Maximum efficiency operation of Synchronous Reluctance Machine using signal injection

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Abstract-- **This paper introduces a new maximum efficiency operation method of Synchronous Reluctance Machine (SynRM) based on a signal injection. To control SynRM in the maximum efficient operating point, the sum of the copper losses and the iron losses should be minimized. Although many kinds of efficient operating method had been introduced, most of them were dependent upon the machine parameters. The inaccuracy of the machine parameters, especially d-/q-axis inductances which are known to vary extremely according to the operating condition, makes the maximum efficiency operating point be out of the target. In this paper, a new maximum efficiency operating method of SynRM is proposed. Adopting the high frequency signal injection concept, the maximum efficiency operating point can be traced without dependency on the machine parameters. The effectiveness of the method is verified by experimental results.**

Index Terms — **Synchronous Reluctance Motor (SynRM), Maximum Efficiency Operation, Signal Injection Method**

I. Introduction

The Synchronous Reluctance machine (SynRM) is a kind of synchronous electric motor that has no permanent magnet or excitation windings. Torque is generated through the saliency of magnetic reluctance. The stator and the rotor have projecting poles along with the air gap and torque is produced by the tendency of the rotor to line up along a minimum reluctance position established by the alignment of the particular stator and rotor saliency [1]. As there are no current conducting parts in the rotor, the rotor losses are minimal compared to those of induction machine. The absence of the rotor losses and the simplicity of the control suggest the possibility of performance and the cost advantage over the induction machine and the permanent magnet synchronous machine [2]. Furthermore, the flux weakening control can be easily achieved because of no magnet in the rotor. Hence, the constant power speed range(CPSR) can be extended to infinity, in theory.

The operating efficiency optimization of AC machine has been pursued since the AC machine drive system is used in the industry. However, the importance of efficiency optimization and energy minimization is getting a hot issue ever before because of CO2 minimization against global warming. The researches regarding the operating efficiency optimization have been focused on the minimization of the sum of the copper loss and the iron loss of SynRM. The copper loss is proportional to the current magnitude, and the iron loss is related with the air-gap flux level. At the first, to minimize the copper loss, the Maximum Torque Per Ampere (MTPA) operating point should be detected. In the case of Permanent Magnet Synchronous Machine, the MTPA operating point was considered as the maximum efficiency operating point due to the relatively small iron loss. Second, to minimize the iron loss, the air-gap flux level should be minimized. In SynRM, the variation of the iron loss due to the operating condition is extremely large even at the constant magnitude of the current. Therefore, the iron loss as well as the copper loss should be simultaneously considered to maximize the efficiency of SynRM.

The most of the efficiency optimizing method of SynRM have relied on the machine parameters [1]-[3]. However, the parameters of SynRM vary extremely according to the d-/q-axis currents [4]. In this paper, a new maximum efficiency operating method was proposed, which is robust to parameter variations. Using a signal injection method, the maximum efficiency point can be traced without dependency on the machine parameters.

The maximum efficiency operation stands for that the total input power including the mechanical output power, the copper loss, and the iron loss should be minimized while maintaining constant torque at a certain speed. Therefore, the maximum efficiency operation is identical to the Minimum Power Per Torque (MPPT) operation. The copper loss and the iron loss vary according to the ratio of d-/q-axis currents at the same operating point in the torque-speed plane. Injecting the small sinusoidal signal into the current reference angle, the input power variation according to the current angle can be obtained. At the MPPT operating point, the input power variation according to the current angle should be zero. Using this inherent characteristic of the MPPT operating point, the maximum efficiency point can be traced using simple signal process without dependency on SynRM parameters.

II. Characteristics of SynRM

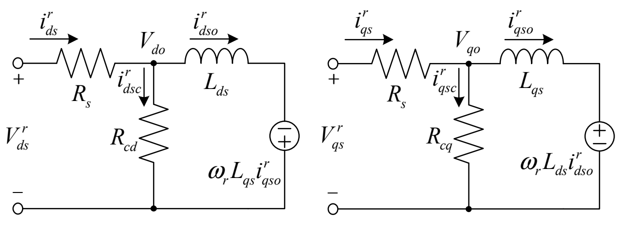


Fig. 1. SynRM equivalent model with consideration of iron loss

In the rotor reference frame, the d-/q-axis equivalent circuits for the SynRM, including iron loss, are shown in Fig. 1 [3]. Note that the resistance R_{cd} and R_{cq} represent the iron loss connected in parallel to both rotational and transient back-EMF in this Fig. 1 [5]. The d-/q-axis voltage equations in the rotor reference frame for SynRM can be derived as (1) and (2). The current components which are directly responsible for the torque production are i_{dso}^r and i_{qso}^r. These currents differ from the measureable terminal current i_{ds}^r and i_{qs}^r, because of the existence of iron loss branch. From the equivalent circuit, the electromagnetic torque is proportional to the product of currents i_{dso}^r and i_{qso}^r, as (3).

$$V_{ds}^r = R_s i_{ds}^r + L_{ds}\frac{di_{dso}^r}{dt} - \omega_r L_{qs} i_{qso}^r \tag{1}$$

$$V_{qs}^r = R_s i_{qs}^r + L_{qs}\frac{di_{qso}^r}{dt} + \omega_r L_{ds} i_{dso}^r \tag{2}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(L_{ds} - L_{qs}\right) i_{dso}^r i_{qso}^r \tag{3}$$

Assuming the iron loss resistance, R_{cd} and R_{cq} are infinite, the current producing the torque, i_{dso}^r and i_{qso}^r are identical to the measurable current, i_{ds}^r and i_{qs}^r, respectively. In this case, it can be easily seen that the optimal current angle for minimizing the stator copper loss is 45° [6] in the constant inductance condition. However, non-negligible iron loss resistance, R_{cd} and R_{cq} produce the cross-coupling effects between the d-axis circuit and the q-axis circuit, resulting in the shift of the optimal current angle from 45° . Furthermore, the variation of inductance according to the d-/q-axis current makes the current angle be shifted additionally. Consequently, for the maximization of the efficiency when the iron loss and the inductance variation are considered, the voltage equations for the SynRM should be expressed using the torque currents, rather than the terminal currents.

The copper loss, P_c and the iron loss, P_i of the SynRM can be calculated as (4) and (5), respectively. Thus, the total power loss of the SynRM can be the sum of (4) and (5). And, the input electric power, P_e consisted of losses and a mechanical power, (6), can be described as (7).

$$P_c = \frac{3}{2} R_s \left(i_{ds}^{r\,2} + i_{qs}^{r\,2} \right) \tag{4}$$

$$P_i = \frac{3}{2} R_c \left(i_{dsc}^{r\,2} + i_{qsc}^{r\,2} \right) \tag{5}$$

$$P_m = T_e \omega_{rm} = \frac{3}{2}\frac{P}{2}\left(L_{ds} - L_{qs}\right) i_{dso}^r i_{qso}^r \omega_{rm} \tag{6}$$

$$P_e = P_c + P_i + P_m \tag{7}$$

III. Conventional Maximum Efficiency Operation

The d- and q-axis voltages and currents in the d- and q-axis equivalent circuit of the SynRM can be rewritten as (8)-(11). The total power loss can be written as (12).

$$V_{ds}^r = R_s i_{ds}^r - \omega_r L_{qs} i_{qso}^r \tag{8}$$

$$V_{qs}^r = R_s i_{qs}^r + \omega_r L_{ds} i_{dso}^r \tag{9}$$

$$i_{dso}^r = i_{ds}^r + \frac{\omega_r L_{qs} i_{qso}^r}{R_c} \tag{10}$$

$$i_{qso}^r = i_{qs}^r - \frac{\omega_r L_{ds} i_{dso}^r}{R_c} \tag{11}$$

$$\begin{aligned} P_{loss} &= P_c + P_i \\ &= \frac{3}{2}\left\{ R_s + \frac{\left(\omega_r L_{ds}\right)^2}{R_c} + \frac{R_s}{R_c^2}\left(\omega_r L_{ds}\right)^2 \right\} i_{dso}^{r\;2} \\ &+ \frac{3}{2}\left\{ R_s + \frac{\left(\omega_r L_{qs}\right)^2}{R_c} + \frac{R_s}{R_c^2}\left(\omega_r L_{qs}\right)^2 \right\} i_{qso}^{r\;2} \\ &+ \frac{3}{2}\left\{ \frac{2R_s}{R_c}\omega_r \left(L_{ds} - L_{qs}\right) \right\} i_{dso}^r i_{qso}^r \end{aligned} \tag{12}$$

The efficiency can be maximized by minimizing the loss in (12). Let's define the ratio of torque producing d-axis current to torque producing q-axis current as $\zeta \equiv i_{qso}^r / i_{dso}^r$, and then the optimal ratio minimizing the total losses can be found under the given speed and load conditions as (13). In the calculation of (13), the constraint is that the generated torque should be constant at the given operating point as (14). By solving (13) and (14) simultaneously, the optimal ratio of currents producing the specified torque can be found as (15) under the assumption that the parameters of the equivalent circuit of SynRM in Fig. 1 are constant regardless of the variation of i_{dso}^r and i_{qso}^r.

$$\frac{\partial P_{total}}{\partial \zeta} = 0 \tag{13}$$

$$i_{dso}^r i_{qso}^r = \text{constant} \tag{14}$$

$$\zeta_{opt} = \sqrt{\frac{R_s R_c^2 + \left(R_s + R_c\right)\left(\omega_r L_{ds}\right)^2}{R_s R_c^2 + \left(R_s + R_c\right)\left(\omega_r L_{qs}\right)^2}} \tag{15}$$

However, the inductances vary according to the current. Moreover, the iron loss resistance varies with operating frequency and magnetizing current. In addition that, the measurement of the iron loss resistance is quite difficult in real SynRM drive. Therefore, the control based on (15) is not practical in the industrial field.

IV. PROPOSED MPPT METHOD OF SYNRM

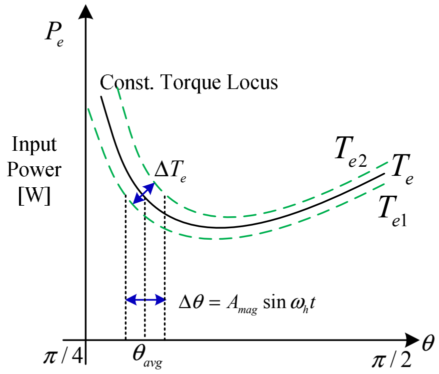
The most efficient operation of SynRM means that the total losses, included a copper loss and iron loss, should be minimized with a constant mechanical power. To detect the most efficient operating point of SynRM, the signal injection method can be used. In the maximum efficiency point, the input power variation due to the current angle would be zero under the constant load torque and the constant operating speed. Then, in this operating condition, the input power variation according to the current angle, shown in (16), can be a criteria to determine whether the operating point is on the maximum efficiency point or not. By injecting a small sinusoidal signal to the current reference angle onto the constant torque locus, the maximum efficiency criteria in (16) can be calculated. In this paper, this maximum efficiency operation is defined as Minimum Power Per Torque (MPPT) operation.

$$\frac{\partial P_e}{\partial \theta} = 0 \quad \text{at} \quad T_e = \text{constant} \tag{16}$$

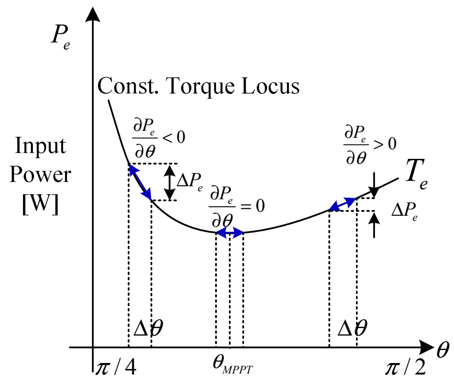
If the sinusoidal signal is injected to the current reference angle, some mechanical power variation due to the torque variation appears as Fig. 2(a). To detect the criteria of MPPT operating point, the injected signal should be swung onto the constant torque locus as Fig. 2(b). When the operating current angle is smaller than the MPPT point, the power variation according to the current angle is negative and vice versa. At the MPPT point, the criteria would be zero.

To keep the constant torque, the magnitude of current should be adjusted. By the injected angle signal, the torque would be trembled. To compensate this torque trembling, ΔT_e in Fig. 2(a), the magnitude of current, I_{sh} in Fig. 3, could be added to the original current magnitude, I_S. Unless I_{sh} is added, the operating point would be out of the constant torque locus. With I_{sh}, the operating point be on the constant torque locus. The torque variation can be directly identified by the speed variation.

The block diagram of I_S compensation is shown in Fig. 4, where the injected frequency components in the measured speed are suppressed by regulating the magnitude of the current. The mechanical system can be described as (17). If the torque trembling, ΔT_e happens due to the injected signal, a speed ripple, $\Delta\omega_{rm}$ would be generated in the injected signal frequency. Because the torque trembling can't be measured in real system, speed ripple can be used to detect the torque trembling depending on (18).



(a) Sinusoidal signal injection



(b) Sinusoidal signal injection with current magnitude compensation

Fig. 2. Signal injection to the current angle onto the constant torque locus

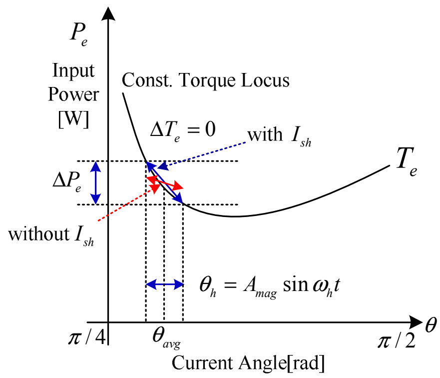


Fig. 3. Current magnitude compensation to keep the constant torque

$$T_e = J\frac{d\omega_{rm}}{dt} + B\omega_{rm} + T_L \tag{17}$$

$$\Delta T_e = J\frac{d\Delta\omega_{rm}}{dt} + B\Delta\omega_{rm} \tag{18}$$

If friction coefficient, B, can be ignored in (18), the differential value of speed is proportional to the torque trembling. Therefore, to get a torque trembling, the speed is band-pass-filtered at the injection frequency, and the phase is delayed by differentiation or phase shift filter. After this signal processing, the output should be controlled as zero. The proportional controller is used as a regulator. To circumvent the noise issues related to the differential operation, the differentiator and the Band-Pass-Filter can be merged.

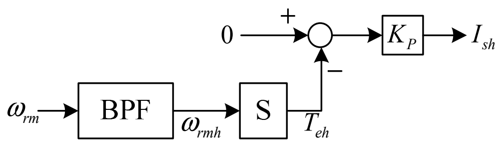


Fig. 4. Block diagram of current magnitude(I_S) compensator to keep the constant torque

The MPPT tracking method is implemented in MPPT Tracking block, which is illustrated in Fig. 5. Assuming the torque trembling is compensated by above current magnitude compensator, the input power variation can be happened by the losses variation according to the current angle variation. Power variation can be calculated by simple signal processing in Fig. 5. By band-pass-filter, the injection frequency component of input electric power can be extracted. At the minimized loss operating point, MPPT, the loss variation according to the current reference angle should be zero. Therefore, the current reference angle can be controlled by the signal processing result, P_o, with integral controller, in Fig. 5.

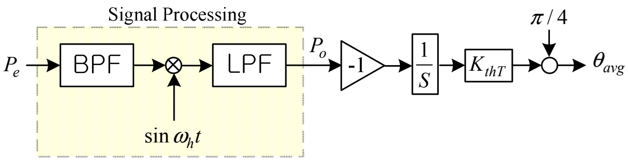


Fig. 5. Block diagram of MPPT tracking method

The entire system block diagram is shown in Fig. 6. The main control loop consists of speed controller and current controller. The d-/q-axis current reference can be calculated by current magnitude and current reference angle. The speed controller determines the current magnitude, I_{sf} to regulate the motor speed to the desired speed. And, the current reference angle can be used for MPPT operation and adjusted according to the MPPT tracking block. The high frequency signal in current reference angle, $A\sin\omega_h t$ is added to the current reference angle, θ_{avg}. The injection frequency should be inside of the current control loop bandwidth and outside of speed control loop bandwidth.

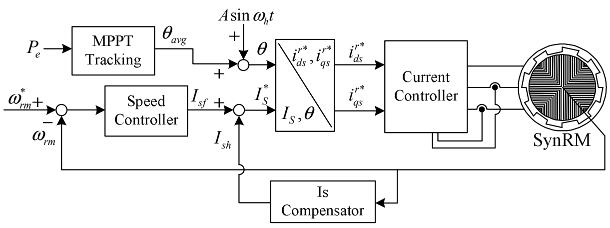


Fig. 6. Block diagram of speed control system with MPPT tracking method

V. Experimental Results

The experiments based on axially laminated 3.75kW SynRM and load machine were carried out in order to verify the validity of the proposed MPPT tracking method. The rated torque was 20 Nm and the rated speed, 1800 r/min. The detail parameters and rated values of SynRM are listed in Table I.

TABLE I
RATED VALUES AND PARAMETERS OF SYNRM

Item	Value	Unit
Rated Power	3.75	kW
Rated Torque	20	N·m
Rated Speed	1800	r/min
Inertia	0.026	kg·m^2
Number of Pole	4	-
Stator Resistance	0.238	Ω
Nominal Inductances	L_{ds}=43 L_{qs}=3.5	mH

Fig. 7 shows the experimental results of the MPPT tracking in 300 r/min. At every load torque from 1.8 Nm to 9 Nm, the input electric power was measured in the current reference angle range from 0.8rad to 1.45rad per 0.05rad. At every load torque curve, the minimum input electric power point exists. To operate the SynRM efficiently, the MPPT tracking method should find the minimum power operating point. To verify the proposed MPPT tracking method, 50Hz signal was injected and the MPPT was tracked. The blue line, is the MPPT trace by the proposed signal injection method. The traced operating point coincides quite well to the minimum input power point.

In Fig. 8, the results at the 1500r/min were shown. Same as the before, the trace well matched to the exact MPPT points.

To confirm the MPPT tracking performance, the more rigorous tests were performed. In Fig. 9(a), the current magnitude and the electric input power were measured according to the current reference angle from 0.78rad to 1.35rad. In the constant speed, 1700r/min and the constant load torque, 6Nm, the magnitude of the current varies according to the current reference angle. At 0.93rad, the magnitude of the current was minimized, that means 0.93rad is the Maximum Torque Per Ampere (MTPA) operation point.

As expected, the input power minimum point was quite different with the current magnitude minimum point. Also, in the same operating condition, the operating angle minimizing input power was 1.23rad, which can be called as MPPT operating point. The input electric power at 1.23rad is less than that at 0.78rad, 45°, which is MTPA operating point without consideration of iron loss and parameter variations. The input power at MPPT point is smaller than that of the MTPA point at 0.93rad. This input power difference between MTPA point and MPPT point clarify that the maximum efficiency operating point is different with the MTPA operating point in SynRM. In Fig. 9(b), the dynamic performance of the proposed MPPT tracking method was shown. The MPPT tracking method found the exact MPPT point in a few seconds.

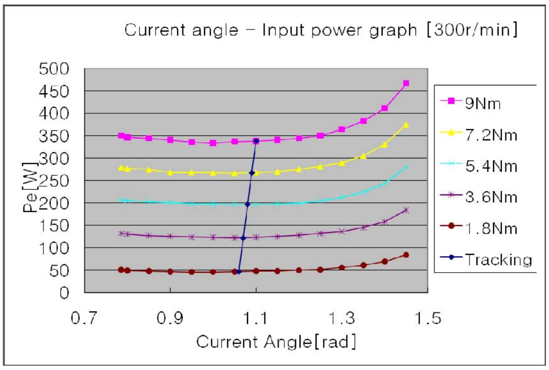


Fig. 7. MPPT tracking results in 300r/min

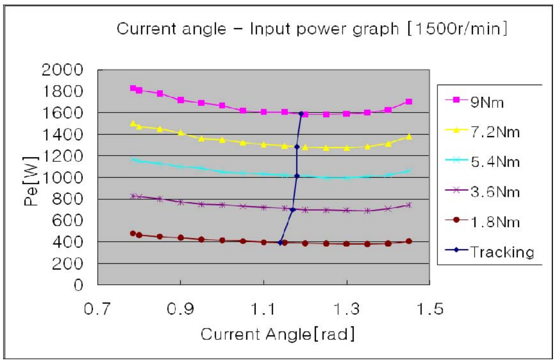
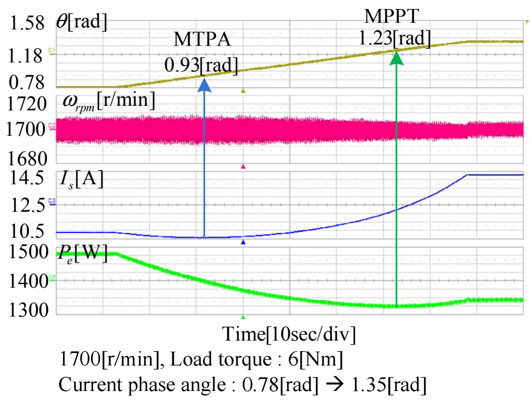
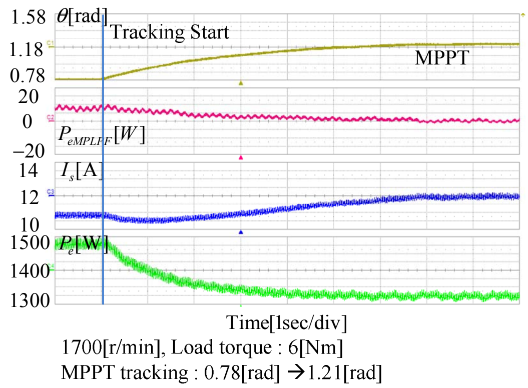


Fig. 8. MPPT tracking results in 1500r/min



(a) Current magnitude and input power according to the current angle increment



(b) MPPT tracking results; the current angle of tracked point is similar with (a)

Fig. 9. MPPT tracking results in 1700r/min

VI. CONCLUSIONS

This paper presents a new maximum efficiency operating method of SynRM, which is Minimum Power Per Torque (MPPT) operation. The proposed method is exploiting the inherent characteristics of the MPPT definition, that is that the input power variation according to the current angle on the constant torque locus should be zero at the operating point. By injecting the high frequency sinusoidal signal to the current angle reference, the input power variation can be calculated with a simple signal processing and the MPPT operating point can be traced easily. To keep the constant torque, the current magnitude compensator was added based on the measured motor speed. To prove the feasibility of the proposed method, experiments were carried out. In these experiments, the MPPT operating points of the proposed method were compared with the pre-made input power information in all over operating range. The proposed method can track the minimum input power point in a few seconds. It is possible to operate the SynRM in the maximum efficiency point without machine parameters.

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