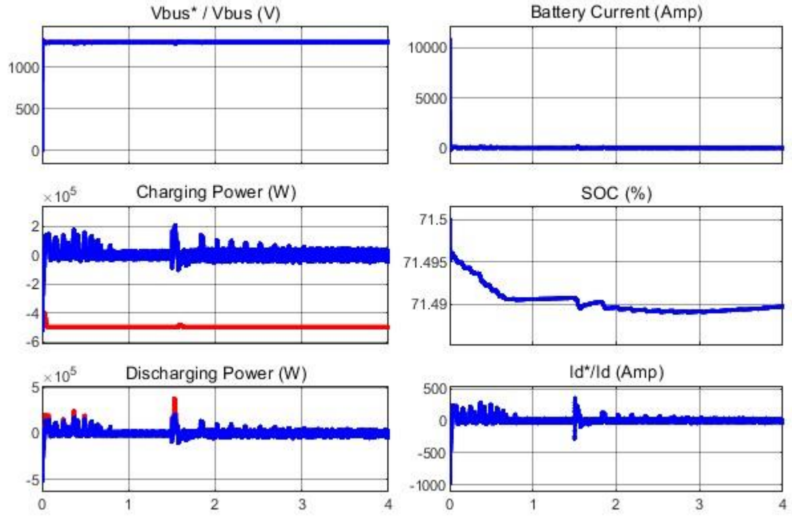


Fig. 12. Battery Energy Storage response

Among various techniques, compensation of reactive power stands out as the best efficient approach for seamlessly integrating a DFIG based WECS with grid under instances of grid perturbations. Within the research scope, both STATCOM and Battery Energy Storage System are interconnected to the system with the intention of enhancing system behaviour. Enhancements in power quality become evident at the point of common coupling when the Simplified SVPWM based controller is in the activated state. The conducted assessments of the suggested approach reveal not only the power quality enhancement aspect but also its capacity to consistently sustain the load through energy storage using batteries.

5. Conclusions

This article introduces a simplified SVPWM method based STATCOM for enhancing the power quality of grid-connected wind energy systems. The paper presents the enhancing the grid behavior and power quality improvement using STATCOM. The STATCOM plays a crucial role in addressing issues voltage fluctuations, and meeting the reactive power demands of both loads and wind turbines. As wind power plants lack adequate reactive power, an external compensatory device is employed. STATCOM proves to be a significant tool for rectifying reactive power imbalances. However, STATCOM's control over active power is limited. To achieve enhanced control over real power, a Battery Energy Storage System (BESS) is introduced. The research concludes that by combining STATCOM and BESS, substantial improvements in power quality within wind power distribution networks can be effectively achieved.

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