Performance Investigation of Grid Connected DFIG Based Wind Energy System

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Abstract

The paper realizes the investigation of control operation and performance in grid integrated Doubly Fed Induction Generator (DFIG) system. Battery Energy Storage (BES), coupled at the DC link of DFIG is controlled by bidirectional power converter to compensate for utility/load demand. Rotor side converter (RSC) uses tip-speed ratio maximum power point tracking (MPPT) algorithm to harness maximum power from the wind turbine. An adjustable step size least mean square (LMS) based adaptive control is implemented for the grid side converter (GSC) of DFIG system that besides managing power balance at the Point of Common Coupling (PCC) also addresses power quality issues encountered in the system due to the presence of non-linear, unbalanced loads. The step size changes with the mean square error enabling the adaptive filter to detect system changes while producing a small steady state error. Performance of the system is exhibited and validated through simulated results in a developed Simulink model for steady state and dynamic

conditions. The Total Harmonic Distortion (THD) in grid currents and voltage is within IEEE 519 standard guidelines.

1 Introduction

The electric power generation has emanated as the primary application of wind energy across the globe. Economic growth, technological breakthroughs, expanding population and environmental concerns have all contributed to a considerable increase in wind power penetration. Consequently, the control of wind energy conversion systems to endorse system stability and power quality in the connected system is an absolute necessity. Wind turbines with variable speeds have come a long way in recent years. The variable speed wind turbines employing Doubly Fed Induction Generator (DFIG) topology are gaining popularity with advanced power electronics and control systems due to increased energy capture, higher stability, decoupled control of active and reactive power, lower mechanical stresses and enhanced power quality [1–3]. The stochastic nature of wind energy source, however, continues to pose issues for smooth grid integration and in this aspect, energy storage is a potential option. The incorporation of energy storage emphasises the efficient use of wind energy for high-quality and reliable electricity [4, 5].

Integrating an energy storage device with a wind energy system to reduce wind generation uncertainty will improve grid dependability and security. Various energy storage systems (ESS) have been used with DFIG-based wind energy systems based on their operating suitability over various time spans. The flywheel energy storage offers a boost of power in the event of low wind generation and stores surplus power during high wind generation with a fuzzy logic-based supervisor to deal with uncertain wind power [6]. Supercapacitor energy storage has been employed to successfully minimise the issue of power fluctuations and improve FRT capability of DFIG system [7]. The author in [8] focuses on a new SMES with fault current limitation function (SMES-FCL) setup and optimization technique for boosting LVRT capabilities and mitigating power fluctuation of DFIG wind energy system. However, BES is still gaining traction as one of the key solutions for integrating large scale of wind energy into the power systems both in low and high power applications. As batteries are expensive and considerably

increase system expenditure and maintenance, a control approach is critical for optimising BES utilisation and, as a result, lowering its capacity and investment [9, 10]. The vector control strategy finds wide application in control of DFIG converters. S Puchalapalli [11], Naidu [12] and Tourou [13] used BES for DFIG systems to achieve grid power smoothing and voltage and frequency regulation for standalone operation. However, the BES was integrated to the DC link without any control. Many conventional control schemes operating on instantaneous reactive power theory [14], enhanced phase locked loop [15], synchronous reference frame theory [16], reduced-order multiple integrator (ROMI) [17] have been utilised for the control of grid interfaced converters.

The vector control approach is mainly used in DFIG wind energy systems to execute converter control as reported in [18–21]. Contrary to vector control strategy, adaptive control has rarely been investigated for DFIG systems particularly in the context of power quality enhancement. In such a control, the error between the desired output and output obtained is minimized based on the mean square error. The error as a cost function is optimised to the smallest possible value by an algorithm that continuously alter its weights until the intended output is obtained [22]. In this paper, a grid connected DFIG system along BES has been modelled to examine the control and operation of the system for grid power regulation and power quality mitigation challenges. The main objectives of the paper are as follows:

(i) Maximize power capture from the DFIG wind energy system under variable wind speed employing MPPT algorithm.
(ii) Implementation of variable step size least mean square (LMS) based adaptive control for GSC of DFIG system to maintain power balance in the system and address power quality issues emerging from harmonics, unbalanced load and other grid disturbances.
(iii) Integration of BES at the DC link of the system that acts as a standby supply to compensate for the utility/load demand.
(iv) To evaluate controller performance under steady state condition, variable wind speed, non-linear unbalanced loads and during other dynamic conditions.

2 System Description

The schematic diagram of the proposed grid tied DFIG wind energy system is represented in Figure 1. The system constitutes of the wind turbine connected to generator shaft through a gearbox. The stator directly connects with the
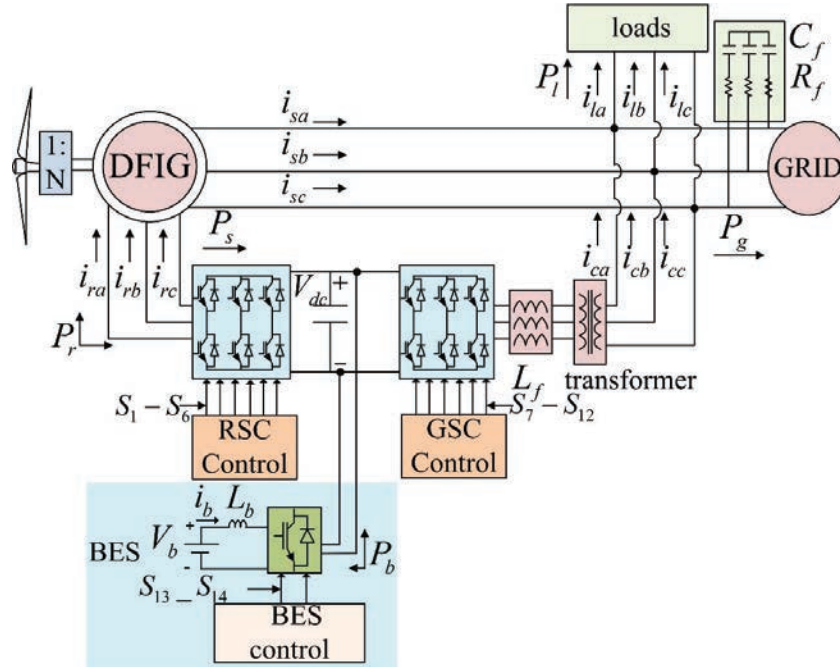
Figure 1 Schematic diagram of proposed grid tied DFIG system.

Table 1 Specifications of proposed grid connected DFIG wind turbine

Parameter	Rating	Parameter	Rating
Wind turbine	11 kW	Transformer	10 kVA
Rotor diameter	4.34 m	Interfacing inductors L_f	1.135 mH
Air density	1.1514 kg/m^3	Ripple filter	$R_f = 5\,\Omega$, $C_f = 15\,\mu F$
Gear-box ratio	16.84	DC link voltage	240 V
Rated wind speed	9 m/s	Battery voltage V_b	180 V
DFIG	8.75 kW	Battery capacity	360 Ah

system of loads and the power grid while as machine rotor is assessed through power electronic converters that process about 25–30% of the rated power. A bidirectional DC-DC converter connects energy storage to the DC link of DFIG converters, keeping its operation within safe limits. A three phase transformer steps up the low rating voltage of converter system to the line voltage for operational compatibility of the system. Three phase interfacing inductor (L_f) and ripple filter (C_f, R_f) takes the edge of current and voltage ripples in the system. The design of each component of the system including wind turbine is reported in [23–25]. The ratings of various components of the proposed system is given in Table 1 above.

2.1 Wind Turbine Rating

The following equation determines the amount of power that can be extracted from the wind energy [26].

$$P_m = 0.5\rho\pi r^2 V_w^3 C_p(\lambda, \beta) \tag{1}$$

where V_w represents wind speed in (m/s), ρ is air specific density in (kg/m^3), r is the radius of turbine in (m) and C_p is the power coefficient of the turbine. The coefficient of performance C_p is a function of tip speed ratio λ and blade pitch angle β (deg). C_p is determined by the following set of equations.

$$C_p = [(C_2/\lambda_j) - C_3\beta - C_4\beta^{C_7} - C_5]C_1 e^{C_6/\lambda_j} \tag{2}$$

$$1/\lambda_j = 1/(\lambda + 0.08\beta) - 0.035/(\beta^3 + 1) \tag{3}$$

The pitch angle β in this study has been taken as zero degree.

3 Control Scheme

The entire control operation of the presented grid integrated DFIG wind energy conversion system is realized by the independent control of three different power electronic converters. Each converter is dedicated to its own control objectives for the rotor side, grid side and battery energy storage system. The detail of each control is presented in the following sub-sections.

3.1 RSC Control

RSC control is allocated to active and reactive power generation of DFIG machine. The vector control based on d-q reference frame with stator voltage positioned along d axis is used to execute the desired control by generating d and q axis rotor current references appropriately. The TSR MPPT algorithm is utilised to extract optimum power from the wind turbine. From the sensed wind speed and specified turbine parameters reference; a rotor speed ω_{r_ref} is generated that is compared with sensed rotor speed ω_r to build direct axis rotor reference I_{dr}^* after fixing the error by PI controller. The quadrature axis rotor current reference I_{qr}^* is generated from DFIG parameters that considers reactive power requirement for machine magnetization. The rotor current references in d-q frame are transformed into natural frame references with the aid of transformation angle as shown in Figure 2. The rotor current references i_{rabc}^* and sensed rotor currents i_{rabc} are compared and the pulses for RSC are generated by the hysteresis current controller.
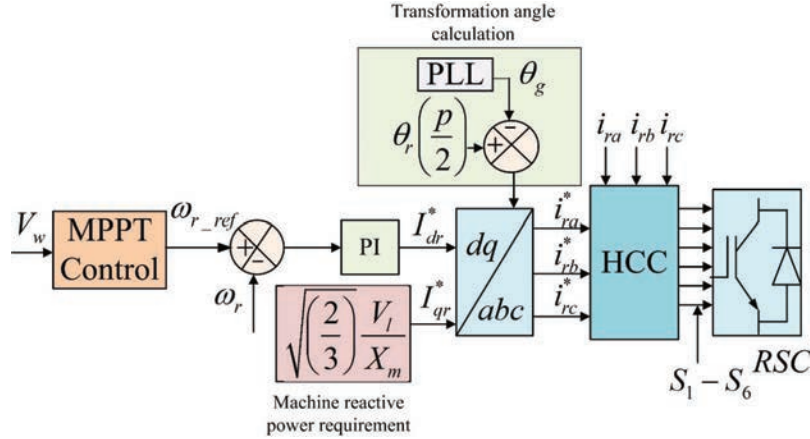
Figure 2   RSC control implementation.

3.2 GSC Control

The role of GSC control in grid integrated DFIG system is multifunctional. The controller in addition of regulating wind power to the connected network, addresses power quality issues prevalent in the system due to the presence of non-linear loads, reactive power requirement of loads, load unbalance and other grid disturbances. For this purpose, a single layer variable step size least mean square based adaptive filter has been employed for grid interfaced converter of DFIG system where the active load component weight is derived as shown in Figure 3 below. The active fundamental weight of load currents for each phase are calculated by following set of equations.

$$w_{ilabc}(k+1) = w_{ilabc}(k) + \beta \times \tau_{al}(k) \times u_{iabc}(k) \times e_{ilabc}(k) \qquad (4)$$

$$e_{ilabc}(k) = i_{labc}(k) - u_{iabc}(k) \times w_{ilabc}(k) \qquad (5)$$

$$\tau_{al}(k+1) = \alpha \times \tau_{al}(k) + \gamma^2 \times e_{ilabc}(k) \qquad (6)$$

where $w_{ilabc}(k)$, $u_{iabc}(k)$, $e_{ilabc}(k)$, $i_{labc}(k)$ and $t_{al}(k)$ are the weight, in-phase unit vector templates, adaptive error, desired load components and step-size of each phase. α, β and γ are the constant values used for the determination of step size τ_{al} parameter adjusted suitably to obtain balance between rate of convergence and response of adaptive control.

The DFIG wind feed-forward term is estimated as.

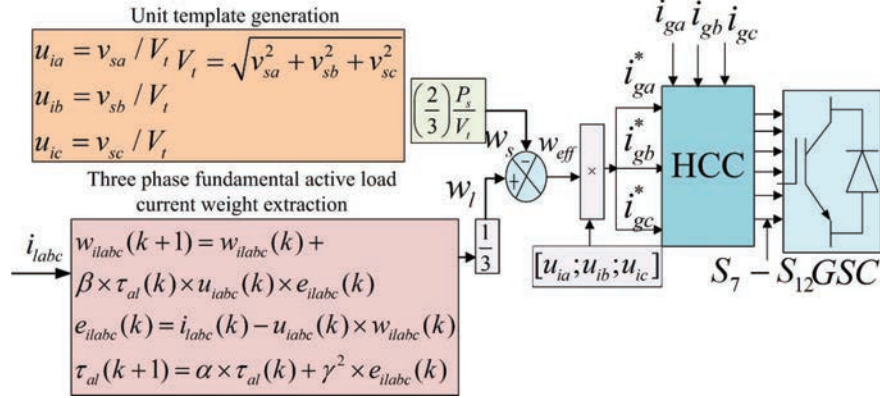$$w_s = \left(\frac{2}{3}\right)\frac{P_s}{V_t} \qquad (7)$$

Figure 3 GSC control implementation.

where P_s is the power generated by DFIG machine and V_t is the magnitude of terminal voltage.

The effective weight concerning active reference component is given as.

$$w_{eff} = w_l - w_s; \; w_l = \frac{(w_{ila} + w_{ilb} + w_{ilc})}{3} \tag{8}$$

where w_l is the weight of the load current components on average. The three phase active grid current reference are further calculated as.

$$\begin{aligned}
i^*_{ga} &= w_{eff} \times u_{ia} \\
i^*_{gb} &= w_{eff} \times u_{ib} \\
i^*_{gc} &= w_{eff} \times u_{ic}
\end{aligned} \tag{9}$$

The active grid current references i^*_{gabc} are compared with sensed grid currents i_{gabc} and the gating pulses for GSC are generated by the hysteresis current controller.

3.3 Battery Energy Storage Control

BES system constitutes of battery energy storage with bidirectional DC-DC converter. Depending on the operation of switches, the bidirectional converter can work in two modes: buck and boost. The converter comprises of an inductor L_b and two IGBT switches S_{13} and S_{14} with anti-parallel diodes D_1 and D_2 respectively as shown in Figure 4. The duty cycle of the switches is controlled for regulating amount of battery power exchange with the grid. The battery operation is controlled by employing a control loop that regulates
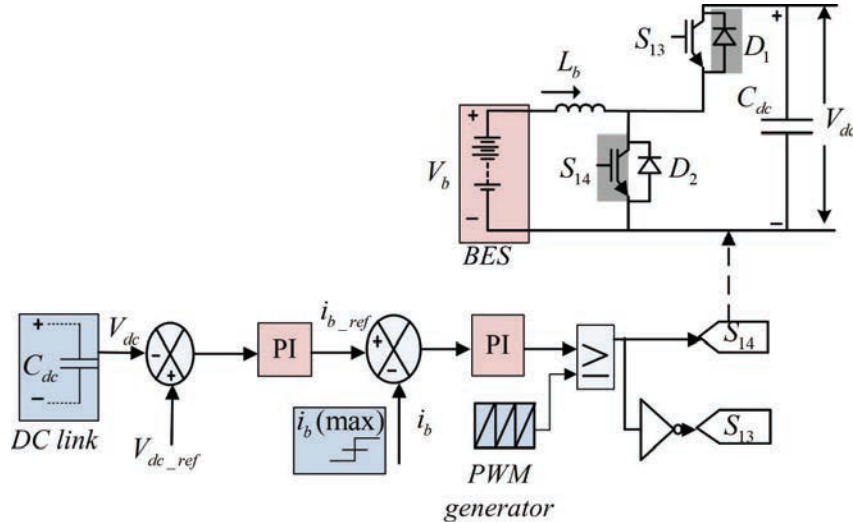
Figure 4   Bidirectional buck-boost control for BES.

the DC link voltage at a specified value. The reference V_{dc_ref} and measured DC link voltage V_{dc} is compared; the resulting error is processed by a PI controller that determines the battery reference current i_{b_ref}. In the inner control loop, i_{b_ref} is compared with measured battery current i_b and the PI controller outputs reference signal of duty cycle which is compared with PWM generator to generate pulses for the converter switches. In cases, when battery is required to release energy, the bidirectional converter operates in boost mode with switch S_{14} and diode D_1 functional thereby discharging the battery. In cases, when the generation from the wind energy source is more than that required to fulfil the demand the surplus power is diverted to the storage and henceforth the converter operates in buck mode with switch S_{13} and diode D_2 functional there by battery charges. However, an additional limiter block is introduced in the control that operates the battery within safe limits to ensure its optimal performance. The peak battery current occurs when DFIG energy source generates maximum power with zero energy demand on AC side.

4 Results and Discussion

The proposed grid tied DFIG system along with associated control schemes for RSC, GSC and BES is designed in MATLAB software and the
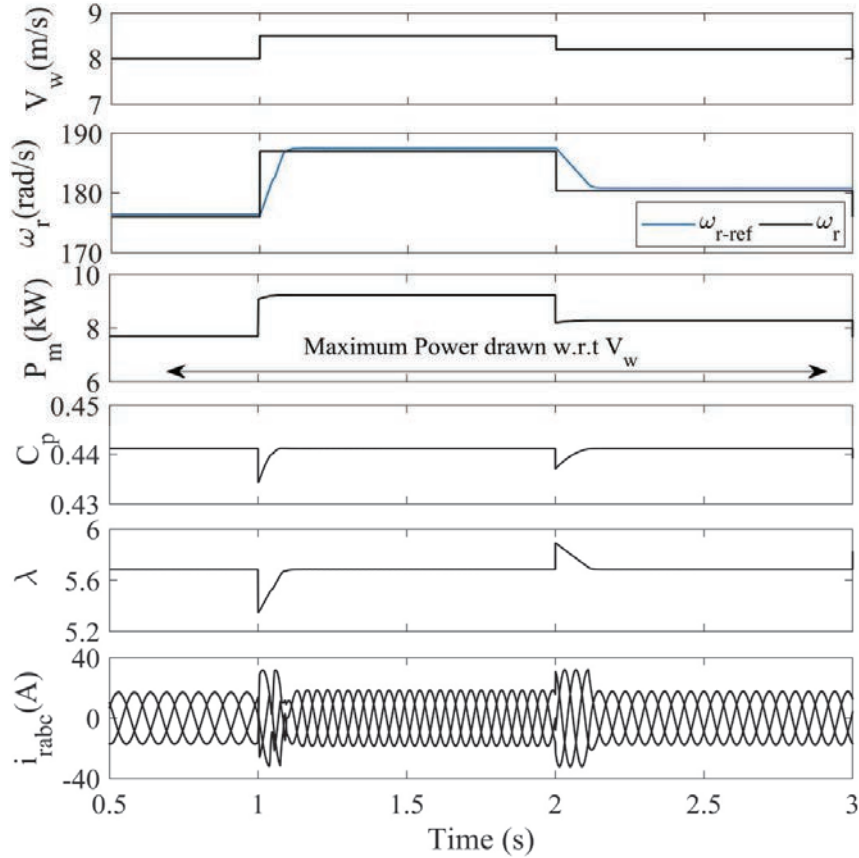
Figure 5 MPPT operation of grid tied DFIG system.

performance of the system is evaluated for different operating conditions as explained below.

4.1 MPPT Algorithm Operation of DFIG System

Figure 5 shows that the MPPT algorithm used in the RSC control of the DFIG system provides a suitable response. The rotor speed ω_r of the machine properly tracks the reference speed ω_{r_ref} in accordance with the changing wind profile V_w. The amount of power produced by wind turbine P_m is at its maximum value depending on the variable speed. The power coefficient C_p and tip speed ratio λ of the turbine are at their optimal values irrespective of V_w variation. The frequency of rotor i_{rabc} is also seen changing with V_w

that consequently maintains DFIG output at constant frequency as that of connected grid.

4.2 Steady State Operation of DFIG System

At a rated wind speed of 9 m/s, the active power P_m generated by the DFIG wind turbine is around 11 kW with the wind energy source operating at maximum power point (MPP). The grid currents i_{gabc}, stator voltage V_{sa}, stator currents i_{sabc} and rotor currents i_{rabc} are all sinusoidal and balanced as seen in Figure 6(a). The response of grid P_g and battery power P_b is
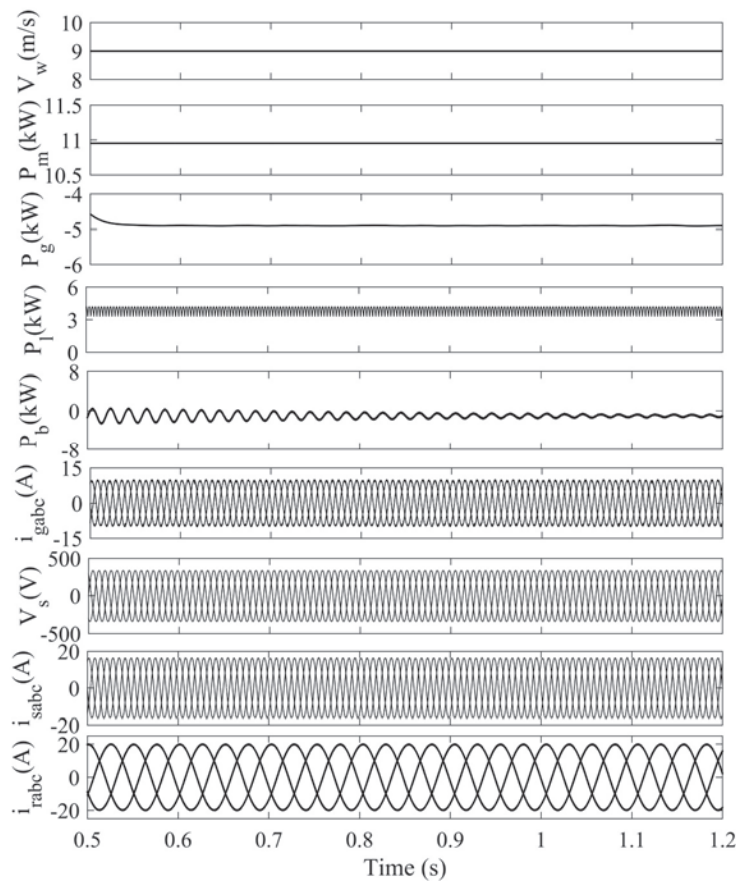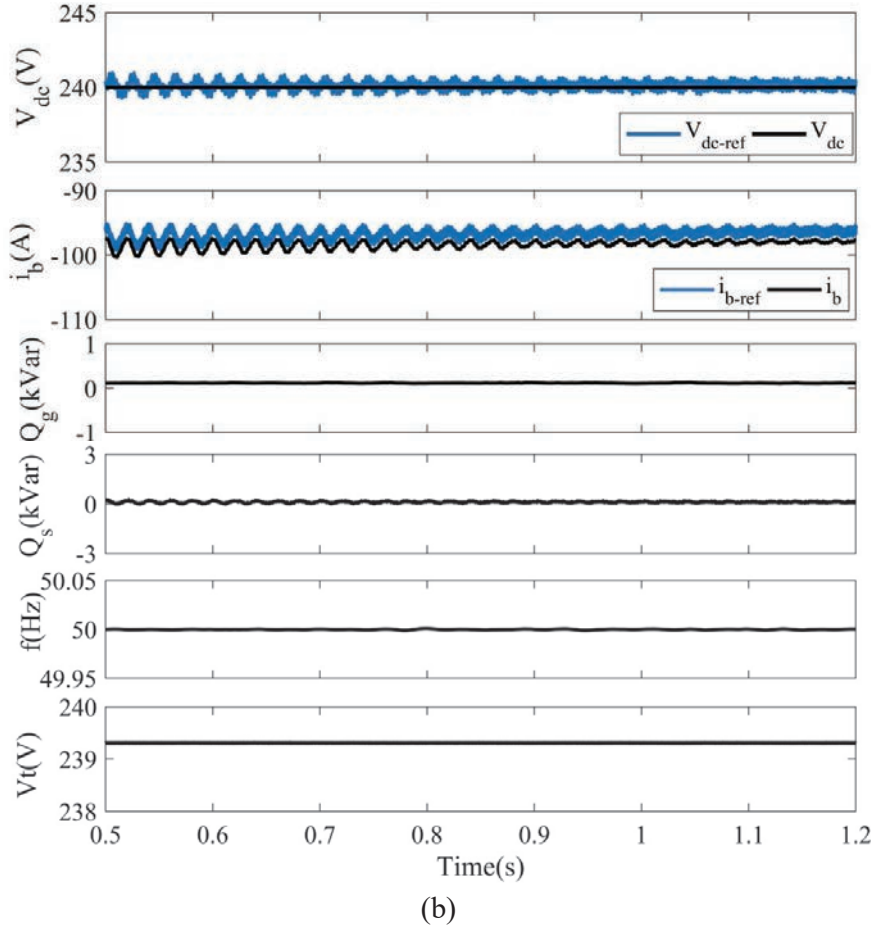

(a)

Figure 6 Continued

Figure 6   Performance of system at steady state (a) V_w, P_m, P_g, P_l, P_b, i_{gabc}, V_{sa}, i_{sabc} and i_{rabc} (b) V_{dc}, i_b, Q_g, Q_s, f and V_t.

also shown in figure. The system after feeding a load of $P_l = 4$ kW directs remaining power to the grid. The bidirectional converter control for the BES also depicts satisfactory performance by maintaining DC link voltage V_{dc} at a predefined value of 240 V and tracking battery reference current i_{b_ref} as shown in Figure 6(b). As illustrated in Figure 6, the system maintains unity power factor on both the grid and stator sides, with negligible reactive power consumption at both ends ($Q_s = Q_g = 0$). The terminal voltage V_t and frequency f at the connected grid are also maintained at their respective rated values as seen in figure.

4.3 System Operation During Wind Speed Variation

The performance of DFIG system under varying wind speed is shown in Figure 7(a–b). The wind turbine is also subjected to a step wind speed changeat the instant of t = 1 s. The active power output P_m of the DFIG changes with variable V_w. However, irrespective of wind power generation, a fixed amount of power P_g is supplied to the grid as shown in Figure 7(a). The battery in this case compensates for any deviation in power to be supplied to the grid. BES either charges or discharges depending on the generation and demand from the grid and fed loads. The response of grid currents i_{gabc}, stator voltage V_{sa}, stator currents i_{sabc} and rotor currents i_{rabc} with variable V_w is also shown in figure. DC link voltage controller although experiences
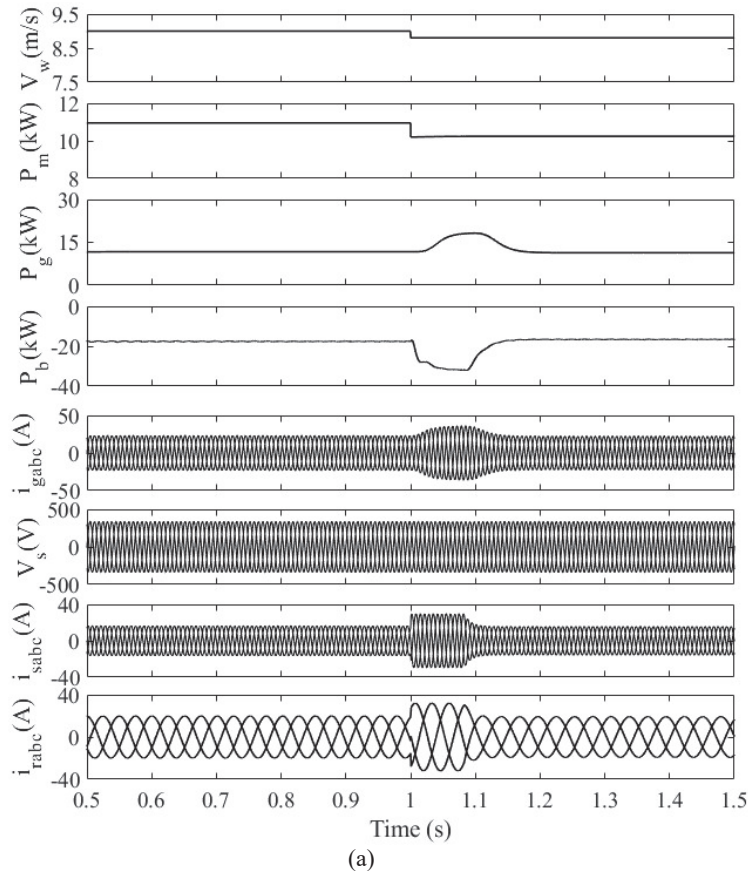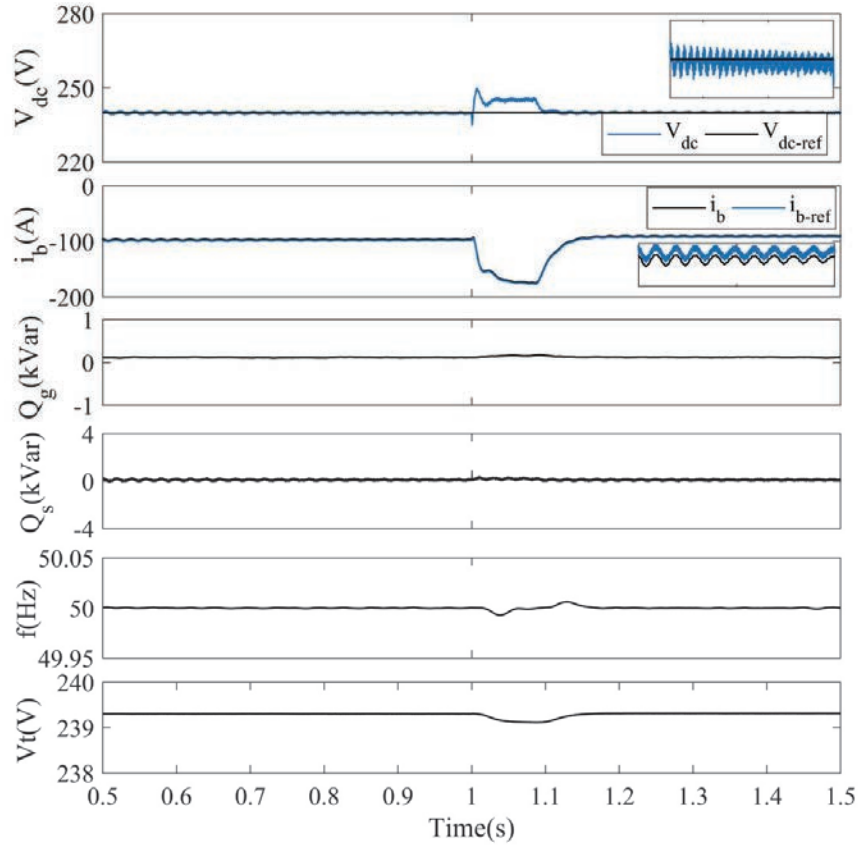

(a)

Figure 7   Continued

Figure 7   Performance of system at steady state (a) V_w, P_m, P_g, P_b, i_{gabc}, V_{sa}, i_{sabc} and i_{rabc} (b) V_{dc}, i_b, Q_g, Q_s, f and V_t.

transients due to sudden change in V_w but following that it again attains stable steady state value as shown in Figure 7(b). Unity power factor operation is maintained throughout the variation as seen in figure. The DFIG operates at different speeds and irrespective of this variation, the terminal voltage and frequency of the system remains equal to that of connected grid.

## 4.4 System Operation at Unbalanced Load

At the time instant from t $= 0.6$ s to t $= 0.7$ s, phase a of load is disconnected to create unbalance; such loads draw unbalanced currents from the source

and affect system stability. GSC control compensates for the unbalanced load by supplying converter currents i_{cabc} that result in sinusoidal and balanced currents being drawn from the source as depicted in Figure 8(a). Also due to the presence of non-linear loads, harmonics are introduced in source i_{sabc} and grid currents i_{gabc} that can deteriorate system performance considerably. The presented variable step LMS based adaptive control executed for the GSC compensates for these harmonics and reduces total harmonic distortion (THD) in the currents. The response of V_{sabc}, i_{gabc}, i_{sabc}, load currents i_{labc}, converter currents i_{cabc} and rotor currents i_{rabc} during unbalanced operation is shown in figure. GSC also considers reactive power requirement of load.
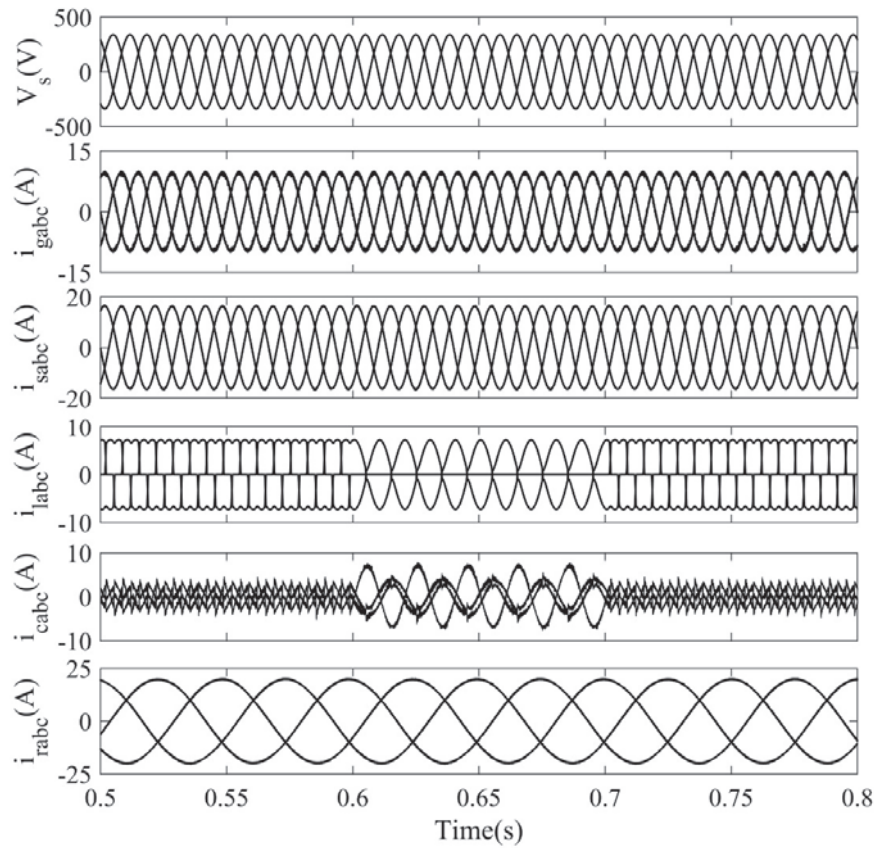
(a)

Figure 8 Continued
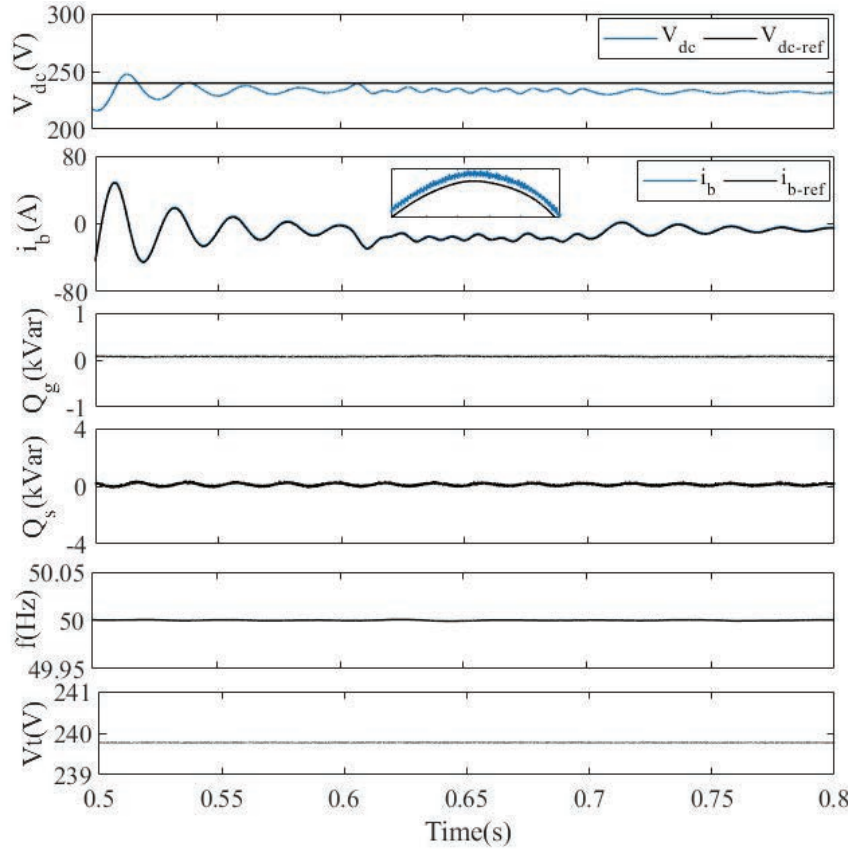
(b)

Figure 8 Performance of system at steady state (a) V_{sabc}, i_{gabc}, i_{labc}, i_{cabc}, and i_{rabc} (b) V_{dc}, i_b, Q_g, Q_s, f and V_t.

Unity power factor is maintained throughout the operation with negligible Q_s and Q_g. The performance of BES controller executed in the system is intact with V_{dc} maintained at defined value and i_b following i_{b_ref}. V_t and f are also at their operating values as shown in Figure 8.

4.5 Frequency Spectrum of System Parameters

Figure 9(a–d) below demonstrates the total harmonic distortion (THD) in grid voltage V_{gabc}, grid current i_{gabc}, source current i_{sabc} and load current il_{abc}.
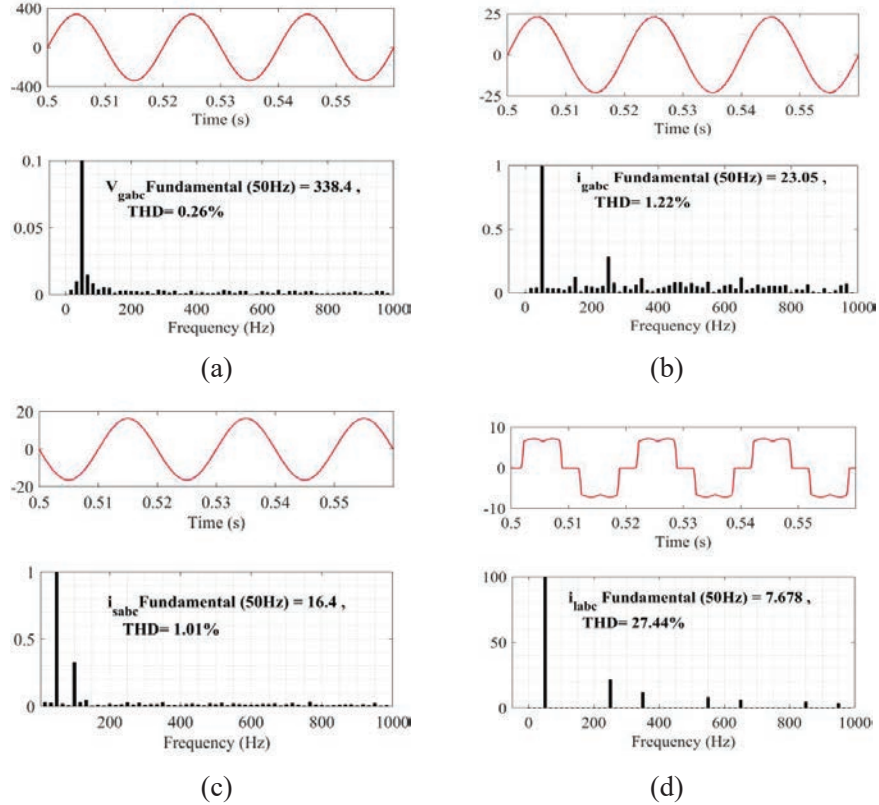
Figure 9   Frequency Spectrum of system parameters(a) V_{gabc} (b) i_{gabc} (c) i_{sabc} and (d) i_{labc}.

It can be seen that THD in grid current and voltage is within 5% that is in accordance with IEEE Standard limits.

5 Conclusion

This paper focuses on control operation of grid connected DFIG/BES based wind energy system. The peak power extraction is realized by employing tip speed ratio MPPT control. BES with bidirectional DC-DC converter control is used to regulate the grid power and address wind intermittency. A variable step size least mean square based adaptive control maintains quality power at both stator and grid side with unity power factor operation. The adaptive control also reduces system complexity by eliminating complex reference transformations for load current components. Simulated results

depict satisfactory response of all the system parameters under changing operating conditions.

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