오픈 와인딩 머신을 이용한 계통 연계형 분산 발전 시스템의 제어

곽무신 설승기
서울대학교 전기컴퓨터공학부

Control of an Open Winding Machine in a Grid-Connected Distributed Generation System

Mu-Shin Kwak and Seung-Ki Sul
School of Electrical Engineering and Computer Science, Seoul National University

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Abstract

A grid-connected distributed generation system which consists of engine generator, dc link with multiple energy sources and inverter is proposed. All six of the stator leads of the generator, which is a surface mount permanent magnet machine, are brought out to the terminal of the generator. Three leads are connected to the inverter and the others are connected to the utility grid. In this proposed system the power from the engine-generator and the power from dc link can be controlled simultaneously by only one three-phase power converter. A control algorithm for the system is developed and verified by experiment results.

1 Introduction

Recently, engine generation systems are widely used in distributed generation systems or micro-grid systems. The micro-grid system is defined as a small power system which is able to supply a generating power to the entire local load and have the ability to work in grid-connected or islanded modes [1~3]. This distributed generation system is motivated to diversify the nature of energy sources and to improve the reliability, power quality and the cost effectiveness of the system [4, 5].

If this micro-grid system is to include the wind power system or photovoltaic system, additional power converter is also required to set up dc link voltage since the generated power is usually in dc as shown in Fig.1. An open winding machine has been used for high power ac drive systems [6] and also can be used in propulsion systems where dc link voltage is limited [7]. However the previous study of open winding machines has been focused on the control method using a full-bridge configuration for each phase. In this paper, the open winding surface mount permanent magnet machine (SMPMM) is used as a generator and a new generation system including open winding SMPMM is described. A new idea of the vector control and the power control with an open winding machine connected to the grid is proposed and its operation principle is verified by experiment results.

2 Proposed System Structure

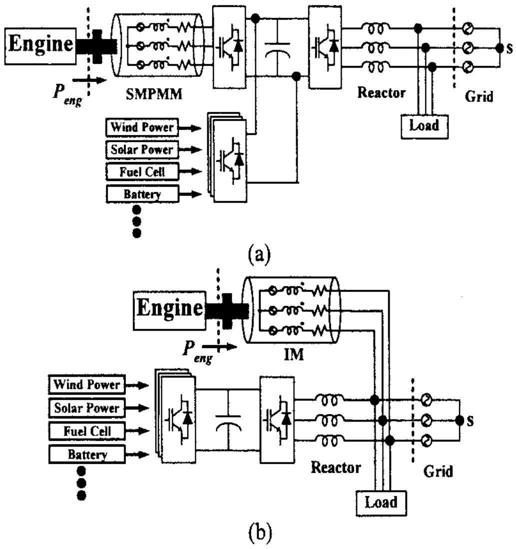

Fig.1 Conventional generation systems with multiple power sources
(a) Engine generation system connected to a grid in cascade
(b) Engine generation system directly connected to a grid

Fig.1 shows the conventional engine generation systems with dc link tied to several power sources. In system of Fig.1(a), the engine power (P_{eng}) is converted to dc power using the left-side converter and to the ac power again by the right-side inverter. This system is comparatively expensive because two converters are used for engine generation power, and the efficiency of generation is poor due to the double power conversion. In system of Fig.1(b), the engine power can be directly supplied to the grid without any power conversions. However, it is quite difficult to use a permanent magnet machine as a generator because it is hard to control the power of the generator under the synchronous operation with the grid due to lack of a field winding. Therefore an induction machine which has low efficiency compared to a permanent magnet machine has been usually used as a generator in this configuration exploiting the possibility of the slip.

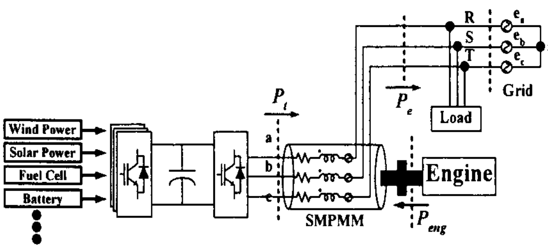

Fig.2 Proposed open winding generator system capable of generator control and converter control

Fig.2 shows the proposed generation system with only one inverter while performing the same functions with those systems in Fig.1. All six of the stator leads are brought out to the terminal of the SMPMM. The generator can be easily controlled to operate at constant speed all the time for synchronization with grid. Besides the component of the system such as ac reactors and an additional inverter can be removed using an open winding permanent magnet machine as a generator.

3 Proposed Control Algorithm

In order to control both of the power from dc link and the generated power from engine-generator by only one inverter, first of all the modeling of the open winding machine should be clearly derived and analyzed. Then the control strategy can be proposed based on the derived power equation.

The voltage equations of an open winding SMPMM connected to an inverter and utility grid are,

$$\mathbf{V}_{abcs} = \mathbf{r}_s \mathbf{i}_{abc} + p\boldsymbol{\lambda}_{abc} + \mathbf{e}_{abc} \quad (1)$$

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & 0 & 0 \\ 0 & r_s + pL_s & 0 \\ 0 & 0 & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} \phi_f \cos\theta_r \\ \phi_f \cos(\theta_r - \frac{2}{3}\pi) \\ \phi_f \cos(\theta_r + \frac{2}{3}\pi) \end{bmatrix} + \begin{bmatrix} -E\sin(\omega_e t) \\ -E\sin(\omega_e t - \frac{2\pi}{3}) \\ -E\sin(\omega_e t + \frac{2\pi}{3}) \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} V_{ds}^s \\ V_{qs}^s \end{bmatrix} = \begin{bmatrix} r_s + pL_s & 0 \\ 0 & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} -\omega_r\phi_f \sin\theta_r \\ \omega_r\phi_f \cos\theta_r \end{bmatrix} + \begin{bmatrix} -E\sin\theta_e \\ E\cos\theta_e \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_{ds}^r \\ V_{qs}^r \end{bmatrix} = \begin{bmatrix} r_s + pL_s & -\omega_r L_s \\ \omega_r L_s & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r\phi_f \end{bmatrix} + E\begin{bmatrix} -\sin(\theta_e - \theta_r) \\ \cos(\theta_e - \theta_r) \end{bmatrix} \quad (4)$$

where θ_r is the rotor angle of SMPMM, θ_e is the synchronous angle of grid and E is the peak value of utility grid phase voltage. Phase voltage equation is expressed by (2) and d-q voltage equation in stationary reference frame is given by (3). D-q voltage equation in a rotor reference frame can be deduced as (4). From these voltage equations, the power equation at the inverter terminals can be derived as (5). P_t, P_{eng} and P_e are the powers depicted in Fig.2. P_{eng} is the input power from an engine and P_e is the total converted power to the grid. P_t is the power including P_{eng}, P_e, system loss and variation of inductively stored energy.

$$\begin{aligned} P_t &= \frac{3}{2}(V_{ds}^r i_{ds}^r + V_{qs}^r i_{qs}^r) \\ &= \frac{3}{2} r_s (i_{ds}^{r\,2} + i_{qs}^{r\,2}) + \frac{3}{2} p(\frac{1}{2} L_s i_{ds}^{r\,2} + \frac{1}{2} L_s i_{qs}^{r\,2}) \\ &+ \frac{3}{2}\omega_r\phi_f i_{qs}^r + \frac{3}{2}E(-i_{ds}^r \sin(\theta_e - \theta_r) + i_{qs}^r \cos(\theta_e - \theta_r)) \\ &= (copper\ loss) \\ &\quad + (variation\ of\ inductively\ stored\ energy) \\ &\quad - P_{eng} + P_e \end{aligned} \quad (5)$$

Basically the rotor speed of SMPMM should be synchronized with the frequency of the grid. Once the angle between rotor of SMPMM and utility grid, $\theta_e - \theta_r$, is controlled to be constant, the voltage equation in (4) and the power equation in (5) become time invariant. For example, when the angle is controlled to be,

$$\theta_{sl} = \theta_e - \theta_r = \frac{\pi}{2} \quad (6)$$

the voltage, the power and the torque equations become as follows.

$$\begin{bmatrix} V_{ds}^r \\ V_{qs}^r \end{bmatrix} = \begin{bmatrix} r_s + pL_s & -\omega_r L_s \\ \omega_r L_s & r_s + pL_s \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} -E \\ \omega_r\phi_f \end{bmatrix} \quad (7)$$

$$\begin{aligned} P_t &= (copper\ loss) \\ &\quad + (variation\ of\ inductively\ stored\ energy) \\ &\quad + \frac{3}{2}\omega_r\phi_f i_{qs}^r - \frac{3}{2}E i_{ds}^r \end{aligned} \quad (8)$$

$$T_e = \frac{3}{2}\frac{P}{2}\phi_f i_{qs}^r \quad (9)$$

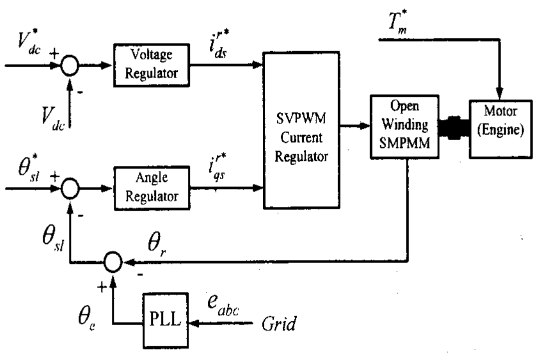

Fig.3 Control block diagram of open winding generator system

From (8) and (9), it can be seen that the q-axis current (i_{qs}^r) can be used to control the slip angle (θ_{sl}) by controlling rotor angle (θ_r) and the d-axis current can be used to control the terminal power (P_t) so as to regulate dc link voltage. The general control strategy to take advantage of the angle control according to the various operating conditions will be left as further works. The block diagram to implement the control principle in (6) is shown in Fig.3.

4 Experimental Results

To verify the feasibility of the proposed idea, 11kW open winding SMPMM is used as a generator and another 11kW ac machine is used for emulating the engine. Fig.4 shows the experimental result. At first, the engine starts to the idle speed while the inverter is regulating the DC link voltage in grid angle reference frame. The inverter starts to control the currents in rotor angle reference frame as proposed in the previous section so as to control the rotor angle and dc link voltage after synchronization. Once the generator is synchronized to the grid, external dc power is supplied to dc link for about 5 seconds. As dc power is supplied, it can be seen that the d-axis current (i_{ds}^r) varies to regulate dc link voltage, which means that the power from dc source is transferred to the load at the grid in Fig.2. After that, the engine torque is stepped up to show the controllability of the power from engine generator. As the engine torque increases, the q-axis current (i_{qs}^r) is also increased to the negative direction to transfer the power from the engine to load at the grid. During this process the angle is kept to be a constant value, $\pi/2$. As shown in this figure, the d-axis current is regulated so as to keep dc link voltage to be constant all the time, which means that the power from the dc link is supplied to the grid.

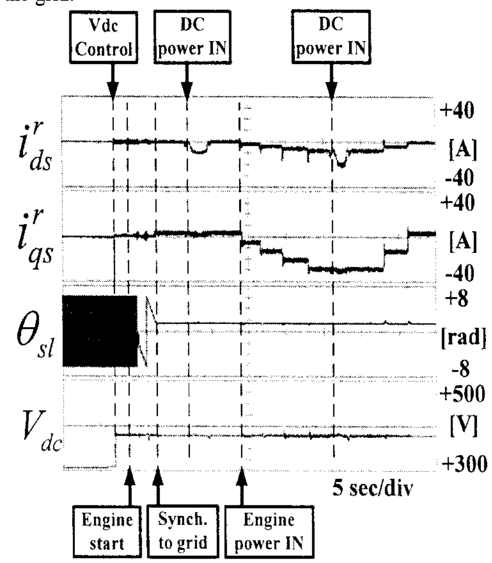

Fig.4 Test waveform of DC link voltage regulation and the angle control with multiple power sources

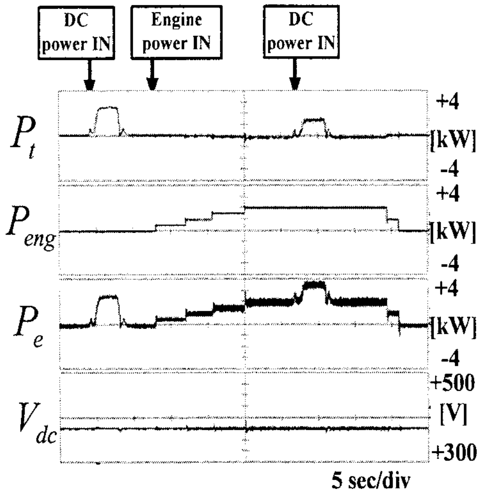

Fig. 5 Test waveform of power flow with multiple power sources

Fig.5 shows the power at couple of terminals which is calculated based on the measured value such as current and voltage after the synchronization. P_t, P_{eng} and P_e are the powers depicted in Fig.2. P_{eng} is the input power from an engine and P_e is the total converted power to the grid. P_t is the power including P_{eng}, P_e, system loss and variation of inductively stored energy. As can be seen in Fig.2, P_t is the three phase output power at inverter terminal. As the external dc power is supplied, P_t becomes positive which means that the power from dc source is transferred to the load or grid through the inverter. As the engine power (P_{eng}) increases, the total converted power (P_e) to the grid increases while the power through inverter (P_t) is kept constant, which means that the engine power is directly supplied to the grid.

By adjusting the magnitude and the polarity of d- and q-axis current, the power flow from engine-generator, dc link and grid can be controlled in bi-direction. So, the power generation from multiple energy sources can be optimally coordinated.

5 Conclusions

A new engine generation system has been proposed based on open winding SMPMM using only one inverter without any ac reactor. The proposed system is able to regulate dc link voltage to handle power from multiple power sources tied to dc link and simultaneously to control the power from the engine-generator by a vector control scheme. The power generated from the engine can be directly fed to the grid without energy conversion and its magnitude can be controlled by adjusting power from the engine generator and from dc link. Compared to the conventional system, the proposed configuration can improve the efficiency of the power conversion from the engine to the grid and it can be expected to reduce the system cost. The operation principle has been verified by the experimental results.

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