A New Structure for PMG-Based WECSs With Battery Storage Systems

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ABSTRACT This paper develops and tests the performance of a new structure for grid-connected permanent magnet generator (PMG)-based wind energy conversion systems (WECSs) that have battery storage units (BSUs). The new structure is called the split dc-bus, and it is designed to reduce the pulsations in PMG developed torque and fluctuations in the power delivered to the grid. The reduction in PMG torque pulsations is achieved by employing a 5-level ac-dc power electronic converter (PEC) as the generator-PEC, whose dc outputs are processed by a two-port active dc-link. This active dc-link charges the BSUs and supplies the discharging PEC. The reduction of fluctuations in the delivered power is achieved by discharging the BSUs at point-of-common-coupling (PCC). The generator-side PEC, dc-link, grid-side PEC, and discharging PEC, are operated by a supervisor droop controller. The split-dc bus PMG-based WECS is implemented for performance testing under different wind speeds and levels of power delivery. Test results demonstrate reductions in PMG torque pulsations, along with reductions in the power delivered to the grid. These features of the split-dc bus PMG-based WECS are found to be complimented with a minor sensitivity to the changes in wind speed and changes in the power delivered to the grid.

INDEX TERMS Battery storage systems, wind energy conversion systems, permanent magnet generators, torque pulsations, and frequency variations.

I. INTRODUCTION

A. GENERAL

Over the past few years, several power systems have been integrating different types of renewable energy sources (REs) to offset the power production of conventional generation units [1]–[6]. The integration of REs has allowed introducing the generation mix, where conventional generation units and REs (e.g. wind energy conversion systems (WECSs)) can be dispatched to meet load demands. Permanent magnet generator (PMG)-based WECSs have shown remarkable potentials for grid-connected operation. Such potentials are supported by rapid advancements in power electronic converters (PECs), control systems, and instrumentation. PMG-based WECSs are manufactured with power ratings to accommodate a wide range of operating conditions [7]–[10]. However, the integration of PMG-Based WECSs can create impacts on the host power system. Among such impacts is the frequency variations at the point-of-common-coupling (PCC) due to continuous variations in PMG power generation resulting from wind speed variations [11]–[15]. In addition, the employment of PECs in PMG-based WECSs leads to harmonic components in PMG stator currents, which produce torque pulsations. Torque pulsations cause mechanical vibrations in turbine components, and impose limits on the power generated by a PMG [16]–[21].

B. REVIEW OF METHODS TO MITIGATE FREQUENCY VARIATIONS

The intermittency in the power generated by WECSs has prompted the development of methods to mitigate frequency variations at a PCC. These methods include the maximum-power-point-tracking (MPPT) control and collector systems for multiple WECSs [7]–[9]. Other methods have proposed the use of energy storage units (fly-wheels, battery banks, etc.) to mitigate frequency variations at a PCC [9]–[12]. The introduction of energy storage is supported by the recent advancements in energy storage units for power system applications [14]–[18]. Battery storage units (BSUs) have demonstrated several advantages over other energy storage systems for power system applications. The fast response, modular
Achieving these objectives supports the following contributions:

i) The implementation of a new structure for PMG-based WECSs with BSUs.

ii) The performance testing of the new structure for PMG-based WECSs under different operating conditions.

II. MODELING A PMG-BASED WECS

A. POWER GENERATION OF A PMG

PMG-based WECSs have an advantage of generating power over a wide range of wind speeds. This advantage can be exploited by employing PECs to regulate the variations in the generated power (due to changes in wind speed) prior to its utilization [1]–[6]. The active power generated by a PMG, \((P_e)_{PMG}\), is a function of the wind speed \(v_w\), air density \(\rho\), efficiency of the PMG \(\eta_{PMG}\), and the turbine sweep radius \(r\) as [18], [23]:

\[
(P_e)_{PMG} = \left(\frac{\eta_{PMG}}{2}\right) C_p \rho \pi r^2 v_w^3 = (K_{PMG}) v_w^3
\]

where \(C_p\) is the power coefficient. Typical values of \(\eta_{PMG}\) are selected as 85% \(\leq \eta_{PMG} \leq 95\%\) [23].

B. TORQUE PULSATIONS OF A PMG

The wind turbine and PMG assembly experiences exerted mechanical and developed electromagnetic torques. In such an assembly, the wind turbine exerts the mechanical torque \(T_m\), and the PMG develops the counter electromagnetic torque \(T_e\). Theses two torques can be mathematically stated as:

\[
T_m = \frac{1}{2} \rho \pi r^3 \left(\frac{C_p}{\lambda}\right) v_w^3 + J_r \left(\frac{d\omega_s}{dt}\right)
\]

\[
T_e = \frac{3}{4} \rho (L_d - L_q) i_d i_q - \psi i_q + J_g \left(\frac{d\omega_s}{dt}\right)
\]

where \(\omega_s\) is drive-shaft speed, \(\lambda\) is the tip-speed ratio, \(J_r\) is the inertia constant of the turbine and drive-shaft, \(J_g\) is the inertia constant of the PMG rotor, \(\rho\) is the number of stator poles, \(L_d\) and \(L_q\) are the \(d-q\) axis components of the stator inductance, \(i_d\) and \(i_q\) are the \(d-q\) axis components of the stator currents, and \(\psi\) is the flux constant of the rotor magnets. Torques \(T_m\) and \(T_e\) can be used to express the dynamics of the wind turbine and PMG assembly as:

\[
T_m = T_e + J \left(\frac{d\omega_s}{dt}\right) + B \Omega_g
\]

where \(J\) is the equivalent inertia constant of the wind turbine and PMG assembly, and \(B\) is the coefficient of friction. A change in the wind speed can cause a mismatch between exerted and developed torques, that is:

\[
\Delta T = T_m - T_e \neq B \omega_g
\]

Such a mismatch results in \(\frac{d\omega_s}{dt} \neq 0\), thus triggering torque pulsations as the wind turbine and PMG assembly attempts to regain a steady-state condition. In addition, \(\Delta T\) can be

C. PAPER OBJECTIVES AND CONTRIBUTIONS

The challenges of reducing PMG torque pulsations and eliminating frequency variations, can be overcome by a new structure of PMG-based WECSs with BSUs. This paper intends to overcome these challenges through achieving the following objectives:

- Developing a new structure for PMG-based WECSs with BSUs. The new structure is called the split-dc bus.
- Evaluating the ability of the split-dc bus structure to reduce torque pulsations and eliminate frequency variations.
impacted by changes in \(i_d\) and \(i_q\) that can be triggered by harmonics in PMG stator currents. Harmonics in PMG stator currents create a time varying components in \(T_e\) that cause \(\Delta T \neq 0\). As the wind turbine and PMG assembly attempts to reach a steady-state condition, counter mechanical torques are developed in a form of mechanical vibrations experienced by the wind turbine and PMG assembly [17], [23].

**C. FREQUENCY VARIATIONS AT PCC**

Changes in the wind speed \(v_w\) causes fluctuations in the power injected \((P_i)\) into the PCC. Such fluctuations in \(P_i\) create frequency variations that may violate the grid-connection requirements. The active and reactive powers injected by the PMG-based WECS into the host grid can be stated as:

\[
P_i = \frac{1}{X_L} (V_i V_G \sin(\delta)) : \delta \in [-\pi, \pi]
\]

\[
Q_i = \frac{1}{X_L} (V_i^2 - V_i V_G \cos(\delta)) : \delta \in [-\pi, \pi]
\]

In majority of grid-connected WECSs, current controllers are used to regulate the power injection into the host grid. Actions of such controllers aim to adjust the angle \(\delta\) to regulate \(P_i\), and control \(V_t\) to regulate \(Q_i\) [23]. Changes in \(P_i\) can trigger frequency variations that can be expressed as (see Appendix B for the derivation):

\[
\Delta f = \frac{V_i V_G \sin(\Delta \delta) \cos(\delta) - X_L \Delta P_i}{2\pi L (P_i + \Delta P_i)}
\]

where \(f\) is the frequency of the host grid, \(L\) is the equivalent inductance of the grid-tie filter and grid-connection transformer, and \(\Delta \delta\) is the change in \(\delta\) due to \(\Delta P_i\).

The expression for \(\Delta T\) indicates that changes in wind speed and PMG stator currents can create torque pulsations. These torque pulsations vary \(P_i\), which in turn leads to \(\Delta f \neq 0\). A basic approach to reduce \(\Delta T\) is founded by reducing harmonic components in PMG stator currents. An effective reduction of such harmonic components can ensure \(\Delta P_i \rightarrow 0\), and help reducing \(\Delta f\) at the PCC. Furthermore, the employment of a controlled source of active power injection into the PCC can support the regulation of \(P_i\), and maintain \(\Delta f \rightarrow 0\).

**III. THE SPLIT-DC BUS FOR PMG-BASED WECSs**

The previous section has shown that harmonics in PMG stator currents contribute to creating torque pulsations in PMGs. Torque pulsations can cause mechanical vibrations, damages to PMG rotor bearings, fluctuations in PMG generated power, damages to dc-link components, etc. [21]–[23]. The minimization of such harmonics can be a key to reduce PMG torque pulsations. One of the approaches to achieve this objective is the use of a multi-level ac-dc PEC as a generator-side PEC. However, a multi-level generator-side ac-dc PEC requires a special design of the dc-link to process its dc outputs [21].

**A. A MULTI-LEVEL GENERATOR-SIDE AC-DC PEC**

Several reported works have recommended multi-level PECs to employed as generator-side PECs in PMG-based WECSs. Reference [18] has developed a new multi-level ac-dc PEC (called the modified cascaded H-bridge (MCHB)) for PMG-based WECSs. The MCHB ac-dc PEC has shown a promising ability to reduce the harmonics in its input ac currents. This ability is supported by series combinations of switching elements in each leg for each level, where one dc output is produced. Furthermore, since the MCHB ac-dc PEC does not use capacitors, it may have minor interactions with PMG stator windings [18], [22]. Finally, the structure of the MCHB ac-dc PEC ensures independent output dc voltages \((V_{d1} \text{ and } V_{d2})\). This feature is an advantage, as it eliminates the need for actions to balance \(V_{d1}\) and \(V_{d2}\) [18]. Fig. 2 shows a circuit diagram for a 5-level MCHB ac-dc PEC, which is used in this paper.

A 5-level MCHB ac-dc PEC (used in this paper) produces two dc output voltages. One dc output voltage is continuous \((V_{d1})\), while the other dc output voltage \((V_{d2})\) is discontinuous. Both dc output voltages can be regulated by using pulse-width modulated (PWM) techniques, including the level-shifted PWM (LSPWM) that is used in this paper [18], [21].

**B. THE DC-LINK**

The 5-level MCHB ac-dc generator-side PEC produces two independent dc outputs, which can be regulated using a multi-port dc-link. In reference [21], a new active multi-port dc-link has been developed and tested for regulating the dc outputs of a multi-level MCHB ac-dc PEC. This dc-link is based on splitting the dc bus at the input side of the dc-link to create two independent regulated dc outputs. One output of the dc-link \((V_{d1})\) feeds the grid-side dc-ac PEC, while the other output \((V_{d2})\) charges the BSUs. The active multi-port dc-link is constructed using two dc-dc PECs, one is a boost dc-dc PEC and the other is a reverse fly-back dc-dc PEC. A circuit diagram for the active multi-port dc-link is shown in Fig. 3.

The boost dc-dc PEC operates with a continuous dc input voltage, and produces a continuous regulated dc voltage, which is fed the grid-side dc-ac PEC. The reverse fly-back dc-dc PEC operates with a discontinuous dc input voltage, and produces a continuous regulated dc voltage to charge...
the BSUs. The high frequency transformer (in the reverse fly-back dc-dc PEC) guarantees the stability and continuity of the charging current supplied to the BSUs [21].

### C. CONSTRUCTING THE SPLIT-DC BUS PMG-BASED WECS

The selection of the 5-level generator-side ac-dc PEC and multi-port dc-link allows constructing the split-dc bus PMG-based WECS with BSUs. This WECS structure aims to minimize $\Delta T$ and maintain $\Delta f \rightarrow 0$ at the PCC. These objectives are met by creating multiple paths for the power flow from the PMG to PCC (see Fig. 4). Fig. 4 shows dc-link outputs are split into a primary rail (feeds the grid-side dc-ac PEC), and a secondary rail (charges the BSUs). The grid-side dc-ac PEC is grid-connected via a grid-tie filter and a 3φ transformer. Furthermore, the BSUs have their discharge dc-ac PEC grid-connected via a grid-tie filter and a 3φ transformer. The multiple paths for the power flow facilitate having $\Delta f \rightarrow 0$ at the PCC. In addition, the multiple paths for the power flow facilitate an independent control of the power injected through each path.

### IV. CONTROLLERS FOR SPLIT-DC BUS PMG-BASED WECS

The split-dc bus PMG-based WECS has several PECs operated and controlled to minimize $\Delta T$ and achieve $\Delta f \rightarrow 0$ at the PCC. Fig. 4 shows the layout of the proposed split-dc bus PMG-based WECS with all PECs and their controllers.

Controllers to operate PECs in a split-dc bus PMG-based WECS can be summarized as:

(i) Generator-Side PEC Controller: Inputs to this controller are the 3φ voltages on the terminal of the PMG and the command active and reactive powers ($P_1^*$ and $Q_1^* = 0$), while its outputs are switching pulses to operate the 5-level generator-side ac-dc PEC. The command active and reactive powers are provided by the supervisory power controller. The generator-side PEC controller is designed as a proportional-integral (PI) decoupled current (DC) controller, where $P_1^*$ and $Q_1^*$ are converted into command $d-q$-axis currents ($i_{ds}^*$ and $i_{qs}^*$) as [18], [19]:

$$i_{ds}^* = \frac{v_{ds}}{v_{qs}} i_{qs}^*$$  
$$i_{qs}^* = \frac{2v_{qs}}{3\left(v_{ds}^2 + v_{qs}^2\right)} P_1^*$$  \hspace{1cm} (9)

where $v_{ds}$ and $v_{qs}$ are the $d-q$-axis components of the PMG output voltages. Fig. 5 shows a block diagram for the PI-DC controller.

(ii) Controller for the Boost DC-DC PEC: The stability and functionality of the grid-side dc-ac PEC are dependent on its input dc voltage $V_D$. In order to regulate $V_D$, a PI controller is designed to operate the boost dc-dc PEC. A block diagram for this controller is shown Fig. 6.

(iii) Controller for the Reverse Fly-back DC-DC PEC: The reverse fly-back dc-dc PEC is responsible for charging the BSUs. A PI controller is designed to adjust the charging current $I_{CH}^*$, as shown in Fig. 7. The command charging current, $I_{CH}^*$, is calculated as:

$$I_{CH}^* = \frac{P_{CH}^*}{V_B}$$  \hspace{1cm} (10)

where $P_{CH}^*$ is the command power determined by the supervisory power controller, and $V_B$ is the voltage on terminals of the BSUs. The determined value of $I_{CH}^*$ is used to set the duty cycle $D$ for the reverse fly-back (charging) PEC. It should be noted that when...
the BSUs are not being charged, the PI controller maintains a trickle-charge set-point. This setting maintains the state-of-charge of BSUs, and allows a currents flow on the input side of the reverse fly-back dc-dc PEC [21].

(iv) Controller of the Grid-Side PEC: This dc-ac PEC is tasked with delivering stable and controllable power into the PCC. The PI current controller (CC) (see Fig. 8) is widely for operating grid-connected dc-ac PECs. These controllers can offer an independent control the active and reactive powers delivered to the grid. Command currents $i_{d1}^*$, $i_{q1}^*$ for this PI controller are determined as [23]:

$$i_{d1}^* = \frac{2P_D^*}{3v_d} - \frac{v_d}{v_d} i_{q1}^*$$  \hspace{1cm} (11)

$$i_{q1}^* = \frac{2v_d^2}{3(v_d^2 + v_q^2)} \left( \frac{Q_D^*}{v_d} + \frac{v_q}{v_d} P_D^* \right)$$  \hspace{1cm} (12)

The space-vector modulator (SVM) is selected to generate the switching pulses for the grid-side dc-ac PEC.

In addition, $v_d^*$ and $v_q^*$ are used to calculate a command value for the dc link voltage ($V_D^*$) as:

$$V_D^* = \frac{\pi}{2} \sqrt{(v_d^*)^2 + (v_q^*)^2}$$  \hspace{1cm} (13)

A similar PI current controller is designed to operate the discharge dc-ac PEC. The command currents $i_{d2}^*$, $i_{q2}^*$ are determined as:

$$i_{d2}^* = \frac{2P_{DS}^*}{3v_d} - \frac{v_d}{v_d} i_{q2}^*$$  \hspace{1cm} (14)

$$i_{q2}^* = \frac{2v_d^2}{3(v_d^2 + v_q^2)} \left( \frac{Q_{DS}^*}{v_d} + \frac{v_q}{v_d} P_{DS}^* \right)$$  \hspace{1cm} (15)

(v) Supervisory Power Controller: This controller generates values of the command active and reactive powers for all other controllers. It is designed as two PI droop controllers; one for the frequency and another for the voltage. Droop controllers determine the deviations in the frequency ($\Delta f$) and voltage ($\Delta V$), and use them to adjust the command powers for all controllers. Frequency and voltage deviations are determined as:

$$\Delta f = f_o - f$$

$$\Delta V = V_o - V$$

where $f_o$ is the grid frequency, $V_o$ is the voltage at the PCC. These droop controllers are designed as [24]:

$$\Delta f = -k_{PP} (P_i^* - P_i) - k_{fP} \int (P_i^* - P_i) dt$$  \hspace{1cm} (16)

$$\Delta V = -k_{PQ} (Q_i^* - Q_i) - k_{IQ} \int (Q_i^* - Q_i) dt$$  \hspace{1cm} (17)

where $k_{PP}$ and $k_{fP}$ are the parameters of the PI frequency droop controller, $k_{PQ}$ and $k_{IQ}$ are the parameters of the PI voltage droop controller. $P_i^*$ and $Q_i^*$ are command values of the active and reactive powers injected into the PCC, and $P_i$ and $Q_i$ are the actual active and reactive powers injected into the PCC. The values of $P_i$ and $Q_i$ are determined as:

$$P_i = P_d + P_{DS}$$

$$Q_i = Q_d + Q_{DS}$$  \hspace{1cm} (18)

where $P_d$ and $P_{DS}$ are the active powers delivered by the grid-side and discharge dc-ac PECs, and $Q_d$ and $Q_{DS}$ are the reactive powers delivered by the grid-side and discharge dc-ac PECs. Values of command active and reactive powers generated by the supervisory controller are set as:

- Using the wind speed $v_w$, values of $P1^*$ and $Q1^*$ are:

$$P1^* = \eta_{PMG} (K_{PMG}) v_w^3$$

$$Q1^* = 0$$  \hspace{1cm} (19)

- Using $P_i^*$, $P_i$, and state-of-charge ($S$) of BSUs, $P_{CH}^*$ is set as:

$$P_{CH}^* = \begin{cases} 
\hat{P1}^* - P_i^* & P_i^* > P_i^* \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (20)
where \( \hat{P}_1^* \) is given as:

\[
\hat{P}_1^* = \frac{P_i}{(P_{e, \text{PMG}})} \times P_1^*
\]

The value of \( S \) is estimated at sample \( n \) as [25]:

\[
S[n] = \begin{cases} 
S[n-1] - \frac{I_{DS[n]} T_S}{Q_R} & \text{Discharging} \\
S[n-1] + \frac{I_{CH[n]} T_S}{Q_R} & \text{Charging}
\end{cases}
\]

(21)

where \( I_{DS[n]} \) is the \( n \)-th sample of the discharge current, \( Q_R \) is the battery nominal capacity (provided by the manufacturer), and \( T_S \) is the sampling time.

- Using \( P_i^*, P_{CH}^*, \text{and } P_i^*, \) the value of \( P_d^* \) is set as:

\[
P_d^* = \begin{cases} 
\hat{P}_1^* - P_{CH}^* & P_1^* > P_i^* \\
\hat{P}_1^* - P_{DS}^* & \text{otherwise}
\end{cases}
\]

(22)

The command reactive power \( Q_d^* \) is set as:

\[
Q_d^* = \begin{cases} 
Q_i^* & P_1^* > P_i^* \\
Q_i^* - Q_{DS}^* & \text{otherwise}
\end{cases}
\]

(23)

- Using \( P_i^* \) and \( P_d^* \), the value of \( P_{DS}^* \) is set as:

\[
P_{DS}^* = \begin{cases} 
P_i^* - P_d^* & P_1^* \leq P_i^* \text{ and } S \geq 0.7 \\
0 & \text{otherwise}
\end{cases}
\]

(24)

The command reactive power \( Q_{DS}^* \) is set as:

\[
Q_{DS}^* = \begin{cases} 
Q_i^* - Q_d^* & Q_i^* \geq Q_d^* \text{ and } S \geq 0.7 \\
0 & \text{otherwise}
\end{cases}
\]

(25)

The values of \( P_d^*, Q_d^*, P_{CH}^*, P_{DS}^*, Q_{DS}^*, \text{and } \text{state-of-charge } S \), are updated each \( T_S \).

V. SIMULATED PERFORMANCE OF SPLIT-DC BUS WECS

The split-dc bus PMG-based WECS was constructed as a 60 kW, grid-connected WECS with a 40 kW battery bank. Fig. 9 shows a schematic diagram for the test system, and Table 1 lists its specifications.

Moreover, Table 2 provides parameters for the droop controllers used in the supervisory controller.

The values for \( K_{P1}, T_{I1}, K_{PV}, K_{IC}, T_{IL}, K_{P2}, \text{and } K_{I2} \) were determined using the pole-placement method [24]. The test split-dc bus PMG-based WECS was constructed using a MATLAB/SIMULINK model with the data in Table 1 and Table 2. The constructed model was operated under different wind speeds and levels of power delivery to the grid.

A. VARIABLE WIND SPEED AND VARIABLE POWER DELIVERY

This test aimed to investigate the performance of the split-dc bus PMG-based WECS for a variable wind speed and a variable power delivery to the grid. During this simulation test, the wind speed and power delivery to the grid were varied as:

\[
v_w = 5 \frac{t=9}{t=6} 8 \frac{t=16}{t=6} 6 \text{ m/sec.}
\]

(26)

| TABLE 1. Specifications for the 60 kW split-DC bus PMG-based WECS. |
| --- | --- |
| **Wind Turbine** | 3-Blade, Direct-Coupled |
| **Turbine Constant** \( K_{PMG} \) | 112.44 kNm |
| **PMG** | Rated Power and Terminal Voltage: 73 kW, 480 V  
Number of Poles: 12  
Stator Resistance \( R_s \): 0.048 Ω/Phase  
D = q-axis Inductance \( L_q = 4.64 \text{ mH} \)  
Voltage-Flux Constant \( \psi_f \): 0.567 V/rad/s |
| **Generator-Side AC-DC PEC** | Structure: 5-Level MCHB  
Rated Power and Voltage: 100 kW and 600 V  
Switching Elements: 18 IGBTs  
Switching Frequency: 1.08 kHz  
DC Link Controller: \( K_{P1} = 7.75, T_{I1} = 0.023 \)  
Outputs: 18 LSPWM Switching Signals |
| **DC-Link: Part 1** | Construction: Boost DC-DC PEC  
Inductance and Capacitance: \( L = 2.25 \text{ mH}, C_1 = 360 \mu F \)  
Switching Frequency: 50 kHz  
DC-Link: Part 2 | PI Voltage Controller: \( K_{Pc} = 0.003, T_{Ic} = 0.059 \)  
Outputs: 1 Switching Signal |
| **Grid-Side DC-AC PEC** | Construction: Isolated DC-DC PEC  
Inductance and Capacitance: \( L_{mp} = 2.5 \mu H, C_2 = 380 \mu F \)  
Switching Frequency: 13.0 kHz  
PI Charge Controller: \( K_{P2} = 0.122, T_{I2} = 25.625 \)  
Outputs: 6 Switching Signals |
| **Discharge DC-AC PEC** | Rated Power and Voltage: 73 kW, 600 V  
Switching Elements: 6 IGBTs  
Switching Frequency: 1.74 kHz  
Switching Frequency: 1.74 kHz  
Output Control: \( K_{P2} = 1.40, T_{I2} = 4.00 \)  
Output Control: 6 Switching Signals |

*IGBT: Insulated gate bipolar transistor;  
MCHB: modified Cascaded H-Bridge;  
PI: Proportional-Integral;  
4 x 10: 4 parallel strings, each has 10 series-connected battery units.

| TABLE 2. Parameters of the droop controllers. |
| --- | --- |
| \( P_i^* \) | 30 \( \frac{t=6}{t=5} \) 40 \( \frac{t=9}{t=6} \) 20 kW |
| \( Q_i^* \) | 12 kVAR |
generator-side PEC was able to supply the first dc bus with active power following the command value \( P_e^* \) set by the supervisory controller based on \( v_w \). The close match between \( P_e \) and \( P_e^* \) (Fig. 10 (c)) was achieved by adjusting \( T_{se} \), which regulated the PMG speed (Fig. 10 (a)) in response to changes in \( P_e^* \) and \( v_w \). The power fed to the first dc bus allowed the grid-side PEC to deliver its power with a close match to \( P_d^* \) and \( Q_d^* \) (Fig. 10 (d)). When \( P_e < P_i \), the supervisory controller discharged the BSUs to ensure a close match between \( P_i \) and \( Q_i \) with \( P_i^* \) and \( Q_i^* \). When \( P_e^* \) was decreased, the supervisory controller charged the BSUs to ensure \( P_e \) closely follow \( P_e^* \). The results of this test demonstrated the abilities of the split-dc bus PMG-based WECS to maintain a close match between the power delivered to the grid and its command values (Fig. 10 (f)). These capabilities remained consistent for different wind speeds and different power delivery to the grid.

**VI. EXPERIMENTAL TEST RESULTS**

The experimental testing of the split-dc bus was conducted using a 7.5 kW, grid-connected, PMG-based WECS with a 3.52 kW BSUs. The experimental setup of the test system was implemented with software and hardware parts. Appendix A provides details for the experimental setup.
FIGURE 11. Experimental results for the split-dc bus PMG-based WECS, when operated for a constant wind speed and a variable power delivery to the grid: (a) The PMG speed $\omega_g$, developed torque $T_e$, and command actual power delivered to the boost dc-dc PEC ($P_e^*$ and $P_e$). $\omega_g$ scale is 50 (rad/sec.)/Div., $T_e$ scale is 15 N.m/Div., and time scale is 50 sec./Div. (b) The command and actual charging power ($P_{CH}^*$ and $P_{CH}$), battery charging $I_{CH}$ and discharging $I_{DS}$ currents. $P_{CH}$ scale is 0.2 kW/Div., $I_{CH}$ scale is 2 A/Div., $I_{DS}$ scale is 5 A/Div., and time scale is 50 sec./Div. (c) The command and actual discharge active ($P_{DS}^*$ and $P_{DS}$) and reactive ($Q_{DS}^*$ and $Q_{DS}$) powers. $P_{DS}$ scale is 0.3 kW/Div., $Q_{DS}$ scale is 0.1 kVAR/Div., and time scale is 50 sec./Div. (d) command and actual active ($P_i^*$ and $P_i$) and reactive ($Q_i^*$ and $Q_i$) powers delivered to the host grid. $P_i$ scale is 3.0 kW/Div., $Q_i$ scale is 1.5 kVAR/Div., and time scale is 50 sec./Div. (e) The 3φ currents on the secondary side of Transformer 1. Current scale is 20 A/Div. and time scale is 50 sec./Div. (f) The 3φ currents on the secondary side of Transformer 2. Current scale is 10 A/Div. and time scale is 50 sec./Div. (e1) Zoomed-in of the 3φ currents on the secondary side of Transformer 1. (f1) Zoomed-in of the 3φ currents on the secondary side of Transformer 2.

A. FIXED WIND SPEED AND VARIABLE POWER DELIVERY

The objective of this test was to operate the split-dc bus PMG-based WECS for a variable power delivery to the grid at a fixed wind speed ($\Omega_g = 62$ rad/sec.). In this test, the power delivery to the grid was varied as:

$$P_i^* = 2.5 \rightarrow 4.0 \rightarrow 2.5 \rightarrow 5.0 \rightarrow 2.5 \text{ kW} \quad (29)$$
$$Q_i^* = 1.5 \rightarrow 2.0 \rightarrow 2.0 \text{ kVAR} \quad (30)$$

The results collected for this test are shown in Fig. 11.

Fig. 11 shows that the split-dc bus PMG-based WECS was able to produce power to match the command values for power delivery. This ability was achieved by accurate responses of all controllers. The generator-side ac-dc PEC was able to supply the first dc bus with $P_e^*$ set by the supervisory controller (Fig. 11 (a)). The power fed to the first dc bus allowed operating the grid-side PEC to deliver its power following $P_i^*$ and $Q_i^*$ (Fig. 11 (d)). When $P_e$ was less than $P_i$, the BSUs were discharged to ensure a close match between $P_i$ and $Q_i$ with $P_e^*$ and $Q_e^*$. When $P_i^*$ was decreased, the BSUs were charged. The results of this test confirmed the capabilities that were observed in simulation tests, where the split-dc bus PMG-based WECS was able to maintain a close match between the power delivered to the grid and it command values. These capabilities remained consistent for different levels of power delivery to the grid.
FIGURE 13. Photographs of the experimental setup of the 7.5 kW split-dc bus PMG-based WECS with the 3.52 kW battery storage system.

TABLE 3. A comparison between the split-DC bus, Hybrid-BSS, and conventional PMG-based WECSs.

| Criteria                          | Split-DC Bus | Hybrid-BSS | Conventional |
|----------------------------------|--------------|------------|--------------|
| DC-Link                          |              |            |              |
|                                  | Active       | Active     | Active or    |
|                                  | Multi-port   | Two-port   | Passive      |
| $\eta$ [Average]                 | 86%          | 83%        | 90%          |
| $\Delta P_f$ [max.]              | 10%          | 16%        | 23%          |
| $\Delta f$ [max.]                | 3.8%         | 8.4%       | 12.2%        |
| $\Delta T_T$ [Hz]                | 0.022 Hz     | 0.031 Hz   | 0.040 Hz     |

the grid, without producing high torque pulsations or harmonic components (Fig. 11 (e) and (e1)). Several test were conducted for different wind speeds with rated power delivery to the grid. For each wind speed, the fluctuations in the active power ($\Delta P_f$) delivered to the grid, frequency change ($\Delta f$) at the PCC, and PMG torque pulsations ($\Delta T_T$) were calculated. Fig. 12 shows $\Delta P_f$, $\Delta f$, and $\Delta T_T$ for $v_w = 4, 5, \ldots, 15$ m/sec. Another demonstration of the advantages of the split-dc bus PMG-based WECS, is provided in Table 3, which summarizes a comparison with the hybrid-BSS and conventional PMG-based WECSs. The data for the hybrid-BSS and conventional PMG-based WECSs are obtained from discussions in references [9], [17], and [22].

VII. CONCLUSION

This paper has presented the development and testing of a split-dc bus structure for grid-connected PMG-based WECSs. The proposed WECS structure is developed to ensure reduced PMG torque pulsations and minimized frequency variations at the PCC. The reduction of PMG torque pulsations has been achieved by employing a 5-level MCHB ac-dc PEC as the generator-side PEC to reduce harmonics in PMG stator currents. This generator-side PEC produces two dc outputs, which are independently split to create a primary and a charging dc-links. The primary dc-link is implemented by a boost dc-dc PEC that is responsible for supplying the grid-side dc-ac PEC. The charging dc-link is implemented by a reverse fly-back dc-dc PEC that is responsible for charging BSUs. The responsiveness of the developed WECS is achieved by designing a controller for each PEC. Individual controllers are commanded by a droop supervisory controller. Test results for the developed split-dc bus PMG-based WECS have shown its ability to maintain reduced PMG torque pulsations and minimized frequency variations at the PCC for different wind speeds and/or levels of power delivery to the grid. Performance features of the developed WECS demonstrate validate its applicability.

APPENDIX A

THE EXPERIMENTAL SETUP

The setup for the 7.5 kW PMG-based WECS with a 3.52 kW battery storage was implemented with the following parts.

A. THE SOFTWARE PART

This part was implemented by three dSPACE ds1104 digital signal processing (DSP) boards, which were employed as:

i) The first DSP board implemented the PI-DC controller (to operate the generator-side 5-level ac-dc PEC) and voltage controller (to operate the boost dc-dc PEC). This DSP board was operated at a time step of $T_S = 200 \mu$s.

ii) The second DSP board implemented the charge controller (to operate the reverse fly-back dc-dc PEC) and PI current controller (to operate the discharge ac-dc PEC). Similar to the first DSP board, this DSP board was operated at a time step of $T_S = 200 \mu$s.

iii) The third DSP board implemented the PI current controller (to operate the grid-side dc-ac PEC) and droop controllers (to set the command powers for all other
TABLE 4. Data for the 7.5 kW split-DC bus PMG-based WECS.

| Wind Turbine Emulator | Variable Speed |
|-----------------------|----------------|
| PMG                   |                |
| Rated Power and Terminal Voltage | 7.5 kW, 280 V |
| Number of Poles | 8             |
| Stator Resistance | 1.24 1/Phase |
| d – q-axis Inductance | Ld = 21.3 mH, Lq = 24.2 mH |
| Voltage-Flux-Constant | v_f = 0.542 V/rd/s |
| Generator-Side AC-DC PEC |                |
| Structure | 5-Level Modified CHB |
| Rated Power and Voltage | 40 kW and 600 V |
| Switching Elements | 18 IGBTs |
| Switching Frequency | 1.08 kHz |
| PI DC Controller | Kp1 = 7.75, T1 = 0.023 |
| Outputs | 18 DSPPWM Switching Signals |
| DC-Link: Part 1 |                |
| Construction | Boost DC-DC PEC |
| Inductance and Capacitance | L = 2.2 mH, C1 = 470 μF |
| Switching Frequency | 3.5 kHz |
| PI Voltage Controller | Kp = 0.0013, T1 = 0.059 |
| Outputs | 1 Switching Signal |
| DC-Link: Part 2 |                |
| Construction | Isolated DC-DC PEC |
| Inductance and Capacitance | Lm = 2.5 mH, C2 = 390 μF |
| Switching Frequency | 18.0 kHz |
| PI Current Controller | Kp = 0.122, T1 = 25.625 |
| Outputs | 6 Switching Signals and V1 |
| Lead-Acid Battery Unit | 0.44 kW, 13 V |
| Battery Bank Layout | 2 × 4 units |
| Grid-Side DC-AC PEC |                |
| Rated Power and Voltage | 30 kW, 600 V |
| Switching Elements | 6 IGBTs |
| Switching Frequency | 1.74 kHz |
| PI Current Controller | Kp2 = 1.40, T1 = 4.00 |
| Outputs | 6 Switching Signals and V1 |
| Discharge DC-AC PEC |                |
| Rated Power and Voltage | 20 kW, 300 V |
| Switching Elements | 6 IGBTs |
| Switching Frequency | 1.74 kHz |
| PI Current Controller | Kp = 1.40, T1 = 4.00 |
| Outputs | 6 Switching Signals |
| Grid Connection Circuits |                |
| Grid Tie Filter | LCL |
| Filter Elements | L1 = 2.0 mH, L2 = 5.0 mH |
| 3Φ Transformer 1 | 10 kVA, ∆ – Y, 60 Hz, 208/220/240 V |
| 3Φ Transformer 2 | 5 kVA, ∆ – Y, 60 Hz, 480/100 V |
| Droop Controllers |                |
| PI Controllers | Kp = 1.25 x 10^-4, KP = 1.50 x 10^-4, KQ = 2.75 x 10^-4, KIQ = 1.00 x 10^-4 |
| Outputs | P1, Q1, P1, Q1 |

controllers). The third DSP board was operated at a time step of T_S = 200 μsec.

Required voltages and currents by each controller were measured and fed to the ADC ports of the three DSP boards. The angular position θ of the PMG rotor was measured by an optical incremental encoder, the output of which was to the first DSP board through an encoder interface [26]. The rotor speed ω_r was calculated by the backward difference interpolation method. The switching pulses produced for each PEC were fed to driver circuits before being applied to the gates of switching elements in each PEC. The data for all parts used to construct the experimental setup are listed in Table 4. Fig. 13 shows photographs for the experimental setup.

APPENDIX B
THE DERIVATION OF EQUATION (8)

A change in the active power (ΔP_i) injected into the host power system can be stated as:

\[
P_i + ΔP_i = \frac{V_iV_G \sin(δ + Δδ)}{2\pi L (f + Δf)} \tag{B-1}
\]

where \(f\) is the frequency of the host grid, \(L\) is the equivalent inductance of the grid-tie filter and grid-connection transformer, and \(Δδ\) is the change in \(δ\) due to \(ΔP_i\). It should be noted that equation (B-1) is stated based on the assumption that \(ΔP_i\) does not create any changes in \(V_i\) due to the controller actions. Recall that \(P_i\) can be expressed as:

\[
P_i = \frac{V_iV_G \sin(δ)}{X_L} \tag{B-2}
\]

Substituting equation (B-2) into equation (B-1), expanding \(\sin(δ + Δδ)\), and setting \(V = V_iV_G\) yield:

\[
ΔP_i = \frac{V (\sin(δ) + \sin(Δδ) \cos(δ))}{X_L + 2\pi L Δf} - \frac{V \sin(δ)}{X_L} \tag{B-3}
\]

In equation (B-3), an assumption is made as \(\cos(Δδ) \approx 1\). Equation (B-3) can be rearranged as:

\[
ΔP_i = \frac{X_L V (\sin(δ) + \sin(Δδ) \cos(δ))}{X_L^2 + X_L 2\pi L Δf} - \frac{V (X_L + 2\pi L Δf) \sin(δ)}{X_L^2 + X_L 2\pi L Δf} \tag{B-4}
\]

Equation (B-4) can be simplified as:

\[
X_L^2 + X_L 2\pi L Δf = \frac{X_L V (\sin(δ) \cos(δ) - V 2\pi L Δf \sin(δ))}{ΔP_i} \tag{B-5}
\]

Rearranging equation (B-5) produces:

\[
Δf = \frac{V \sin(Δδ) \cos(δ) - X_L ΔP_i}{ΔP_i} \tag{B-6}
\]

Equation (B-6) can be manipulated as:

\[
Δf \left(1 + \frac{P_i}{ΔP_i}\right) = \frac{V \sin(Δδ) \cos(δ) - X_L ΔP_i}{2\pi L ΔP_i} \tag{B-7}
\]

Finally, the change in the frequency \(Δf\) (due to a change in the active power injected by the PMG-based WECS into the host grid) can be obtained as:

\[
Δf = \frac{V_iV_G \sin(Δδ) \cos(δ) - X_L ΔP_i}{2\pi L (P_i + ΔP_i)} \tag{B-8}
\]
REFERENCES

[1] F. Blaabjerg, Y. Yang, D. Yang, and X. Wang, “Distributed power-generation systems and protection,” Proc. IEEE, vol. 105, no. 7, pp. 1311–1317, Jul. 2017.

[2] B. K. Bose, “Global energy scenario and impact of power electronics in 21st century,” IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2638–2651, Jul. 2013.

[3] F. Blaabjerg, R. Teodorescu, M. Lisserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[4] Z. Chen, J. M. Guerrero, and F. Blaabjerg, “A review of the state of the art of power electronics for wind turbines,” IEEE Trans. Power Electron., vol. 24, no. 8, pp. 1859–1875, Aug. 2009.

[5] F. Blaabjerg and K. Ma, “Wind energy systems,” Proc. IEEE, vol. 105, no. 11, pp. 2116–2131, Nov. 2013.

[6] M. Edrash, K. L. Lo, and O. Anaya-Lara, “Impacts of high penetration of DFIG wind turbines on rotor angle stability of power systems,” IEEE Trans. Sustain. Energy, vol. 6, no. 3, pp. 759–766, Jul. 2015.

[7] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya, and L. Anderson, “Control strategies for battery energy storage for wind farm dispatching,” IEEE Trans. Energy Convers., vol. 24, no. 3, pp. 725–732, Sep. 2009.

[8] J. Kabouris and F. D. Kanellos, “Impacts of large-scale wind penetration on designing and operation of electric power systems,” IEEE Trans. Sustain. Energy, vol. 1, no. 2, pp. 107–114, Jul. 2010.

[9] M. Gholami, S. H. Fathi, J. Milimonfared, Z. Chen, and F. Deng, “A new strategy based on hybrid battery–wind power system for wind power dispatching,” IET Gener., Transm. Distrib., vol. 12, no. 1, pp. 160–169, Jan. 2018.

[10] G. Wang, G. Konstantinou, C. D. Townsend, J. Pou, S. Vazquez, G. D. Demetriades, and V. G. Agelidis, “A review of power electronics for grid connection of utility-scale battery energy storage systems,” IEEE Trans. Sustain. Energy, vol. 7, no. 4, pp. 1778–1790, Jul. 2016.

[11] D. Bazargan, S. Filizadeh, and A. M. Gole, “Stability analysis of converter-connected battery energy storage systems in the grid,” IEEE Trans. Sustain. Energy, vol. 5, no. 4, pp. 1204–1212, Oct. 2014.

[12] X. Y. Wang, D. Mahinda Vilathgamuwa, and S. S. Choi, “Determination of battery storage capacity in energy buffer for wind farm,” IEEE Trans. Energy Convers., vol. 23, no. 3, pp. 868–878, Sep. 2008.

[13] J. Song-Manguelle, J.-M. Nyobe-Yome, and G. Ekemb, “Pulsating torques in PWM multi-megawatt drives for torsional analysis of large shafts,” IEEE Trans. Ind. Appl., vol. 46, no. 1, pp. 130–138, Jan. 2010.

[14] J. P. Barton and D. G. Infield, “Energy storage and its use with intermittent renewable energy,” IEEE Trans. Energy Convers., vol. 19, no. 2, pp. 441–448, Jun. 2004.

[15] D. L. Yao, S. S. Choi, K. J. Tseng, and T. T. Lie, “Determination of short-term power dispatch schedule for a wind farm incorporated with dual-battery energy storage scheme,” IEEE Trans. Sustain. Energy, vol. 3, no. 1, pp. 74–84, Jan. 2012.

[16] F. Zhang, Z. Xu, and K. Meng, “Optimal sizing of substation-scale energy storage station considering seasonal variations in wind energy,” IET Gener., Transm. Distrib., vol. 10, no. 13, pp. 3241–3250, Oct. 2016.

[17] Y. Hu, M. Odavic, and Z. Q. Zhu, “DC bus voltage pulsation suppression of the permanent magnet synchronous generator with asymmetry accounting for torque ripple,” IEEE Trans. Energy Convers., vol. 31, no. 3, pp. 1080–1089, Sep. 2016.

[18] S. A. Saleh, F. St. Onge, J. D. McLeod, and W. M. McGivney, “The experimental performance of a multi-level AC-DC power electronic converter for PMG-based WECSs,” in Proc. IEEE/IAS 53rd Ind. Commer. Power Syst. Tech. Conf. (ICPS), Niagara Falls, ON, Canada, May 2017, pp. 1–9.

[19] X. F. St. Onge and S. A. Saleh, “Split-DC bus for PMG-based WECSs with battery storage units,” in Proc. 56th IEEE IAS Ind. Commercial Power Syst. Tech. Conf. (I&CPS), Las Vegas, NV, USA, Apr. 2020, pp. 1–12.

[20] J. G. Slottweg, S. W. H. de Haan, H. Polinder, and W. L. Kling, “General model for representing variable speed wind turbines in power system dynamics simulations,” IEEE Trans. Power Syst., vol. 18, no. 1, pp. 144–151, Feb. 2003.

[21] X. F. St-Onge, C. Richard, K. M. McDonald, and S. A. Saleh, “Performance testing of an active multiport DC link for grid-connected PMG-based WECSs,” IEEE Trans. Ind. Appl., vol. 54, no. 6, pp. 5579–5589, Nov. 2018.

[22] M. Chinchilla, S. Arnaltes, and J. C. Burgos, “Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid,” IEEE Trans. Energy Convers., vol. 21, no. 1, pp. 130–136, Mar. 2006.

[23] S. A. Saleh, “Testing a unit commitment based controller for grid-connected PMG-based WECSs with generator-charged battery units,” IEEE Trans. Ind. Appl., vol. 55, no. 3, pp. 2185–2197, May 2019.

[24] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodriguez, and R. Teodorescu, “Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes,” IEEE Trans. Ind. Electron., vol. 56, no. 10, pp. 4088–4096, Oct. 2009.

[25] J. Chiasson and B. Vairamohan, “Estimating the state of charge of a battery,” IEEE Trans. Control Syst. Technol., vol. 13, no. 3, pp. 465–470, Apr. 2005.

[26] Digital Signal Processing and Control Engineering, dSPACE Gmbh, Paderborn, Germany, 2017.