Unity power factor control for surface mounted permanent magnet synchronous generator (PMSG) based on polar coordinate current locus

Wenshan Li¹,²,³,⁴, Zhang Chen⁵,⁶, Xuhui Wen¹,²,³,⁴ and Jian Zhang²,³,⁴,⁵

¹University of Chinese Academy of Science, China
²Institute of Electrical Engineering, Chinese Academy of Science, China
³Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering, Chinese Academy of Sciences, China
⁴Collaborative Innovation Centre of Electric Vehicles in Beijing, China
⁵The State Key Lab of Heavy Duty AC Drive Electric Locomotive Systems Integration Zhuzhou, China
⁶E-mail: ahchenz@126.com

Abstract. This paper proposes a unity power factor control for PMSG based on current angle, which replaces the conventional $i_d$-$i_q$ plane with polar coordinate. The polar coordinate takes the current angle as polar angle and the phase current magnitude as polar radius. The method presented simplify the UPF current locus for PMSG, therefore, the design process of UPF control strategy was simplified. As verification to the proof -of-concept, a simulation model is developed, and also a hardware prototype of a PMSG generation system is constructed and test up to 320kW. The experimental results show that a power factor of 0.9812 with the UPF control method proposed.

1. Introduction

Micro turbine generation used in renewable energy power generation system, remote area power supply and backup power station as a DG source due to its high efficiency, fast starting speed and favorable peak shaving capacity [1]. However, the high frequency power generated by micro turbine generator cannot be used directly. Multi pulse diode rectifiers are used as power conditioner is often used as front converter to transfer AC power to DC.

To reduce the harmonic currents three phase (pulse width modulation) PWM converter is used instead of a diode rectifier [2, 3] for microturbine generation systems. However, the power factor of the converter is low for the input current phase varies from control method to method. To minimize overall power loss and improves input power factor, unity power control [4, 5] is needed in AC-DC PWM rectifier. Conventional unity power factor control for PWM rectifier in wind turbine system [5] is $i_d=0$ strategy. Ref. [3] presented a digital based pulse train control technique for AC-DC converter to obtain unity power factor.

But for PMSG based PWM rectifier, the phase current ahead of voltage is the main characteristic in these systems. It may be generated reactive power in PWM rectifier. The capacity and the loss of PWM rectifier will increase due to reactive power. Therefore, it is necessary to improve the power factor of the PWM rectifier based on PMSG to reduce the power level. Therefore, unity power factor control of PWM rectifier is related to the generator in microturbine system. Therefore, $i_d=0$ strategy is
not suitable for PMSG based PWM rectifiers control system. In this system, UPF control is implemented by specific current locus in id-iq plane. Many power factor improvement methods have been proposed for PWM rectifier [6-13].

YAO Jun proposed the use of a back to back PWM converter with the unity power factor operation of PMSG based on d-axis voltage is controlled to zero. An improved $i_d=0$ strategy is discussed in Ref. [7] proposed a unity power factor control of interior PMSM using power angle as a compensation for rotor position. Ref. [8] discussed the current locus in $i_r$-$i_q$ current plane under unity power factor control method for PMSG, which is applied in direct driven wind energy conversion system based on PLL.

In this paper, we proposed a new unity power factor control method for PMSG in microturbine generation system, as shown in Figure 1. Current angle was used to redesign the current locus in $i_d$-$i_q$ plane, which can reduce the dependency on motor parameter. The performance of the method is validated by detailed simulations and experiments.

2. System topology
Microturbines are small gas turbines, generating power in the range of 25kW to 500kW. The microturbine generation system shown in Figure 1, contains microturbine, IPMSG and controlled PWM rectifier.

Figure 2 shows the proposed control strategy for PMSG based PWM rectifier. The control system contains double-closed voltage regulating system with the voltage loop and current loop. Park’s transformation is applied to feedback current and the transformation angle derived from the position detection sensor mounted on the shaft of PMSG.

3. Unity Power Factor control method design for PMSG based PWM rectifier

3.1. PMSG Model and conventional UPF current locus
In the case of PMSG UPF control, the dq frame model of PMSG is needed. With assumptions that the PMSG is unsaturated and eddy currents and hysteresis losses are negligible, it can be represented as

$$u_d = -Ri_d - L_d \pi_i_d + \omega L_q i_q$$
$$u_q = -Ri_q - L_q \pi_i_q + \omega L_d i_d + \omega \phi_r$$

(1)

Where, $i_{d,q}$, and $u_{d,q}$ represent the dq axis current, dq axis voltage in rotation frame. $R$, $L_{d,q}$, $\phi_r$, represent the resistance, dq axis inductance, permanent magnet flux, respectively.

If the resistance of the winding is neglected, then the static voltage equation can be described as

$$u_d = \omega L_q i_q$$
$$u_q = -\omega L_d i_d + \omega \phi_r$$

(2)

And, the active and reactive power are represented as

$$P_s = u_d i_d + u_q i_q$$
$$Q_s = u_q i_d - u_d i_q$$

(3)

Thus, unity power factor control will be achieved as $Q_s=0$, and we get

$$i_d = \frac{u_d}{u_q}$$
$$i_q = \frac{u_d}{u_q}$$

(4)

By substituting (2) into (4), the locus of unity power factor control in $i_d-i_q$ plane can be described as

$$\frac{L_q}{L_d} i_q^2 + \left(i_d - \frac{\phi_r}{2L_d}\right)^2 = \left(\frac{\phi_q}{2L_d}\right)^2$$

(5)
Surface mounted PMSG is often used in microturbine generation system owing to the heat dissipation request of magnetic steel. It has been further assumed that as the surface mounted PMSG is nonsalient, \( L_d \) and \( L_q \) are equal and are taken as \( L \), Eq(5) can be expressed as

\[
i_q^2 + \left( i_d - \frac{\phi_r}{2L} \right)^2 = \left( \frac{\phi_r}{2L} \right)^2
\]

\[
i_d = \frac{1}{2L} \left( -\phi_r \pm \sqrt{\phi_r^2 - 4Li_q^2} \right)
\]

The vector diagram and current locus in \( i_d - i_q \) plane is shown in Figure 3 and Figure 4, respectively.

In Figure 3 \( u \) and \( i \) represent the voltage and current space vector, respectively.

![Figure 1. Microturbine generation system.](image1)

![Figure 2. Control system of PMSG based PWM rectifier.](image2)
3.2. Proposed method

The UPF control method using eq(6) is difficult to achieve for its nonlinearity. To obtain an engineering method, a current angle based UPF control strategy is introduced in this section. The definition of the current angle is shown in Figure 5. Taking the current angle and current magnitude as the polar angle and radius, respectively.

\[ i_{q}^{\text{ref}} = I_{d}^{\text{ref}} \sin \xi \]
\[ i_{d}^{\text{ref}} = I_{q}^{\text{ref}} \cos \xi \]  \hspace{1cm} (7)

Where, \( \xi \) is defined as current angle.

The UPF current locus and current limit represented in Figure 6.
Substituting (7) into (6), the UPF locus can be described as

\[ I_s \left( I_s - \frac{\phi_r \sin \xi}{L} \right) = 0 \]  \hspace{1cm} (8)

There are two solutions to the equation (8),

\[ I_s = 0 \]

\[ \xi = \arcsin \left( \frac{L \sqrt{i_d^2 + i_q^2}}{\phi_r} \right) \]  \hspace{1cm} (9)

From eq(9), current angle can be calculated, and the dq axis current reference can be obtained across eq(7). Compared to Eq.(6), Eq.(9) and Eq.(7) are much more achievable. Although, generator parameter are contained in Eq.(9), they are simplified. Furthermore, engineers can make lookup table about \( \xi \) and current amplitude, which reduce the dependence on generator parameter. It is difficult to obtain from conventional UPF current locus in \( i_d-i_q \) plane.

4. Simulation and experimental results

The simulation and experimental system were designed to verify the validity of the method proposed in this paper. The parameter of the PMSG is 8 pole pairs with 1000rpm. The vector diagram is described in Figure 7 under UPF condition. Simulation result with line voltage and phase current is shown in Figure 8.

![Figure 7. Vector diagram of UPF.](image)

![Figure 8. Simulation results.](image)
From Figure 8, the phase current lag the line voltage $0.1722\pi$, thus the phase current lag the phase voltage $0.0056\pi$ while the power factor is 0.9998.

UPF control method presented is implemented in the 320kW PMSG control system, shown in Figure 9, $U_{AB}$ and $i_A$, $i_B$ were shown in Figure 10.

![Universal converter](image)

**Figure 9.** Experimental setup of PMSG control system.

It can be seen from Figure 10, the frequency of phase current is 300Hz, and the phase difference between phase current and line voltage is $11^\circ$, and the power factor is 0.984.

Figure 11 shows the id and iq wave, which is from DSP28335 and record in PC shown in Figure 9. It is can be seen from Figure 11, the dynamic performance of id and iq is acceptable when load in increased step by step. Steady state performance can be seen from the right side of Figure 11 and Figure 10.
Figure 11. Dynamic performance of id, iq when load increased.

5. Conclusions
In this paper, a new UPF control method based on polar coordinate current locus for PMSG is proposed. A proof-of-concept of PMSG generation system is developed and tested up to 320kW. The proposed UPF control method based on polar coordinate current locus is verified to be simpler and easier to implement than conventional method. Unity power factor current locus in $i_d-i_q$ plane is replaced by linear equation in polar coordinates. The UPF locus in polar coordinates can also replaced by lookup table in engineering application. The motor parameter dependency is reduced with power factor of 0.9812. Good dynamic performance was also obtained with the load increasing.

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