This is an author produced version of a paper published in:
*The Journal of Engineering*

Cronfa URL for this paper: http://cronfa.swan.ac.uk/Record/cronfa45065

**Paper:**
http://dx.doi.org/10.1049/joe.2018.9359

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New control paradigm for both islanded and grid-connected operation of PMSG-based wind turbine

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Abstract: This article proposes a new control paradigm for the seamless operation of a permanent magnet synchronous generator (PMSG) based wind energy conversion system (WECS) in both islanded and grid-connected modes. Conventionally, grid-connected WECS are controlled to extract the maximum power from the wind, known as maximum power point tracking (MPPT). However, in islanded operation, the objective is to control the power generated from the WECS to match the load demand, which here is called load following power generation (LFGP). This article proposes a power management system (PMS) which integrates the MPPT and LFGP capabilities of the WECS into a single-control paradigm. This enables the WECS to seamlessly achieve MPPT in grid operation, LFGP in islanded mode and low-voltage ride-through (LVRT) during fault. The proposed scheme is validated using MATLAB/SIMULINK simulations.

1 Introduction
The increasing energy demands, depletion of fossil fuel reserves, and global warming have accelerated the implementation of renewable energy sources (RESs)-based distributed generators (DGs). DG units are usually connected in a cluster to form a microgrid which can operate independently or in parallel with the grid network [1, 2].

DG units designed for islanded operation are usually termed as grid-forming units; this is because they are equipped with control structures which enable regulation of the local voltage and frequency within stipulated standards. In this mode of operation, the power generated by the DG must match the load demand to maintain stable operating conditions [3, 4].

When DG units are operating in grid-connected mode, a synchronism mechanism, usually a phase-locked loop (PLL), is implemented to keep the DG units synchronised with the grid. This units are primarily required to exchange active and reactive power with the grid, since voltage and frequency are maintained by the grid [1, 5]. However, in the event of a fault on the grid side, the microgrid must be disconnected after a stipulated time frame. This will lead to power interruption to the local loads if the DG units are not equipped with grid-forming ability. Hence, to maximise the available RES and enhance power reliability to local loads, DG units must be capable of operating seamlessly in both grid-connected and islanded mode [3].

Several literatures have discussed control techniques of WECS in grid-connected or islanded mode; however, only a handful of previous arts have discussed control of the WECS in both modes. Erlich et al. [6] proposed a direct voltage control technique which regulates the voltage of the WECS following a fault on the grid side. An emergency-frequency controller was also designed to reduce power generation when frequency rises above nominal value. However, this control was only tested for transient periods of fault condition and its capability to effectively support local loads was not evaluated. In [7], the authors implemented the conventional droop control in both grid-connected and islanded operating modes. However, there is no provision for MPPT during normal operation. In addition, the adopted grid synchronisation scheme will not work for multiple systems, as this will lead to conflicting phase angles between the output from the droop and the grid voltage. Rizo et al. [8] proposed a single control structure for grid and islanded mode. The authors suggested using pitch control and breaking chopper to dump the excess power in islanded mode. However, the passive islanding technique implemented for transition from grid-connected to islanded mode suffers from a relatively large non-detection zone (NDZ) [9].

As discussed above, most of the earlier works do not guarantee optimal operating conditions in both operating modes simultaneously. In addition, they required some switching mechanism (from grid-connected to islanded mode of operation and vice versa), which may undermine the seamless operation of the system. This paper proposes a single-control paradigm for permanent magnet synchronous generator (PMSG)-based WECS that enables (1) seamless transition from grid-connected to islanded operation (and vice versa); (2) maximum power point tracking (MPPT) and load following power generation (LFGP) in grid-connected and islanded modes, respectively, (3) low-voltage ride-through (LVRT) capability during faults. This paper is organised as follows: A comprehensive description of the proposed control structure is presented in Section 2. Simulation results have been presented in Section 3 to corroborate the proposed control technique. Section 4 concludes the paper.

2 Proposed method
For the sake of simplicity in the presentation of the results, the understudy system (Fig. 1) consists of only one PMSG WECS. However, the control method can be implemented for large wind farms as well as DFIG-based WECS.

2.1 Wind turbine modelling
The mechanical power $P_m$ captured by the wind turbine is expressed by the following equation [10]:

$$P_m = 0.5 \rho \lambda \beta C_p(\lambda, \beta)$$

(1)

$$T_m = \frac{P_m}{\omega_r}$$

(2)

where $\rho$ is the air density in kg/m³, $A$ is the area swept by the turbine blades in m², $\nu$ is the wind speed in m/s, $T_m$ is mechanical torque in Nm, $\omega_r$ is the rotor speed in rad/s and $C_p(\lambda, \beta)$ is the power coefficient. The $C_p(\lambda, \beta)$ is a non-linear function of the tip speed ratio $\lambda$ and the pitch angle $\beta$, which is given by (3) and (4) [10]:

$$C_p(\lambda, \beta)$$

(3)

$$C_p(\lambda, \beta)$$

(4)
\[ C_p(\lambda, \beta) = 0.5176116 - 0.4\beta - 5e^{-21/\lambda} + 0.0068\lambda \]  
\[ \lambda_i - 0.08\beta - 0.035\beta^3 + 1 \]  
\[ \lambda_{i\text{opt}} \]  
\[ \lambda_{i\text{rated}} \]

Fig. 2 illustrates the power-speed characteristics of the wind turbine, where \( \omega_{i\text{opt-re}} \) refers to the minimum rotor speed at which the WECS begins to operate, \( \omega_{i\text{opt-max}} \) is the maximum operating speed of the rotor on the MPPT curve and \( \omega_{i\text{rated}} \) is the rated speed of the rotor. When WECS are connected to the grid, they are usually operated at MPPT. The MPPT curve defines the optimal rotor speed \( \omega_{i\text{opt}} \) that the WECS must maintain to extract the maximum power from the wind \( (P_m = P_{\text{max}}, \text{where } P_{\text{max}} \text{ is the maximum power available from the wind}).

However, for islanded operation, the mechanical power generated \( P_m \) must be curtailed to match the load demand \( P_L \) \( (P_m = P_L, P_m \leq P_{\text{max}}) \). To achieve this, the WECS is required to operate in the suboptimal power point region (SOPPT) which is to the right of the MPPT curve and \( \omega_{i\text{rated}} \) is the rated speed of the rotor. As illustrated in Fig. 2, for operation in SOPPT \( \omega_{i\text{opt}} > \omega_{i\text{opt-max}} \) when \( P_L < P_{\text{max}} \). In this scheme, the standard pitch angle control \[ \theta \] is only required when the rotor speed exceeds its rated value \( \omega_{i\text{opt}} > \omega_{i\text{rated}} \) or the mechanical power exceeds its rated capacity \( P_m > P_{\text{max}} \).

The drive train of the WECS is governed by (5) \[ 13]:

\[ J \frac{d\omega}{dt} = T_m - T_e - B\omega_i \]  

where \( J \) is the equivalent inertia of the turbine and the generator in Kg\(m^2\), \( B \) is the friction coefficient in Nms, and \( T_e \) is the electrical torque in Nm.

2.2 Machine-side converter control

The machine-side converter (MSC) regulates the electrical power \( P_e \) the PMSG extracts from the wind turbine. The PMSG is controlled in the \( d-q \) frame with the magnetic flux aligned with the rotor angle \( \theta \). The dynamic equation of the PMSG in the rotor-field coordinates is given by (6) and (7) \[ 14]:

\[ V_{sd} = L_d i_{sd} - R_i i_{sd} - L_m \omega_m i_{sq} \]  
\[ V_{sq} = L_q i_{sq} - R_i i_{sq} - \lambda_m \omega_i \]

where \( V_{sq}, V_{sd}, i_{sq}, i_{sd}, L_q, L_d \) represent the \( d-q \) component of the stator terminal voltages, current and self-inductances, respectively. \( \lambda_m \) is the rotor flux linkage, \( R_i \) is the stator resistance, and \( \omega_i \) is the rotor speed. The non-salient surface mounted PMSG \( (L_q = L_d) \) is implemented for this design and the electrical torque \( T_e \) and the active power \( P \) generated by the PMSG are given by (8) and (9), respectively \[ 14]:

\[ T_e = \frac{3}{2}(\lambda_m i_{sq}) \]  
\[ P_e = \frac{3}{2}(V_e i_{sq}) \]

In this scheme (Fig. 3), the MSC, unlike conventional schemes, controls the DC-link voltage \( V_{dc} \). Based on this design, the PMSG acts as a current source, whose power output \( P_e \) is strictly determined by the power reference \( P_{e*} \) from the grid-side converter (GSC). The magnitude of the active power \( P_e \) generated by the PMSG is governed by the power balance principle explained in (10), neglecting losses \[ 13]:
where $P_g$ is the power transferred to the GSC through the DC link and $C$ is the DC-link capacitor. From (10), it is evident that power balance is maintained by regulating $V_{dc}$ at the nominal value. In this scheme, $V_{dc}$ is regulated by comparing $V_{dc}^2$ with $V_{dc}^2$, the PI controller eliminates the steady-state error and provides $P_e^*$, for the power control loop as illustrated in Fig. 3. From (9), it is evident that the active power flow in the system is associated with zero to minimise ohmic losses and maximise available power [9, 11, 14].

### 2.3 Grid-side converter control

The GSC is the interface between the WECS and the grid network. It regulates power exchange and ensures safe operation of the grid-connected operation, and ensures LFPG in islanded mode. The proposed GSC employs a single-control paradigm, which enables MPPT in grid-connected operation, LFPG in islanded mode and LVRT during faults. The base of the GSC employed in this scheme is detailed in [9], the main addition is the proposed power management system (PMS). The GSC consists of three main components: virtual automatic voltage regulator (AVR), virtual governor, and the PMS. The standard $d$-$q$ frame current controllers have been implemented for this design [14] and the control structure is illustrated in Fig. 4.

#### 2.3.1 Virtual governor:

The role of the virtual governor in this scheme is to regulate the frequency $f$ of the microgrid within the nominal value. In grid-connected mode, the PLL ensures the GSC is synchronised with the grid and $f$ is dictated by the grid network. In islanded operation, the same PLL maintains the $q$-component of the voltage, $V_q$ at 0 and $f$ is maintained within acceptable standards, by varying $f$ in proportion to the current demand $I_d$ of the reactive load $Q_d$. Equation (11) explains the $I_q$-$f$ droop illustrated in Fig. 4 [9]:

$$\Delta I_q = K_f(f - f_0)$$

where the reference frequency $f_0 = 1$ pu and $K_f$ is the droop gain which is chosen according to the acceptable frequency deviations in the adopted standard (50 ± .1 Hz in UK).

The output of the $I_q - f$ droop is passed through a first-order low-pass filter $\tau$ to add similar damping characteristics available to the governor of the synchronous generator, where $0.064 < \tau < 0.64$ proves suitable for most applications [9].

#### 2.3.2 Virtual AVR:

The primary function of the Virtual AVR is to regulate the terminal voltage $V = \sqrt{V_d^2 + V_q^2}$ of the converter. In grid-connected operation, the voltage magnitude is maintained by the grid ($V_d \approx 1$ pu) and the WECS exchanges active power as required or dictated by the transmission system operator (TSO).

However, in islanded mode of operation, $V_d$ is varied in proportion to the current demand $I_d$ of the active load $P_L$ as illustrated in Fig. 4 and described in (12) [9]:

$$\Delta I_d = K_v(V_d - V_0)$$

where $V_0$ is the reference voltage ($V_0 = 1$ pu), and $K_v$ is the voltage droop gain.

$K_v$ is determined according to the voltage deviations acceptable by the adopted standards: 0.94 pu < $V$ < 1.07 pu. A 3% safety margin is employed to compensate for losses and voltage drop on transmission line and transformers, hence the droop employed ensures, 0.97 pu < $V$ < 1.07 pu [9]. The output of the $I_d - V$ droop is passed through a first-order low-pass filter to add dynamics which emulate the behaviour of the AVR in the synchronous generator, where $0.02 < \tau < 0.1$ proves suitable for most applications [9].

#### 2.3.3 Proposed power management system:

The proposed PMS regulates the power demanded from the MSC, enables MPPT in grid-connected operation, and ensures LFPG in islanded mode. The operation of the PMS is corroborated by the virtual AVR.
Table 1 System parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMSG rated power</td>
<td>2 MW</td>
</tr>
<tr>
<td>rated voltage</td>
<td>0.7 kV</td>
</tr>
<tr>
<td>rated rotor speed</td>
<td>3.1 rad/s</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>2 kV</td>
</tr>
<tr>
<td>DC link capacitance</td>
<td>4.5 mF</td>
</tr>
<tr>
<td>transformer rating</td>
<td>415/11 kV</td>
</tr>
<tr>
<td>transformers’ leakage reactance</td>
<td>8%</td>
</tr>
<tr>
<td>transmission line impedance Z_l</td>
<td>$R = 0.16,\Omega$, $L = 0.6,\text{mH}$</td>
</tr>
</tbody>
</table>

PMS is integrated to the GSC as illustrated in Fig. 4. In grid-connected operation, the PMS achieves MPPT ($P_{\text{PMS}} = P_{\text{max}}$) by ensuring $P_{\text{PMS}} = K_{\text{opt}}\omega^3$, where $P_{\text{PMS}}$ is the output power from the PMS, $\omega_r$ is the rotor speed and $K_{\text{opt}}$ is a constant denoting the optimal ratio required between $\omega_r$ and $P_m$ to achieve MPPT.

In grid-connected mode, since the voltage is maintained by the grid, $V_g \approx 1\,\text{pu}$, the output of the AVR, $I_{dL} \approx 0$, hence, $I_{d\_PMS} = I_{d^*}$ (see Fig. 4). In islanded operation (e.g., following a fault on the grid), $I_{d^*}$ is determined by the load demand. Hence, the WECS operates in the SOPPT region to reduce power generation. From Fig. 2, in this region, $\omega_r > \omega_{r\_\text{opt}}$ when $P_L < P_{\text{max}}$.

As discussed earlier, in islanded operation, the virtual AVR regulates $I_d$ in proportion to the current demand $I_{dL}$ of the load (see (12)). For $P_{\text{PMS}} \leq 1\,\text{pu}$, $I_d$ is regulated within nominal value, $I_{d^*} = I_{d\_PMS} + I_{d\_e}$ (see Fig. 4) and power generated precisely follows the load demand (LFPG).

However, for $\omega_r > \omega_{r\_\text{opt\_max}}$, since $P_{\text{PMS}} = K_{\text{opt}}\omega^3$, $P_{\text{PMS}} > 1$ pu, which exceeds the AVR capacity. This leads to the increase of $V_d$ beyond the nominal value and eventually the WECS operation becomes unstable. To prevent this scenario, the input $\omega_r$ signal is limited to $\omega_{r\_\text{opt\_max}} = 1\,\text{pu}$ (see Fig. 4). This ensures that, even though actual rotor speed in SOPPT may be greater than 1 pu, the maximum input signal to the PMS is $\omega_{r\_\text{opt\-max}} = 1\,\text{pu}$.

Based on this design, the PMS seamlessly enables MPPT when grid-connected and LFPG in islanded mode without switching control paradigms. It is noted that the WECS blades are not designed to be pitched constantly, as it may reduce the lifetime and increase the required maintenance. Moreover, the slow dynamics of the pitch controller makes it unsuitable for responding to the continuously varying load conditions in the microgrid [7]. Therefore, the pitch controller is only activated for $\omega_r > \omega_{r\_\text{rated}}$ or $P_m > P_{\text{max}}$.

3 Simulation results

The model in Fig. 1 was simulated in the MATLAB/SIMULINK environment. The load PF was maintained at 0.9 lagging all through the simulation. Two scenarios have been simulated and discussed. The system parameters for the WECS are given in Table 1 below:

3.1 Grid-connected to islanded operation

3.1.1 Grid operation (2–4 s): The WECS is connected to the grid and $V$ and $f$ are maintained by the grid. From Fig. 5, it is observed that the WECS is operating at MPPT $P_g = P_{\text{max}}$ and the excess power not consumed by the load $P_1$ is transferred to the grid. It is also observed that $Q_L$ is supplied by the grid $Q_{\text{grid}}$. The slight difference observed between $Q_{\text{grid}}$ and $Q_L$ is a result of the transformer’s leakage reactance. At 3.84 s, a three-phase fault occurs at the grid side, $V \approx 0$. It is observed that the WECS seamlessly rides through the fault as $V_{dc}$ and $f$ are within the nominal value.

The fault is not cleared within 0.16 s, and as stipulated in [15] the WECS is disconnected from the grid by opening the circuit breaker (CB).

3.1.2 Islanded operation (4–9 s): In this operation mode, the WECS reduces generation and operates in the SOPPT region to ensure LFPG. As illustrated in Fig. 5, $P_g$ and $Q_g$ precisely follow the load demand $P_{L}$ and $Q_{L}$, respectively. Fig. 5 also shows that the AVR and virtual governor regulated $V$ and $f$ within nominal values during this period. The three-phase voltage waveform of $V$ in Fig. 6 illustrates that the voltage and frequency are well-controlled, with minimal overshoot and waveform distortion during and after fault occurrence.

3.1.3 Grid reconnection (9–12 s): At $t = 9$ s, the CB is closed and the WECS connected to the grid. As illustrated in Fig. 5, the transition to grid is seamless, $V$ and $f$ are within nominal values. Immediately after the grid is restored, the WECS resumes generation at MPPT.
The above results demonstrate that the proposed PMS effectively manages power flow, achieves seamless operation, and enables MPPT and LFPG operation in grid and island modes, respectively, without switching control paradigms.

4 Conclusion

This paper introduces a new control paradigm for the seamless operation of PMSG-based WECS in both grid-connected and islanded operation. It employs a single-control paradigm, which achieves MPPT in grid-connected operation, LFPG in islanded operation and LVRT during faults. The operation of the proposed control structure has been validated in MATLAB/SIMULINK and the results confirm that the proposed PMS seamlessly enables MPPT and LFPG operation in grid and island modes, respectively, without switching control paradigms.

5 References