Event analysis and real-time validation of doubly fed induction generator-based wind energy system with grid reactive power exchange under sub-synchronous and super-synchronous modes

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Abstract
The insertion of renewable power generators into the power system network has been promoted by the environment protection aspects. Doubly fed induction generator (DFIG)-based wind energy system is one of the most viable technologies for sustained power generation. This paper focuses on the operational analysis of DFIG-based wind energy conversion systems (WECS) with real-time experimental validation. An event analysis is executed under sub-synchronous and super-synchronous speeds with the variation in wind velocity and reactive power exchange by controlling the rotor side converter and grid side converter under MATLAB/Simulink platform. The results of the analysis with reactive power exchange can be utilized for the enhanced control of power electronic converters of DFIG-based WECS for better support to the grid. The validation of results is accomplished by emulation of 2 MW DFIG-based three blade wind turbine system in the laboratory under a real-time hardware-in-the-loop platform.

KEYWORDS
doubly fed induction generator, hardware-in-the-loop, renewable energy sources, renewable power generators, wind energy conversion systems

1 | INTRODUCTION

Renewable energy sources have substantial potential to generate electricity as they are abundant in nature and are harmless as well. Global warming is considered as a major hazard to the environment and the use of conventional generating systems with fossil fuels adds to this crisis. Pollution of the environment can be reduced by renewable energy sources such as solar energy and wind energy which are treated as unpolluted energy with zero carbon dioxide emission. The global installed capacity of wind turbines has been enhanced to over 651 GW in the year 2019 as per the data from the Global Wind Energy Council.¹

Renewable power generators (RPGs) will curtail the conventional fossil fuel generators. Penetration of renewable energy sources in power system, will improve its voltage profile and reliability. Optimal placement of RPGs has been
studied for the improvement of voltage stability and loss reduction. However, addition of RPGs in power system will produce frequency stability issues. Consequently, primary frequency regulation and virtual inertia supports are to be suitably incorporated in RPGs. Power system network with non-synchronous generation will introduce transient stability concerns. Generally, renewable energy sources are integrated to the power system with power electronic converters. RPGs such as solar photovoltaic generators and wind generators have low inertial responses to the transients since they are decoupled from the power system network using power electronic converters. The wind generators are to be controlled for mitigating system transients as similar to the operation of conventional synchronous generators. Therefore, the inertia of power system will be diminished by increased penetration of RPGs and the power system will have an increased rate of change of frequency. Large penetration of RPGs will reduce the share of conventional synchronous generators used for reserve power and hence the frequency variation will be more in the power system.

Of late, permanent magnet synchronous generator (PMSG) and doubly fed induction generator (DFIG) are the two generators used along with power electronic converters for the extraction of wind power. PMSG is generally equipped with full capacity power converter tied to the grid and is dissociated from the spinning inertia. However, DFIG is considered as the most popular generator for the wind energy conversion systems (WECS) owing to its capability for variable speed operation and reactive power control with the help of partially rated power converters. In adjustable speed systems, the generator rotational speed can be regulated corresponding to the wind velocity to sustain the optimal tip speed proportion. As a result, maximum power point tracking (MPPT) can be attained with the help of power converter. One of the recently adopted methods in MPPT is the optimized power point tracking (OPPT) scheme which supports the rapid frequency requirement of power system. In OPPT scheme, the operating point of the turbine can be shifted from the MPPT curve to the virtual inertia control curves by the OPPT controller according to the frequency deviation in DFIG-based WECS.

The control of active and reactive power is an underlying aspect of DFIG-based WECS which can be realized by controlling rotor side converter (RSC) and grid side converter (GSC). Stator active and reactive powers can be controlled by rotor currents so as to avoid the stator active and reactive power pulsations under sub-synchronous and super-synchronous speeds of DFIG. In Reference 15, the real and reactive power control of a wind station is analyzed for improving transient stability of multi-machine power system. In order to improve primary frequency support, a combined active and reactive power control strategy can be adopted for DFIG. The reactive power capability of DFIG under wind speed deviations is restricted by active power output and hence, a coordination between reactive power capability and active power output is required. In Reference 18, the dynamic requirement and reactive power limitation under wind speed variations are investigated. An optimized reactive power flow is illustrated for an over-excited reactive power support combined compensation from both the RSC and the GSC in Reference 19. A dynamic coordination control is needed to improve the reactive power capacity of wind power plants with DFIG. Consequently, the availability of reactive power is maximized in the event of grid faults. WECS which deploy DFIG, can be operated to deliver reactive power to the grid for providing low voltage ride-through during grid voltage dips.

DFIG can be controlled to improve the power sharing in micro-grid with other types of generators which are unable to support the grid during faults. In Reference 24, a saturated core fault current limiter is used in DFIG system to enhance the fault ride-through capability. In Reference 25, a novel structure of modified switch type fault current limiter is presented that protects the DFIG wind turbine during the symmetrical and asymmetrical grid faults. DFIG-based wind farm integrated with one superconducting fault current limiter-based passive voltage compensator and one transient voltage control-based active voltage compensator can be used to improve the transient voltage stability.

The vector control is the recognized and state-of-the-art solution for the back-to-back power electronic converters of DFIG. In Reference 27, the modeling of GSC and the RSC and the parameters design of proportional-integral controller are discussed. Soft computing technique-based controllers such as fuzzy logic controller, genetic algorithm, particle swarm optimization can be adopted instead of conventional controllers. Sliding mode field oriented controls and adaptive controls can be integrated for damping oscillatory dynamics and overall stability improvement of DFIG-based WECS.

Real-time digital simulators are widely used in the electric power industry by utilities, equipment manufacturers, and research organizations. On the contrary, traditional test platform of large rated DFIG system has high investment cost and huge energy consumption. The real-time modeling and evaluation shows better control capability and has greater impact on real-world applications. Most of the researches in the literature validate the large capacity simulated systems with low power prototype systems in the laboratory. However, some researchers have used diverse platforms, for the verification of the large power systems under investigation in real-time. For instance, a test system of DFIG is presented with a field-programmable gate array (FPGA)-based real-time simulation platform using dSPACE controller in Reference 34. Metaheuristic optimisation techniques have been investigated for enhancing the dynamic behavior of WECS with experimental validation using a low power DFIG system with dSPACE in Reference 35. Another study is based on the
modeling and control of a DFIG driven by a wind turbine on a real-time digital simulator, developed by RTDS Technologies Inc. In Reference 37, real-time modeling and simulation of complete closed loop control of DFIG for wind generation system is presented with OPAL-RT digital real-time simulator which is based on RT-LAB platform with the models built-in Simulink. A recurrent neural network and proportional Integral (PI) controller-based hybrid control for DFIG is implemented under real-time simulator-based OPAL-RT and MATLAB/Simulink in Reference 38.

The modern hardware-in-the-loop (HIL) platforms have enhanced features such as smaller simulation step in the range of nanoseconds, smaller digital sampling resolution and smaller model compilation time of less than 1 minute. In Typhoon HIL-402, software and hardware are vertically integrated with FPGA-based processor which enable fast computation and hence, the real-time simulation will be enhanced for complex models of electrical systems.

In view of the above, the focus of this paper has been set to provide a real-time hardware emulation of 2 MW DFIG-based WECS under HIL platform, Typhoon HIL-402. The main contributions and novelty of this paper are as follows.

- The performance analysis of 2 MW DFIG-based three blade wind turbine system and power flows for sub-synchronous and super-synchronous speeds under MATLAB/Simulink platform.
- The real-time experimental validation of results with 2 MW DFIG-based three blade wind turbine system using HIL platform, Typhoon HIL-402.

The analysis presented in this paper focuses on the study of the dynamics of rotor current as the system shifts from sub-synchronous to super-synchronous speeds. This simplified novel approach gives a better understanding of reactive power flow concept and its control which is an added advantage of this paper. Overview of WECS, aerodynamic model of wind turbine, and DFIG modeling are addressed in Section 2. Wind turbine characteristics and system description for the simulation of DFIG-based WECS in MATLAB/Simulink are addressed in Section 3. The results of DFIG for the shift from sub-synchronous to super-synchronous speeds with wind velocity and reactive power exchange are discussed in Section 4. The variation in reactive power exchange with the grid for sub-synchronous and super-synchronous speeds is illustrated. The validation of results is presented in Section 5, with a 2 MW DFIG-based WECS using a HIL real-time emulator system, Typhoon HIL-402. Finally, the inferences from the result analysis of this paper are also summarized.

2 | OVERVIEW AND MODELING OF DFIG-BASED WIND ENERGY SYSTEMS

DFIG is a typical slip ring induction generator and the variable speed operation is attained by managing the rotor circuit by means of external converters. The classic block diagram of DFIG-based WECS is displayed in Figure 1. The stator is tied to the grid and the rotor is also connected to the grid by means of power converters, filter, and transformer. The transfer of power to the grid and vice versa can be accomplished via RSC and GSC. The rating of power electronic converters is only 30% of generator power rating on the grounds that maximum rotor power is only 30% of the stator power rating. By controlling the RSC, it is possible to regulate the speed of generator to achieve highest wind power extraction for varying wind velocities and DFIG can be operated as generator in sub-synchronous and super-synchronous modes.

**Figure 1** Schematic of DFIG-based wind generation system
Power flow in DFIG-based WECS is presented in Figure 2. The rotor can collect or send power from or to the grid according to the slip, positive or negative. The mechanical power from the turbine is transported to the grid via stator and rotor in super-synchronous operation. The power is directly carried to grid from the stator and is transferred through power converters from the rotor to the grid. In sub-synchronous operation, the rotor takes power from grid through converters. The mechanical power and rotor power are transferred to grid through stator.

Due to the decoupling provided by the power converters, it is onerous for the wind turbine to participate in inertia and frequency support during the load disturbance. If the wind turbines are operating at maximum power point for the given wind speed with pitch angle corresponding to maximum power, there will not be any redundant power available to improve the system frequency.

2.1 Wind turbine aerodynamic model

Wind turbine converts the kinetic energy in the wind into mechanical energy. The kinetic energy in the wind is influenced by the air density, area of turbine blades, wind velocity, and power coefficient. The wind power developed by the turbine is given in Equation (1).

\[ P_w = \frac{1}{2} \rho AV^3 C_p(\lambda, \beta) \]  

where \( \rho \) denotes the air density (1.225 kg/m\(^3\)), \( V \) denotes the wind velocity in m/s, \( A \) represents the area of turbine blades in m\(^2\), \( C_p \) denotes the power coefficient, \( \lambda \) denotes the tip speed ratio (TSR), and \( \beta \) denotes the pitch angle of blade.

Power coefficient of a wind turbine represents the portion of kinetic energy which is transformed into mechanical energy. According to Betz’s Law, wind turbines can convert a maximum up to 59.3% of wind kinetic energy into mechanical energy by rotating a rotor (\( C_p \leq 59.3\% \)). The power coefficient is governed by pitch angle and TSR. The TSR can be defined as the ratio of turbine blade linear speed to the wind speed and is represented by Equation (2).

\[ \lambda = \frac{R \omega}{V} \]  

where, \( \omega \) denotes the rotational speed in radians per second and \( R \) denotes the radius of wind turbine in m. Equation (3) represents the power coefficient as, \(^{39}\)

\[ C_p(\lambda, \beta) = k_1 \left( \frac{k_2}{\lambda_i} - k_3 \beta - k_4 \beta \lambda_i - k_5 \right) e^{k_6/\lambda_i} \]  

where \( k_1 \) to \( k_8 \) are constants.

\[ \frac{1}{\lambda_i} = \lambda + k_4 \]  

The variation of power coefficient with TSR for different pitch angle is shown in Figure 3. \(^{39}\)
2.2 | DFIG modeling

The modeling of DFIG is crucial for the performance investigation during the various operating conditions. The stator voltage, \( v_s \), referred to the stator side in Equation (5) can be denoted in \( \alpha \) and \( \beta \) components as in Equations (6) and (7).

\[
\begin{align*}
    v_s &= i_s R_s + \frac{d\varphi_s}{dt} \quad (5) \\
    v_{\alpha s} &= i_{\alpha s} R_s + \frac{d\varphi_{\alpha s}}{dt} \quad (6) \\
    v_{\beta s} &= i_{\beta s} R_s + \frac{d\varphi_{\beta s}}{dt} \quad (7)
\end{align*}
\]

The stator flux, \( \varphi_s \) and rotor flux, \( \varphi_r \) referred to the stator side are characterized as in Equations (8) and (9).

\[
\begin{align*}
    \varphi_s &= i_s L_s + i_r L_m \quad (8) \\
    \varphi_r &= i_s L_m + i_r L_r \quad (9)
\end{align*}
\]

Equation (10) referred to stator side can be attained from the stator voltage and flux. Stator flux variation depends on the time constant, \( L_s/R_s \).

\[
\begin{align*}
    \frac{d\varphi_s}{dt} &= v_s - \frac{R_s}{L_s} \varphi_s + i_r R_s \frac{L_m}{L_s} \\
    \frac{d\varphi_r}{dt} &= (v_s - j\omega \varphi_s) \frac{L_m}{L_s} + \left( R_r + R_s \left( \frac{L_m}{L_s} \right)^2 \right) i_r + \sigma L_s \frac{di_r}{dt}
\end{align*}
\]

The stator flux variation is affected by the rotor current and the rotor voltage can be derived as Equation (11) which is derived from Equations (5)-(9).

3 | SYSTEM DESCRIPTION AND SIMULATION DETAILS

3.1 | System description

A 2 MW DFIG-based WECS has been implemented under MATLAB/Simulink platform. Figure 4 shows the MATLAB/Simulink simulation diagram with wind speed input, wind turbine model, DFIG, RSC and its control, GSC and its
control and grid side filter. The wind speed input is varied at different intervals and a mathematical model of three blade wind turbine is implemented to calculate the torque reference for DFIG corresponding to the wind speed.

DFIG stator windings are connected to the grid and rotor windings are connected to the RSC. An MPPT based on indirect speed controller is implemented to produce a torque reference as in Equation (12).

$$T_{ref} = -\left(\frac{0.5 \rho \pi R^3 C_{p,\text{max}}}{\lambda_{\text{opt}}}\right) \omega^2$$ \hspace{1cm} (12)

where, $C_{p,\text{max}}$ represents peak value of power coefficient, $R$ stands for radius of wind turbine, and $\lambda_{\text{opt}}$ stands for the optimal TSR. Depending on the rotor speed, the reference for $q$-axis rotor current can be obtained and is given in Equation (13).

$$i_{qr,\text{ref}} = -\frac{2}{3} T_{ref} \left(\frac{L_s q_s}{p L_m}\right)$$ \hspace{1cm} (13)

where, $L_s$ represents the stator inductance, $q_s$ represents the stator flux, $\rho$ represents pole pairs, and $L_m$ represents the magnetizing inductance. The block diagram for producing control signals to the RSC is depicted in Figure 5. The $d$-axis rotor current reference can be used for the control of stator flux and reactive power support through the stator. An indirect speed controller-based MPPT is utilized for producing the reference for electromagnetic torque from the rotor speed. The measured stator voltages and rotor currents are utilized for generating the control signals to the RSC.

The block diagram for the generation of control signals to the GSC is depicted in Figure 6. The reference for $d$-axis grid current can be obtained after comparing the DC bus voltage reference with the measured value. The $q$-axis grid current reference will be in compliance with the need of reactive power exchange through the GSC to the grid. Measured values of grid currents and grid voltage are utilized to generate the control signals to GSC. Grid side filters are utilized to connect the GSC to the grid.

A 2.4 MW, three blade wind turbine is modeled in MATLAB. The power characteristics of actual wind turbine are drawn for the variation in wind velocity and are shown in Figure 7.
**FIGURE 5** Block diagram for the generation of control signals to RSC

**FIGURE 6** Block diagram for the generation of control signals to GSC

**FIGURE 7** Power characteristics of a three blade, 2.4 MW wind turbine with respect to the wind speed
The variation of power coefficient with respect to the TSR is plotted as shown in Figure 8. The wind turbine power curve at different wind velocities along with MPPT curve is presented in Figure 9. The detailed specification of DFIG parameters and wind turbine model are given in Table 1.

3.2 Simulation details

Simulations are carried out for the performance analysis of 2 MW DFIG-based three blade wind turbine system using MATLAB-R2019b version. Simulation of DFIG-based WECS is carried out for the variation in wind velocity from 8 to

![Figure 8](image1.png)

**Figure 8** The variation of power coefficient with tip speed ratio of a three blade wind turbine

![Figure 9](image2.png)

**Figure 9** Wind power with respect to rotational speed for different wind speeds

| Parameter details               | Specification |
|--------------------------------|---------------|
| Rated power of DFIG            | 2 MW          |
| Frequency                      | 50 Hz         |
| Rated stator voltage           | 690 V         |
| Synchronous speed              | 1500 rpm      |
| Rated torque                   | 12732 Nm      |
| Maximum slip                   | 1/3           |
| Pole pairs                     | 2             |
| Stator/rotor turns ratio       | 1/3           |
| DC bus voltage                 | 1150 V        |
| Rated power of wind turbine    | 2.4 MW        |
| Number of blades               | 3             |
| Radius of wind turbine blade   | 42 m          |
| Gear box ratio                 | 100           |
| Air density                    | 1.225 kg/m³   |

**Table 1** Specifications of DFIG-based WECS
9 m/s and then to 10 m/s at 10 seconds and 14 seconds, respectively. The variation in waveforms of voltages, currents, torque, and speed are examined in detail. The behavior of rotor current during sub-synchronous and super-synchronous speeds is also scrutinized. Simulation is carried out for the variation of reactive power exchange from 0 to $-200 \text{kVar}$ and $-500 \text{kVar}$ at 10 seconds and 13 seconds, respectively with a wind speed of 8 m/s corresponding to sub-synchronous speed and 10 m/s corresponding to super-synchronous speed. The variation in the waveforms of voltages and currents are analyzed. The behavior of current flow from rotor to the grid is also investigated.

4 | SIMULATION RESULTS AND DISCUSSION

Simulation has been performed for two cases, the detailed outcome of which are given below.

4.1 | Case 1. Performance analysis of DFIG for the shift from sub-synchronous to super-synchronous speed with variation in wind speed

Simulation has been executed for a variation in wind speed from 8 to 9 m/s and then to 10 m/s at 10 and 14 seconds, respectively. The system performance is analyzed in detail. Variation of parameters in RSC of DFIG-based WECS for the change in wind speed is depicted in Figure 10. Rotor speed is varied corresponding to the indirect speed controller-based MPPT as explained in Section 3. The rotor speed is verified as 137, 154, and 171 rps corresponding to the wind velocities 8, 9, and 10 m/s correspondingly. The speeds 137 and 154 rps correspond to sub-synchronous operation. The speed 171 rps corresponds to super-synchronous operation.

The torque is varied as $-0.44$, $-0.55$, and $-0.69 \text{ pu}$ accordingly to generate $q$-axis rotor currents 0.43, 0.54, and 0.67 pu. The negative torque indicates that the doubly fed induction machine is working as generator. The $q$-axis rotor voltage is evaluated as 0.13, 0.03, and $-0.08 \text{ pu}$ for the rotor speeds 137, 154, and 171 rps, respectively. It is also observed that the

![Figure 10](image)

**Figure 10** Variation of parameters in rotor side converter of DFIG-based WECS: (A) rotor speed, (B) torque, (C) $q$-axis rotor current, (D) $q$-axis rotor voltage, (E) $d$-axis rotor current, (F) $d$-axis rotor voltage, (G) stator voltage, (H) stator current, and (I) rotor current; for the change in wind velocity from 8 to 9 m/s at 10 seconds and from 9 to 10 m/s at 14 seconds. DFIG speed increases from sub-synchronous to super-synchronous speed corresponding to the wind speed.
q-axis rotor voltage is zero corresponding to the synchronous speed of 157.14 rps. The d-axis rotor current and voltage are remained at zero since the flux control with d-axis current is not performed. The stator voltage is maintained as 1 pu at a frequency of 50 Hz. The stator current is increased as 0.5, 0.6, and 0.71 pu with the increase in wind speed of 8, 9, and 10 m/s correspondingly.

A prominent variation is seen in the rotor current waveform from sub-synchronous to super-synchronous speeds. The rotor current magnitude is increased as 0.145, 0.18, and 0.225 pu with the increase in wind speed of 8, 9, and 10 m/s correspondingly. The frequency of rotor current is measured as 6.3, 1, and 4.3 Hz with the increase in wind speed of 8, 9, and 10 m/s correspondingly. The vital observation is that the phase sequence of the rotor current is changed from sub-synchronous to super-synchronous mode during the time interval from 14 to 14.5 seconds as shown in Figure 10. It is seen that the rotor currents become constant DC corresponding to the synchronous speed of 157.14 rps as shown in Figure 12D. The steady state values corresponding to the various wind speeds are presented in Table 2.

Variation of parameters in GSC of DFIG-based WECS for the deviation in wind velocity is depicted in Figure 11. The d-axis grid current and q-axis grid voltage are varied with variation in wind velocity. Grid reactive power reference and

| Parameter details                  | Wind speed |
|-----------------------------------|------------|
|                                   | 8 m/s | 9 m/s | 10 m/s |
| Rotor speed (rpm)                 | 137    | 154    | 171 |
| Torque (pu)                       | -0.44  | -0.55  | -0.69 |
| q-axis rotor current (pu)         | -0.43  | -0.54  | -0.67 |
| q-axis rotor voltage (pu)         | 0.13   | 0.03   | -0.08 |
| Stator current (pu)               | 0.5    | 0.6    | 0.71 |
| Rotor current (pu)                | 0.145  | 0.18   | 0.225 |
| Frequency of rotor current (Hz)   | 6.3    | 1      | 4.3 |

TABLE 2 Steady state values for various wind speeds

**FIGURE 11** Variation of parameters in grid side converter of DFIG-based WECS: (A) wind speed, (B) d-axis grid current, (C) d-axis grid voltage, (D) grid reactive power, (E) q-axis grid current, (F) q-axis grid voltage, (G) grid voltage, (H) grid current, and (I) DC bus voltage; for the change in wind velocity from 8 to 9 m/s at 10 seconds and from 9 to 10 m/s at 14 seconds
the DC bus voltage reference are maintained at 0 and 1 pu, respectively. Grid voltage remains at 1 pu and the current supplied to the grid from the GSC is varied with change in wind speed.

The enlarged waveforms of grid voltage, stator current, grid current, and rotor current for various wind speeds corresponding to sub-synchronous and super-synchronous speeds are depicted in Figure 12. It is very obvious from the waveforms that the DFIG functions as a generator in sub-synchronous and super-synchronous speeds. The stator current flows in the same direction from stator to the grid in sub-synchronous and super-synchronous operations. The

**FIGURE 12** (A) Voltages and currents of DFIG-based WECS for the change in wind velocity from 8 to 9 m/s at 10 seconds and from 9 to 10 m/s at 14 seconds. Enlarged waveforms are shown corresponding to (B) super-synchronous speed, (C) sub-synchronous speed, (D) synchronous speed
rotor current flows from grid to rotor in sub-synchronous speed and from rotor to grid in super-synchronous speeds as in Figure 12. The enlarged rotor current waveforms evidence the phase sequence alteration from sub-synchronous to super-synchronous speeds.

The wind turbine power is noted from the power characteristics in Figure 7 corresponding to the wind speed 8, 9, and 10 m/s as 0.77, 1.09, and 1.5 MW correspondingly. The power is calculated using the torque and rotor speed waveforms in Figure 10 and is validated to be the same as per the wind turbine characteristics in Figure 7. The comparison is given in Table 3.

### Table 3
Comparison of power calculated from torque and speed with wind turbine characteristics for various wind speeds

| Parameter details                      | Wind speed |
|----------------------------------------|-----------|
|                                        | 8 m/s     | 9 m/s     | 10 m/s    |
| Rotor speed (rps)                      | 137       | 154       | 171       |
| Torque (Nm)                            | −5602     | −7052     | −8785     |
| Calculated power (MW)                  | 0.767     | 1.086     | 1.502     |
| Power from wind turbine characteristics (MW) | 0.77      | 1.09      | 1.5       |

4.2 | Case 2. Performance analysis of DFIG for reactive power exchange with grid under sub-synchronous and super-synchronous operation

Simulation is performed for a variation in reactive power exchange reference from 0 to −200 kVAr and −500 kVAr at 10 and 13 seconds respectively at a wind speed of 10 m/s corresponding to the super-synchronous speed and 8 m/s corresponding to the sub-synchronous speed. The system performance is analyzed with detailed waveforms. Figure 13 displays

**Figure 13**  Variation of parameters in grid side converter of DFIG-based WECS: (A) grid reactive power, (B) wind speed, (C) d-axis grid current, (D) d-axis grid voltage, (E) q-axis grid current, (F) q-axis grid voltage, (G) DC bus voltage, (H) grid voltage, and (I) grid current; for the reactive power exchange of −200 and −500 kVAr at 10 and 13 seconds respectively with a wind speed of 10 m/s corresponding to super-synchronous speed
FIGURE 14  Variation of parameters in grid side converter of DFIG-based WECS: (A) grid reactive power, (B) wind speed, (C) $d$-axis grid current, (D) $d$-axis grid voltage, (E) $q$-axis grid current, (F) $q$-axis grid voltage, (G) DC bus voltage, (H) grid voltage, and (I) grid current; for the reactive power exchange of $-200$ and $-500$ kVAr at 10 and 13 seconds respectively with a wind speed of 8 m/s corresponding to sub-synchronous speed.

The variation of parameters in GSC for the change in reactive power exchange with a wind speed of 10 m/s corresponding to the super-synchronous speed. The $q$-axis grid current is varied as 0, 0.1, and 0.24 pu for the reactive power zero, $-200$ kVAr and $-500$ kVAr, respectively. The grid current magnitude is varied as 0.065, 0.12, and 0.26 pu for the reactive power zero, $-200$ kVAr and $-500$ kVAr, respectively.

The variation of parameters in GSC for the change in reactive power exchange with a wind velocity of 8 m/s corresponding to the sub-synchronous speed is revealed in Figure 14. The enlarged waveforms of grid voltage, stator current, grid current, and rotor current for the reactive power exchange of 0, $-200$, and $-500$ kVAr for a wind speed of 10 m/s corresponding to super-synchronous speed are shown in Figure 15.

The grid current waveform reveals that the reactive power supply is according to the reference. The steady state values corresponding to the various reactive power exchanges are tabulated in Table 4.

5 | REAL-TIME EXPERIMENTAL RESULTS

5.1 Validation using real-time HIL platform

The validation of results is accomplished by a 2 MW DFIG-based WECS using a real-time emulator system, Typhoon HIL-402. A virtual plant model of 2 MW DFIG-based wind energy system is emulated real-time. Typhoon HIL schematic editor is used to create the mathematical model of an actual 2 MW DFIG-based WECS and real-time simulation is carried out with HIL SCADA using Typhoon HIL control center version 2020.1. Laboratory set up for the real-time emulation of the developed mathematical model of power layer and control layer is shown in Figure 16. The results of MATLAB simulation in Section 4, are verified with the results of real-time experiments and with the power curve of actual 2.4 MW, three blade wind turbine as in Figure 7.

Case 1. Real-time emulation of DFIG during sub-synchronous speed.

HIL SCADA panel for 2 MW DFIG-based WECS operating at sub-synchronous mode corresponding to a wind velocity of 8 m/s is depicted in Figure 17. Stator voltage, status of power electronic converter control, generator speed, wind turbine
**FIGURE 15**  (A) Voltages and currents of DFIG-based WECS for various reactive power with a wind speed of 10 m/s corresponding to super-synchronous speed. Enlarged waveforms with a reactive power exchange of (B) $-500 \text{kVar}$, (C) $0 \text{kVar}$, (D) $-200 \text{kVar}$

| Parameter details | Reactive power exchange |
|-------------------|-------------------------|
|                   | 0           | $-200 \text{kVar}$ | $-500 \text{kVar}$ |
| $q$-Axis grid current (pu) | 0      | 0.1       | 0.24        |
| Rotor current (pu)        | 0.065   | 0.12      | 0.26        |

| TABLE 4 Steady state values for various reactive power exchanges at super-synchronous speed |
**FIGURE 16** Laboratory setup of real-time emulator system with HIL-402

**FIGURE 17** HIL SCADA panel for 2 MW DFIG-based WECS operating at sub-synchronous mode corresponding to a wind velocity of 8 m/s. Stator voltage, status of power electronic converter control, generator speed, wind turbine and generator torque, mode of operation, tip speed ratio, power coefficient, torque coefficient, and generated power are displayed. The waveforms of stator voltage, $d$-axis and $q$-axis rotor currents, rotor side converter control signals, and rotor currents are also displayed.
and generator torque, mode of operation, TSR, power coefficient, torque coefficient, and generated power are displayed. The waveforms of stator voltage, d-axis and q-axis rotor currents, RSC control signals and rotor currents are verified with the MATLAB simulation results in Section 4. For a wind speed of 8 m/s and stator voltage of 690 V, a torque of $-5602 \text{Nm}$ is generated by the DFIG which is given by the wind turbine model in HIL. A TSR of 7.2, power coefficient of 0.44, torque coefficient of 0.0614 has been produced by the wind turbine model. The DFIG speed is obtained as 136.9 rps with a generated torque of $-5602 \text{Nm}$ corresponding to a generated power of $-0.77 \text{MW}$ and the results are matching with the wind turbine power characteristics and the simulation results as compared in Table 3.

HIL SCADA panel for 2 MW DFIG-based WECS operating at sub-synchronous mode corresponding to a wind velocity of 9 m/s is depicted in Figure 18. The waveforms of stator voltage, d-axis and q-axis rotor currents, RSC control signals and rotor currents are verified with the MATLAB simulation results in Section 4. For a wind speed of 9 m/s and stator voltage of 690 V, a torque of $-7090 \text{Nm}$ is generated by the DFIG which is given by the wind turbine model in HIL. A TSR of 7.2, power coefficient of 0.44, torque coefficient of 0.0614 has been produced by the wind turbine model. The DFIG generated power is obtained as $-1.09 \text{MW}$ corresponding to a rotor speed of 154 rps with a generated torque of $-7090 \text{Nm}$ at a wind velocity 9 m/s and the results are matching with the wind turbine power characteristics as compared in Table 3.

Case 2. Real-time emulation of DFIG during super-synchronous speed.

HIL SCADA panel for 2 MW DFIG-based WECS operating at super-synchronous mode corresponding to a wind velocity of 10 m/s is depicted in Figure 19. The wind speed is given as SCADA input and status of power electronic converter control and the mode of operation are displayed. The waveforms of stator voltage, d-axis and q-axis rotor currents, RSC control signals and rotor currents are verified with the MATLAB simulation results in Section 4. For a wind speed of 10 m/s and stator voltage of 690 V, a torque of $-8759 \text{Nm}$ is generated by the DFIG which is given by the wind turbine model in HIL. A TSR of 7.2, power coefficient of 0.44, torque coefficient of 0.0614 has been produced by the wind turbine model. The DFIG generated power is obtained as $-1.5 \text{MW}$ corresponding to a rotor speed of 171 rps with a generated torque of

Figure 18  HIL SCADA panel for 2 MW DFIG-based WECS operating at sub-synchronous mode corresponding to a wind velocity of 9 m/s. Stator voltage, status of power electronic converter control, generator speed, wind turbine and generator torque, mode of operation, tip speed ratio, power coefficient, torque coefficient, and generated power are displayed. The waveforms of stator voltage, d-axis and q-axis rotor currents, rotor side converter control signals, and rotor currents are also displayed.
FIGURE 19  HIL SCADA panel for 2 MW DFIG-based WECS operating at super-synchronous mode corresponding to a wind velocity of 10 m/s. Stator voltage, status of power electronic converter control, generator speed, wind turbine and generator torque, mode of operation, tip speed ratio, power coefficient, torque coefficient, and generated power are displayed. The waveforms of stator voltage, d-axis and q-axis rotor currents, rotor side converter control signals, and rotor currents are also displayed.

TABLE 5  Comparison of MATLAB simulation and HIL real-time experiment

| Parameter details                  | Wind speed |          |          |          |          |          |
|-----------------------------------|------------|----------|----------|----------|----------|----------|
|                                   | 8 m/s      | 9 m/s    | 10 m/s   | 8 m/s    | 9 m/s    | 10 m/s   |
|                                   | MATLAB     | HIL      | MATLAB   | HIL      | MATLAB   | HIL      |
| Rotor speed (rps)                 | 137        | 154      | 171      | 136.9    | 154      | 171      |
| Torque (Nm)                       | −5602      | −7052    | −8785    | −5602    | −7090    | −8759    |
| Generated power (MW)              | 0.767      | 1.086    | 1.502    | 0.77     | 1.09     | 1.5      |
| Power from wind turbine characteristics (MW) |          |          |          | 0.77     | 1.09     | 1.5      |

−8759 Nm at a wind velocity 10 m/s and the results are matching with the wind turbine power characteristics as compared in Table 3. The results obtained in the real-time simulation using HIL-402 are identical to the results of MATLAB simulation as discussed in Section 4. Comparison with the values of various parameters in wind turbine power characteristics, MATLAB simulation, and HIL real-time experiment is given in Table 5. The results obtained in the real-time simulation using HIL-402 corresponding to 8, 9, and 10 m/s are identical to the results of MATLAB simulation discussed in Section 4.

5.2  Discussion on the results evolved

Performance of the DFIG-based WECS for the shift from sub-synchronous to super-synchronous speed with variation in wind speed is analyzed. The rotor speed increases with the increase in wind speed as per the MPPT and the system is
transferred from sub-synchronous to super-synchronous operation. It can also be seen that the DFIG system is operating with a maximum power coefficient of 0.44 for variation in wind speed as displayed in HIL SCADA panels in order to operate at maximum power point. The rotor speed, torque, and generated power obtained in MATLAB simulation, are validated with the HIL real-time experiment and wind turbine power characteristics as detailed in Table 5. The grid current variation is according to the variation of reactive power exchange in sub-synchronous and super-synchronous operations. Hence the GSC can be controlled for the reactive power support to the grid. The variation in the frequency and change in phase sequence of the rotor current for sub-synchronous and super-synchronous operations are also validated in real-time as displayed in Figures 17 and 19. The comparative study of results from MATLAB simulation and HIL real-time experiment shows the accuracy of HIL-based DFIG model. Hence, HIL technology can be incorporated for the analysis and real-time validation for the researches in DFIG-based WECS with large ratings.

6 | CONCLUSION

In this paper, a real-time hardware emulation of 2 MW DFIG-based WECS under HIL platform has been presented. The performance of a 2 MW DFIG-based WECS with a 2.4 MW three blade wind turbine has been explored. An exhaustive operational analysis of DFIG-based WECS is carried out for the sub-synchronous and super-synchronous speeds with a MPPT having indirect speed controller. The changes in the parameters of the system are analyzed under MATLAB/Simulink platform and compared with practical 2.4 MW three blade wind turbine characteristics for the variation in wind velocity and reactive power exchange. The performance of the system and power flows are demonstrated in detail for sub-synchronous and super-synchronous speeds, which will enhance the concept of reactive power support and rotor current dynamics of DFIG-based WECS. The simulation results obtained with MATLAB/Simulink, are validated with real-time hardware emulation of 2 MW DFIG-based WECS using HIL platform, Typhoon HIL-402.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Tomson Thomas: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing-original draft; writing-review and editing. Prince A: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing-original draft; writing-review and editing.

NOMENCLATURE

\( \rho \) air density
\( P_w \) power developed by the turbine
\( V \) wind velocity
\( A \) area of turbine blades
\( C_p \) power coefficient
\( \lambda \) tip speed ratio
\( \beta \) pitch angle of blade
\( \omega \) rotational speed
\( T_{ref} \) torque reference
$C_{\text{pmax}}$  
Crest value of power coefficient

$R$  
Radius of wind turbine

$\lambda_{\text{opt}}$  
Optimal TSR

$P_m$  
Mechanical power input to DFIG

$P_s$  
Stator active power of DFIG

$P_r$  
Rotor active power of DFIG

$P_g$  
Active power transferred to the grid

$Q_s$  
Stator reactive power

$Q_{s\text{,ref}}$  
Stator reactive power reference

$Q_{g\text{,ref}}$  
Grid reactive power reference

$\varphi_s$ and $\varphi_r$  
Stator and rotor flux referred to stator side

$L_s$ and $L_r$  
Stator and rotor self-inductance

$L_m$  
Magnetizing inductance

$p$  
Pole pairs

$v_s$ and $v_r$  
Stator and rotor voltage

$v_{sa}$ and $v_{sb}$  
Stator voltage in $\alpha$ and $\beta$ components

$R_s$ and $R_r$  
Stator and rotor resistance

$i_s$ and $i_r$  
Stator and rotor current

$i_{sa}$ and $i_{sb}$  
Stator current in $\alpha$ and $\beta$ components

$i_{\text{d}_{r\text{,ref}}}$  
D-axis rotor current reference

$i_{\text{d}_{r\text{,m}}}$  
D-axis rotor current

$i_{\text{q}_{r\text{,ref}}}$  
Q-axis rotor current reference

$i_{\text{q}_{r\text{,m}}}$  
Q-axis rotor current

$i_g$  
Grid current

$i_{\text{d}_{g\text{,ref}}}$  
D-axis grid current reference

$i_{\text{d}_{g\text{,m}}}$  
D-axis grid current

$i_{\text{q}_{g\text{,ref}}}$  
Q-axis grid current reference

$i_{\text{q}_{g\text{,m}}}$  
Q-axis grid current

$V_{\text{bus\text{,ref}}}$  
DC bus voltage reference

$V_{\text{bus\text{,m}}}$  
DC bus voltage

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REFERENCES

1. Global Wind Energy Council. https://www.gwec.net/. Accessed April 1, 2020.

2. Khatod DK, Pant V, Sharma J. Evolutionary programming based optimal placement of renewable distributed generators. IEEE Trans Power Syst. 2013;28(2):683-695.

3. Nasef AF, Osheba DS, Khattab HA, Osheba S. Assessment of optimal allocation of renewable distributed generator sources in distribution network. Eng Reports. 2020;2:e12157.

4. Taczi I. Enhancing power system frequency stability with synthetic inertia. Paper presented at: EUROCON 2017-17th International Conf. on Smart Technologies; 2017; Ohrid: IEEE-960–965.

5. Vidyanandan KV, Senroy N. Primary frequency regulation by deloaded wind turbines using variable droop. IEEE Trans Power Syst. 2013;28(2):837-846.

6. Hossain MM, Ali MH. Transient stability improvement of doubly fed induction generator based variable speed wind generator using DC resistive fault current limiter. IET Renew Power Gener. 2016;10(2):150-157.

7. Papadopoulos PN, Milanović J V. Probabilistic framework for transient stability assessment of power systems with high penetration of renewable generation. IEEE Trans Power Syst. 2017;32(4):3078-3088.

8. Lopez-Garcia I, Lopez-Monsalvo CS, Beltran-Carabajal F, Escarela-Perez R, Olivares-Galvan JC. Secure operating bounds for wind energy conversion systems working as conventional power generation plants. IET Gener Trans Distrib. 2019;13(12):2311-2318.

9. Hwang M, Muljadi E, Jang G, Kang YC. Disturbance-adaptive short-term frequency support of a DFIG associated with the variable gain based on the ROCOF and rotor speed. IEEE Trans Power Syst. 2017;32(3):1873-1881.

10. Sadeghfam A, Tohid S, Rostami N. Influence of PMSG-based wind turbine on transient stability of synchronous generators—a comparative study. Int Trans Electr Energy Syst. 2018;28(12):e2639.
11. Chen Z, Yin M, Zou Y, Meng K, Dong Z. Maximum wind energy extraction for variable speed wind turbines with slow dynamic behavior. *IEEE Trans Power Syst.* 2017;32(4):3321-3322.

12. Ochoa D, Martinez S. Fast-frequency response provided by DFIG-wind turbines and its impact on the grid. *IEEE Trans Power Syst.* 2017;32(5):4002-4011.

13. Santos-Martín D, Arnaltes S, Amenedo JR. Reactive power capability of doubly fed asynchronous generators. *Electr Power Syst Res.* 2008;78(11):1837-1840.

14. Subudhi B, Ogeti PS. Optimal preview stator voltage-oriented control of DFIG WECS. *IET Gener Trans Distrib.* 2018;12(4):1004-1013.

15. Firouzi M, Gharehpetian GB, Salami Y. Active and reactive power control of wind farm for enhancement transient stability of multi-machine power system using UIPC. *IET Renew Power Gener.* 2017;11(8):1246-1252.

16. Tu C, Cao J, He L, Fang Y. Combined active and reactive power control strategy to improve power system frequency stability with DFIGs. *J Eng.* 2017;2017(13):2021-2025.

17. Ouyang J, Tang T, Yao J, Li M. Active voltage control for DFIG-based wind farm integrated power system by coordinating active and reactive powers under wind speed variations. *IEEE Trans Energy Convers.* 2019;34(3):1504-1511.

18. Ouyang J, Tang T, Diao Y, Li M, Yao J. Control method of doubly fed wind turbine for wind speed variation based on dynamic constraints of reactive power. *IET Renew Power Gener.* 2018;12(9):973-980.

19. Zhou D, Blaabjerg F, Lau M, Tonnes M. Optimized reactive power flow of DFIG power converters for better reliability performance considering grid codes. *IEEE Trans Indus Electron.* 2015;62(3):1552-1562.

20. Ghosh S, Isbeih Y, Bhattrai R, El Moursi MS, El-Saadany EF, Kamalasadan S. A dynamic coordination control architecture for reactive power capability enhancement of the DFIG-based wind power generation. *IEEE Trans Power Syst.* 2020;35(4):3051-3064.

21. Thomas T, Prince A. LVRT capability evaluation of DFIG based wind farm system using type-A and type-C grid voltage sags. Paper presented at: International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020); 2020; Cochin: IEEE:1-6.

22. Marhaba MS, Farhangi S, Iman-Eini H, Iravani R. Reactive power sharing improvement of droop-controlled DFIG wind turbines in a microgrid. *IET Gener Trans Distrib.* 2018;12(4):842-849.

23. Duong MQ, Sava GN. Coordinated reactive power control of DFIG to improve LVRT characteristics of FSIG in wind turbine generation. Paper presented at: International Conference on Electromechanical and Power Systems (SIELMEN); 2017; Iasi: IEEE:256-260.

24. Tripathi PM, Sekhar Sahoo S, Chatterjee K. Enhancing the fault ride through capability of DFIG-based wind energy system using saturated core fault current limiter. *J Eng.* 2019;2019(18):4916-4921.

25. Asghar R, Rehman F, Ullah Z, Aman A, Iqbal K, Ali NA. Modified switch type fault current limiter for low-voltage ride-through enhancement and reactive power support of DFIG-WT under grid faults. *IET Renew Power Gener.* 2020;14(9):1481-1490.

26. Ou R, Xiao X, Zou Z, Zhang Y, Wang Y. Cooperative control of SPCL and reactive power for improving the transient voltage stability of grid-connected wind farm with DFIGs. *IEEE Trans Appl Superconduct.* 2016;26(7):1-6.

27. Zhou D, Blaabjerg F. Bandwidth oriented proportional-integral controller design for back-to-back power converters in DFIG wind turbine system. *IET Renew Power Gener.* 2017;11(7):941-951.

28. Demirbas S. Self-tuning fuzzy-PI-based current control algorithm for doubly fed induction generator. *IET Renew Power Gener.* 2017;11(13):1714-1722.

29. Moradi H, Alinejad-Beromi Y, Yaghobi H, Bustan D. Sliding mode type-2 neuro-fuzzy power control of grid-connected DFIG for wind energy conversion system. *IET Renew Power Gener.* 2019;13(13):2435-2442.

30. Shihabudheen KV, Raju SK, Pillai GN. Control for grid-connected DFIG-based wind energy system using adaptive neuro-fuzzy technique. *Int Trans Electr Energy Syst.* 2018;28(5):e2526.

31. Zhang S, Mishra Y, Shahidehpour M. Fuzzy-logic based frequency controller for wind farms augmented with energy storage systems. *IEEE Trans Power Syst.* 2016;31(2):1595-1603.

32. Djilali L, Sanchez EN, Belkheiri M. Real-time neural sliding mode field oriented control for a DFIG-based wind turbine under balanced and unbalanced grid conditions. *IET Renew Power Gener.* 2019;13(4):618-632.

33. Mir AS, Senroy N. DFIG damping controller design using robust CKF-based adaptive dynamic programming. *IEEE Transa Sustain Energy.* 2020;11(2):839-850.

34. Gao J, Wang N, Wang J, Wang S, Zhan P. The implementation and test for HIL real-time simulation of doubly-fed induction generator based on FPGA. Paper presented at: 22nd International Conference on Electrical Machines and Systems (ICEMS); 2019; Harbin: IEEE:1-5.

35. Soued S. Experimental behaviour analysis for optimally controlled standalone DFIG system. *IET Electr Power Appl.* 2019;13(10):1462-1473.

36. Zakaria Moustafa MM, Nzimako O, Dekhordi A. Real time simulation of a wind turbine driven doubly fed induction generator. Paper presented at: 19th European Conference on Power Electronics and Applications (EPE’17 ECCE Europe); 2017; Warsaw: IEEE: P1-P10.

37. Maharjan R, Kamalasadan S. Real-time simulation for active and reactive power control of doubly fed induction generator. North American Power Symposium (NAPS). Manhattan, NY: IEEE; 2013:1-6.

38. Jaladi KK, Sandhu KS. Real-time simulator based hybrid control of DFIG-WES. *ISA Trans.* 2019;93:325-340.

39. Thomas T, Cheriyan EP. Wind energy system for a laboratory scale micro-grid. Paper presented at: IEEE Students’ Conference on Electrical, Electronics and Computer Science; 2012; Bhopal: IEEE:1-5.

40. Abad G, Lopez J, Rodriguez M, Marroyo L, Iwanski G. Doubly fed induction machine: modeling and control for wind energy generation. John Wiley & Sons, Inc., Hoboken, New Jersey: Wiley-IEEE Press; 2011.
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