Output power smoothing of grid-connected permanent-magnet synchronous generator driven directly by variable speed wind turbine: a review

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Abstract: The output power of wind farms is fluctuating as a result of the wind speed variation. These power fluctuations disturb the quality of voltage and frequency of the grid. The fluctuated power can be smoothed via many methods such as controlling the pitch angle of blades, the rotor inertia, and using the energy storage systems (ESSs). These ESSs are mostly installed in the renewable energy for load levelling with cost limitations. Owing to the high cost of ESSs, it is required to utilise and enhance different power control techniques. This study introduces different and recent proposed methods and enhancements to smooth the output power of permanent-magnet synchronous generator driven directly (gearless) by a variable-speed wind turbine. Fuzzy logic control, sliding mode control, and evolutionary algorithms are used to enhance the control performance of pitch angle, machine-side converter, and DC–DC converter of ESS.

1 Introduction

The most attractive source of renewable energy is the wind because of the steady decrease in the production costs of wind power over the past few years. Therefore, industry investment in wind energy conversion sources (WECS) is growing rapidly. The global installed wind power industry was ~63 GW in 2015, with an accumulative 17% increase compared with 2014. The cumulative installed worldwide wind power was ~432 GW in 2015. The expected accumulative power in 2020 is ~792 GW, which is almost double that of 2015, as shown in Fig. 1 [1]. Wind turbines can be classified according to speed variation (fixed speed or variable speed), drive train (geared or direct), and converter used for grid connection (full or partial scale). Variable-speed wind turbines (VSWTs) provide a better chance to capture maximum power (MP) from the wind, even at low wind speed, with less mechanical stress compared with fixed-SWTs, as shown in Fig. 2. The VSWT can be connected to the generator either with a gear box or directly. A geared connection converts the low speed to a higher speed, which results in less torque and a smaller generator size.

Gearless connection or direct-drive train (DD-train) between the wind turbine and the generator eliminates the mechanical losses of gears and increases the wind power plants’s (WPP’s) total electrical power efficiency. DD-train means a low rotation speed, which requires a high number of poles to enable the gearless design [2]. The most suitable generator for the low-speed direct drive is the synchronous generator (SG), because of its high number of rotor poles. There are two types of SG excitation: electrical excitation or permanent-magnet (PM) excitation. Recently, the DD-PMSG-VSWT configuration has become the most promising and competitive system, because of the following advantages [3, 4]: higher efficiency and reliability due to the absence of gear losses and slip-ring losses, no external excitation, no field losses that reduce the thermal sources inside the generator, the smaller weight, and size of PMSGs compared with electrically excited SGs, and noise reduction due to the absence of a gearbox. On the other hand, there are some disadvantages of PMSGs: the high cost of PM materials, potential demagnetisation of the PM at higher temperatures, higher cost of full-scale power converters compared with the doubly fed induction generator, and larger size compared with induction machines.

The DD-PMSG-VSWT configuration is shown in Fig. 3, where the rotor shaft of the PMSG is connected directly to the wind turbine without a gearbox. On the electrical side, the stator of the PMSG is linked to the machine-side converter (MSC), which converts the PMSG’s AC output to DC. The MSC can be a fully controllable three-phase voltage-source pulse-width modulation (PWM) converter or a diode bridge rectifier followed by a PWM DC–DC converter. Consequently, the DC side is linked to the grid through a grid-side inverter (GSI). The GSI is most often a four-quadrant voltage-source converter.

The functions of the MSC are [5]: (i) MP-point tracking (MPPT) under varying wind speeds by controlling the frequency, magnitude, and phase of the three-phase voltages applied at the stator terminals; (ii) controlling the power factor to be unity in order to obtain the maximum active power for a given mega volt amper (MVA) rating of the converter; and (iii) providing inertial and frequency support by utilising the inherent inertia of the wind turbine during grid contingencies. The functions of the GSI are: (i) transfer power to the grid, (ii) control the DC-link voltage, and (iii) provide grid support features including a low-voltage ride through (LVRT), support for fault recovery, reactive power control, and voltage regulation.

2 Wind turbine modelling

2.1 Output power of wind turbine

The kinetic energy of the wind is captured by wind turbines and converted to mechanical power, then converted to electricity by the electrical generator [6]. The captured power by a VSWT is modelled as

\[ P_m = 0.5 \rho C_p \lambda \beta Av^3 \]  (1)

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system is modelled as

\[
j \frac{d\omega_m}{dt} + B \omega_m = T_m - T_e
\]

(5)

\[
\omega_e = Pf \omega_m
\]

(6)

where \(T_m\) is the mechanical torque, \(j\) is the total inertia of the turbine and PMSG, \(B\) is the damping coefficient, \(T_e\) is the electromagnetic torque of the PMSG, \(\omega_e\) is the electrical speed, and \(P\) is the number of poles.

2.3 PMSG modelling

The stator voltages of the PMSG are modelled in a \(d-q\) frame using the Park transformation as [11, 13, 14]

\[
\begin{pmatrix}
v_{ad} \\
v_{aq}
\end{pmatrix} = -R_s \begin{pmatrix}
i_{sd} \\
i_{sq}
\end{pmatrix} + \frac{dl}{dt} \begin{pmatrix}
i_{ad} \\
i_{aq}
\end{pmatrix} + \omega_e \begin{pmatrix}
-L_s i_{ad} \\
L_s i_{aq}
\end{pmatrix} + \psi_f
\]

(7)

\[
T_e \approx \frac{3}{2} \frac{P}{2} \psi_f i_{sq}
\]

(8)

where \(v_{ad}, v_{aq}, i_{sd},\) and \(i_{sq}\) are stator voltages and currents in the \(d-q\) frame, \(L_s\) and \(L_q\) are \(d-q\) inductances, \(R_s\) is the stator resistance, \(\omega_e\) is the electrical speed, and \(\psi_f\) is the flux linkage formed by the PM. \(L_d, L_q\) and \(L_m\) are nearly the same, so the electromagnetic torque \(T_e\) is

\[
T_e = \frac{3}{2} \frac{P}{2} \psi_f i_{sq}
\]

3 Grid integration requirements

The main challenge of WPPs is the variable and uncontrollable nature of wind speed compared with that of conventional power plants (CPPs). Transmission system operators (TSOs) establish the operation regulations (grid codes) that regulate the behaviours of CPPs to ensure the stability and reliability of the power system. Recently, the increased penetration level of WPPs has affected the stability and reliability of the entire power system, and requires regulation of WPP behaviour as established for CPPs.

According to the published grid codes of different countries [15–17], WPPs should contribute in frequency and voltage control under normal situations, in addition to LVRT capability and reactive current supply during voltage sags [18]. Wind speed variations cause power fluctuation on the grid, because the output power of a wind turbine is related to the cube of the wind speed as in (1), so any small variation in wind speed causes a large change in generated output power [19]. These fluctuations affect the power quality and increase the losses of the grid.

4 Output power smoothing (OPS) methods

The output power of a PMSG-VSWT fluctuates because of the random nature of wind speed, and these fluctuations can cause power quality problems such as frequency and voltage deviations. Pitch angle control (PAC), the rotor inertia, and energy storage systems (ESSs) are used for OPS as shown in Table 1 [19–22]. Coordination between many methods can be used for OPS as well [23]. ESSs are widely used techniques in WECs for improving the power quality of grid-connected WECs and can be utilised for OPS.

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Table 1 Comparison of OPS methods

| Methods                  | Advantages                                      | Limitations                                    | Notes                  |
|--------------------------|-------------------------------------------------|------------------------------------------------|------------------------|
| PAC                      | • low cost • simple control                     | • slow response • non-linear relationship      |                        |
|                          |                                                 | between pitch angle and rotor speed            | • MPPT and OPS         |
|                          |                                                 | • affects the MPPT • mechanical stress         | should be coordinated  |
|                          |                                                 | • modifying the control of MSC using FLC and   | and optimised to       |
|                          |                                                 | artificial intelligence (AI) can improve the   | achieve better         |
|                          |                                                 | OPS                                           | performance            |
| rotor inertia             | • low cost • faster than PAC • MPPT and         | • mechanical stress • cannot store the energy  |                        |
|                          | smoothing can be coordinated for                | for a long time                                |                        |
|                          | performance without affecting                   |                                               |                        |
| ESS                      | • better power smoothing performance            | • additional cost • BESS capacity              |                        |
|                          | without affecting MPPT tracking • supplies     | • ESS capacity and cost should be              |                        |
|                          | power to peak loads                             | optimised                                      |                        |

4.1 Pitch AC

The blade PAC is important in achieving demanded power from the wind. The operation principle of conventional proportional–integral (PI) controllers for PAC is comparing the generated power with the rated power as shown in Fig. 4 [23, 24]. The gain of PI controllers can be scheduled for better performance.

The input reference power is the most important component in determining the PAC for OPS [25].

Owing to the non-linearity between the pitch angle and the wind speed, the pitch angle reference is produced by the fuzzy logic controller (FLC) for OPS [25, 26], as shown in Fig. 5. Senju et al. [27] used fuzzy neural networks and presented a control strategy based on the average and standard deviation of wind speed for PAC [28]. Uehara et al. [29] used coordination control for PAC and DC-link voltage for OPS, where the DC voltage fluctuations will be suppressed by a chopper circuit placed in DC link.

4.2 Rotor inertia control

The main functions of the MSC are MPPT and power factor control. MPPT is achieved by tracing the optimum rotational speed ($\omega_{ref}$) calculated by the MPPT tracker as in (10) [30]

\[
\omega_{opt} = \sqrt[2]{\frac{E_m}{K_{opt}}} 
\]

\[
K_{opt} = \frac{\rho \pi R^2 C_p \max}{2 \lambda_{opt}} 
\]

The unity power factor is achieved by setting the reference value $i_{dref}$ to zero as shown in Fig. 6 [12, 30, 31].

The kinetic energy stored in the rotor can be utilised to smooth the wind power fluctuation by finding the reference power or reference rotor speed. The kinetic energy stored in the rotor as

\[
E_k = \frac{1}{2} m \omega^2. 
\]

the fluctuation of output power can be represented as

\[
\Delta P = P_w - P_{av}. 
\]

where $P_w$ is the captured power and $P_{av}$ is the average wind power, then the fluctuation of power will equal to

\[
\Delta P = P_w - P_{av} = \frac{dE_k}{dt} = \frac{1}{2} \frac{d\omega^2}{dt}. 
\]

the reference speed $\omega$ is achieved by using PI controllers or fuzzy logic to find $\omega^*$ as shown in Fig. 7.

Abedini and Nasiri [32] used rotor inertia as energy storage to mitigate the power fluctuation of PMSG-VSWT. In [32–34], FLCs were used to utilise the kinetic energy stored by the rotor inertia for OPS. Nguyen et al. [35] proposed a control strategy for MSC based on lead–lag compensation to utilise the kinetic energy caused by the large inertia of wind turbine systems. Coordination between PAC and rotor inertia was used in [36].

4.3 Energy storage system

Storage devices are used in grid-connected wind farms to improve power quality by keeping the power constant. The main purpose of ESSs is increasing wind power penetration, load levelling, frequency control, voltage fluctuation mitigation, and improving power quality and reliability [36–39].

Fig. 4 PAC modelling

Fig. 5 PAC using FLC

Fig. 6 Cascaded control of MSC

Fig. 7 Controlling the generator speed using MSC
ESSs can be classified according to the form of energy used (mechanical, chemical, electrical, electrochemical, and thermal ESS) as shown in Fig. 8. The most common ESSs used in WPPs are battery ESS (BESS), flow battery, flywheel ESS (FESS), electric double-layer capacitor (EDLC) or super capacitor ESS, and superconducting magnetic energy storage (SMES).

BESS, SMES, and EDLC are connected in parallel with chopper circuit in the DC link as shown in Fig. 1. DC–DC buck–boost converter is used to charge and discharge the BESS and EDLC. The insulated gate bipolar transistors operate interchangeably by controlling the gate signals $g_1$ and $g_2$ to be on or off as shown in Fig. 9. Bidirectional DC–DC choppers are used to charge and discharge SMES as shown in Fig. 10. Xu et al. [40] proposed coordinated control between the DC-link voltage and control of the DC–DC converter of ESS for OPS. ESSs (such as SMES and EDLC) were used for OPS in [41, 42]. Muyeen et al. [43] used an adaptive artificial neural network controller for controlling an EDLC connected to the DC bus to minimise the frequency fluctuations. Hasamien and co-workers [44–46] presented adaptive control of SMES based on affine projection algorithm. FESS is used for short-time response to compensate the fluctuation of the output power of wind turbine [47].

5 Conclusion

The power variations of grid-connected WPPs result in voltage and frequency deviations of the grid. These power variations due to the stochastic nature of wind speed. The TSos established regulations that the WPPs should donate in improving the power quality of grid. Then, the WPPs should provide smoothed power into the grid. This paper presented a review of recent proposed methods and improvements for OPS of WPPs based on PMSG directly driven by VSWT. The main methods that are used for OPS are PA controller, rotor inertia, and ESSs. ESS is used in WPPs for load levelling purposes with cost limitations. For lower cost, the proposed improvements are focusing to enhance the controller performance of OPS methods. Fuzzy logic controllers, neural networks, and artificial intelligence are used either instead of or besides to the conventional PI controllers. Determining the reference power or rotor speed is the most used to smoothen the output power.

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Fig. 8 Classification of energy storage devices

Fig. 9 DC–DC buck–boost converter with control

Fig. 10 Bidirectional DC–DC chopper (SMES circuit)
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