Output Power Leveling of Wind Generation System Using Inertia for PM Synchronous Generator

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Abstract -- Wind energy conversion systems have become important in the research of renewable energy sources. This is not a small part due to the rapid advances in the size of wind generators as well as the development of power electronics and their applicability in wind energy extraction. However, wind energy has a drawback of having only 1/800 density as compared to that of water energy, and it does not remain constant and wind turbine output is proportional to the cube of wind speed, which causes the generated power of wind turbine generator (WTG) to fluctuate. In this paper, a technique is proposed for output power leveling of a wind generation system. Wind turbine blades have large inertia compared to the inertia of generator. The inertia of the rotor behaves like an inductor in an electrical circuit. It helps smooth the wind turbine output power, stores energy during acceleration, and restores energy during deceleration. The effectiveness of output power leveling control is verified by simulations for the wind power generation system.

Index Terms -- Permanent magnet synchronous generator, inertia, MPPT, wind power leveling, wind turbine

I. INTRODUCTION

Electric power generation using non-conventional sources is receiving considerable attention throughout the world. Wind energy is a significant and powerful resource. It is safe, clean, and abundant. Unlike conventional fuels, wind energy is a massive indigenous power source permanently available in virtually every nation of the world. It delivers the energy security benefits by avoiding fuel costs, long term fuel price risk, and the economic and supply risks that come with reliance on imported fuels and political dependence on other countries. However, wind energy has a drawback of having only 1/800 density as compared to that of water energy, and it is not constant and wind turbine output is proportional to the cube of wind speed, which causes the generated power of the wind turbine generator (WTG) to fluctuate [1]. How to smooth output power of wind generation system is important. Because of this problem, various schemes have been reported in recent years. For example, using storage battery, superconducting magnetic energy storage (SMES) [2, 3], electric double layer capacitor (EDLC) [4,5], aqua electrolyze with fuel cell [6,7], flywheel energy storage system (FESS), and back-up generator. However, high frequency charge and discharges affect the efficiency of the lead-acid battery thereby shortening its life. SMES and EDLC are very expensive. Aqua electrolyze with fuel cell system is very large. Back-up generator requires operational cost [8].

In this paper, a wind generation system output power leveling technique is proposed. It is realized by two events: increase in wind turbine kinetic energy due to the acceleration of the turbine rotational speed as result of the rapid increase in wind speed, and discharge of wind turbine kinetic energy due to decrease in the wind turbine rotational speed when the wind velocity is dropped.

In the wind generation system, the permanent magnet synchronous generator (PMSG) is introduced because this configuration a gearbox is not needed. Therefore all the problems produced by the gearbox are avoided. The effectiveness of output power leveling control is verified by simulations for the wind power generation system.

II. WIND GENERATION SYSTEM

![](image)

Fig. 1. Wind generation system configuration.

The configuration of the wind power generation system is shown in Fig. 1. The wind energy obtained from the wind
Wind Turbine Kinetic Energy

Wind Turbine Input Power

\( P_{\text{wind}} \)

Wind Turbine Output Power

Wind Turbine Loss

(a) Acceleration

Wind Turbine Kinetic Energy

Wind Turbine Input Power

\( P_{\text{wind}} \)

Wind Turbine Output Power

Wind Turbine Loss

(b) Deceleration

Fig. 2. Power flow.

The wind turbine is sent to PMSG. The PMSG is controlled by the PWM converter and by the output power leveling controller. If all the wind power is converted to mechanical power, the input power \( P_{\text{wind}} \) is expressed as

\[
P_{\text{wind}} = \frac{1}{2} \rho \pi R_o^2 V_w^3
\]

(1)

where \( R_o \) is the wind turbine blade radius, \( V_w \) is the wind speed and \( \rho \) is air density. The wind turbine input torque \( T_{\text{wind}} \) can be described as

\[
T_{\text{wind}} = \frac{\lambda}{\omega_w} P_{\text{wind}} = \frac{1}{2} \rho \pi R_o^2 V_w^2
\]

(2)

where \( \omega_w \) is the angular velocity of wind turbine and \( \lambda \) is the tip speed ratio, can be defined as \( \lambda = \frac{R_o \omega_w}{V_w} \). The wind turbine converts wind power into mechanical power \( P_w \):

\[
P_w = \frac{1}{2} \rho \pi R_o^2 V_w^3 C_p
\]

(3)

The power coefficient \( C_p \) is defined as

\[ C_p = \xi \lambda^3 + \zeta \lambda^2 + \gamma \lambda \]

where \( \xi, \zeta, \) and \( \gamma \) are coefficients that are determined by size, form of blade, the number of blades and pitch angle of wind turbine blade. Wind turbine output torque is defined by

\[
T_w = \frac{1}{2} \rho \pi R_o^3 V_w^2 C_t
\]

(4)

where \( C_t \) is the torque coefficient defined as \( C_t = \frac{C_p}{\lambda} \).

The wind turbine loss torque, \( T_f \), serves as a convex function according to wind velocity and wind turbine rotor speed [9], it can be expressed as an approximation equation

\[
T_f = T_{\text{wind}} - T_w = K_0 V_w^2 + K_1 V_w \omega_w + K_2 \omega_w^2
\]

(5)

Here, the wind turbine loss coefficients \( K_0, K_1 \) and \( K_2 \) are expressed as

\[
K_0 = \frac{1}{2} \rho S R_0^2 (1 - \gamma)
\]

(6)

\[
K_1 = -\frac{1}{2} \rho S R_0^2 \zeta
\]

(7)

\[
K_2 = -\frac{1}{2} \rho S R_0^2 \xi
\]

(8)

where \( S \) is the blade rotation area. The motion equation of the wind turbine is expressed as

\[
T_w = J_w \frac{d\omega_w}{dt} + T_{\text{lw}}
\]

(9)

where \( J_w \) is the wind turbine inertia and \( T_{\text{lw}} \) is the load torque which corresponds to the input torque of generator. Input power to the generator \( P_{\text{in}} \) is expressed as

\[
P_{\text{in}} = -T_{\text{lw}} \omega_m
\]

(10)

where \( \omega_m \) is the angular velocity of the generator. The motion equation of the generator is expressed as

\[
J_m \frac{d\omega_m}{dt} + D_m \omega_m + T_{\text{lw}} = T_m
\]

(11)

where \( J_m \) is the generator inertia, \( D_m \) is the damping coefficient and \( T_m \) is the generator electric torque. Output power of the generator \( P_{\text{out}} \) is expressed as

\[
P_{\text{out}} = T_m \omega_m
\]

(12)

III. OUTPUT POWER LEVELING CONTROL

Wind generation system output power leveling is realized as a result of both charge and discharge of the kinetic energy in response to the wind speed. Charging occurs when the...
wind turbine rotational speed accelerates as the wind speed increases, while discharge follows the deceleration of the wind turbine as the wind velocity decreases. Power flow is shown in Fig. 2. Wind generation system output leveling controller is shown in Fig. 3. First, maximum wind turbine output power, \( P_{mx} \), is calculated from wind velocity. The wind turbine output, \( P_w \), in a steady state is \( P_w = T_w \omega_w \). The wind turbine output serves as the cubic function of wind turbine rotor speed \( \omega_w \), which is described as:

\[
\omega_w^3 = 3K_2 \left( 2 - \frac{1}{2} \omega_w \right) V_w^2 + K_1 V_w \omega_w + K_0
\]

(13)

The optimal wind turbine rotor speed, \( \omega_w^\text{opt} \), is obtained as the local maximum of the following equation due to \( dP_w/d\omega_w = 0 \):

\[
\omega_w^\text{opt} = \frac{-K_1 V_w \omega_w + \sqrt{(K_1 V_w)^2 - 3K_2 \left( \frac{1}{2} \omega_w \right) V_w^2}}{3K_2}
\]

(14)

Wind turbine maximum output power, \( P_{mx} \), is determined as:

\[
P_{mx} = T_w \omega_w^\text{opt} = \left( \frac{1}{2} \rho \pi R_o - K_0 \right) V_w^2 \omega_w^\text{opt} - K_1 V_w \omega_w^2 \omega_w^\text{opt} - K_2 \omega_w^3 \omega_w^\text{opt}
\]

(15)

Next, the charge difference between the maximum output power and the commanded output power (mean of maximum output power), \( \Delta P \), gives the wind turbine kinetic energy:

\[
P^* = \frac{1}{T} \int_{t-T}^{t} P_{mx} \, dt
\]

(16)

where \( t \) denotes the present time and \( T \) is the integral time. Wind turbine kinetic energy, \( E \), is determined as

\[
E = \frac{1}{2} J_w \omega_w^2.
\]

(17)

The wind turbine rotational speed command, \( \omega_w^* \), is determined from kinetic energy command, \( E^* \) (sum of \( \int \Delta P \, dt \) and \( E \)), as

\[
\omega_w^* = \sqrt{\frac{2E^*}{J_w}}
\]

(18)

The generator speed reference \( \omega_m^* \) for the proposed method, is determined from gear ratio, \( R_n \), as

\[
\omega_m^* = \frac{\omega_w^*}{R_n}
\]

(19)

and for the MPPT

\[
\omega_m^* = \frac{\omega_w^\text{opt}}{R_n}
\]

(20)

### IV. PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

The system configuration of the proposed operation system is shown in Fig. 4. The wind generation system output power leveling control is configured using the proposed technique.

The synchronous generator can be electrically represented by a one-phase equivalent circuit as shown in Fig. 5. In power system analysis, the synchronous machine models are usually based on the assumption that the magnetic flux distribution in the rotor is approximately sinusoidal [10]. With this assumption, the flux can entirely be described by a vector and thus the internal voltage \( V \) induced in the stator winding by the permanent magnet flux \( \psi_{PM} \) can be expressed as:

\[
|V| = \omega_m \psi_{PM} = 2f_c \psi_{PM}
\]

(21)

where \( f_c \) is the electrical frequency. Notice that the internal voltage \( V \) depends on the electrical speed of the generator. Under load conditions, the stator current \( I_s \) and the stator reactance in the stator winding produce a magnetic field of its own, which is superposed to the field generated by the permanent magnets. Thus, the voltage \( U_s \) at the stator terminal of PMSG corresponds to the voltage induced by the total magnetic field. Depending on the phase delay (load angle) between the internal voltage \( V \) and the stator voltage \( U_s \), the total magnetic field in the generator either increases or decreases as the current increases. Because of the fluxed
excitation of PMSG, the converter has to provide or consume reactive power, and therefore, the converter must be oversized [11].

The equations of a PMSG can be expressed directly from the equations of a DC excited synchronous generator, with the simplification that PMSG does not have damper winding [10]. The steady-state voltage equations of the generator, expressed in the rotor-oriented dq-reference frame RRF, can be expressed as follows:

\[
u_{sd} = R_{sd}i_{sd} - \omega_{m}\psi_{sq} + \Psi'_{sd}
\]

\[
u_{sq} = R_{sq}i_{sq} - \omega_{m}\psi_{sd} + \Psi'_{sq}
\]

with the stator flux components:

\[
\psi_{sq} = L_{d}i_{sq} + \Psi_{pm}
\]

\[
\psi_{sq} = L_{q}i_{sq}
\]

where \(u_{sd}\) and \(u_{sq}\) are the terminal stator voltages, \(i_{sd}\) and \(i_{sq}\) are the stator currents, \(L_{d}\) and \(L_{q}\) are the stator Inductances in the dq-reference frame. In stability studies, the stator transients can be neglected. If the PMSG is assumed to be a round rotor machine, which is a reasonable approximation for this type of generator [10], the electrical torque of the generator can be expressed in RRF with:

\[
T_{m} = \frac{3}{2}p\psi_{pm}i_{sq}
\]

Furthermore, the power of the synchronous generator can be then expressed as:

\[
P_{gen} = \frac{3}{2}\left[u_{sd}i_{sd} + u_{sq}i_{sq}\right]
\]

V. SIMULATION RESULTS

The effectiveness of the proposed method is demonstrated through simulation results. The system parameters used on the simulation are shown in Table (I) and (II). Output power leveling function, \(*P_{level}\), to evaluate the proposed method, are defined as [12]

\[
*P_{level} = \int_{0}^{t} \left|\frac{dP_{out}(t)}{dt}\right| dt.
\]

The \(*P_{level}\) is the integral of absolute value of derivative of Pout. The fluctuation quantity of output power gets smaller by increasing \(*P_{level}\).
VI. CONCLUSION

A technique for wind generation system output power leveling control using the inertia of the wind turbine has been proposed in this paper. It is realized by transformation of wind energy into wind turbine kinetic energy due to the acceleration of the wind turbine rotational speed on the wind velocity acceleration, and a discharge of the turbine kinetic energy.
energy through decrease of wind turbine rotational speed on
the wind velocity decelerates. The effectiveness of output
power leveling control is verified by simulations for the wind
power generation system. From the simulation results, output
power fluctuation is reduced by using the proposed method.

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