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Analysis of the Saliency Ratio Effect on the Output Torque and the System Efficiency in IPM Drives

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Permanent magnet synchronous motors (PMSM) can be classified into two groups based on the rotor saliency structure as surface mounted permanent magnet synchronous motors (SPM) and interior mounted permanent magnet synchronous motors (IPM). Saliency ratio is defined as the ratio of q- axis inductance to d- axis inductance. While SPMs with the same d- and q- axis inductance values have the capacity to generate only the magnet-based torque IPMs are salient machines and they also produce reluctance torque due to the difference in inductances. This study analyses the influence of the saliency ratio on the drive system efficiency and the torque production capability of salient machines. First, efficient torque control systems have been implemented and successfully achieved for two identical IPMs with only difference in saliency ratios. Then, tests were carried out on the drive systems for two IPMs. It has been validated by extensive simulation results that the torque production capacity and the efficiency of the drive system can be increased considerably if the saliency ratio can be increased at the stage of machine design.

Keywords: IPM, PMSM, saliency ratio, torque control

1. INTRODUCTION

PMSMs attract attention due to their superior features such as high efficiency, low acoustic noise, low rotor losses, and wide speed range [1]. Accordingly, they are widely used in industry such as machine tools, robotics, aeronautics, automotive [2]. Its popularity has increased in recent years with applications such as the increasing use in electric vehicle technology compared to other motors [3] and the increasing use in railway systems due to their high power density and wide speed range of operation [4]. Therefore, the design and modern control strategies for PMSMs are an important research topic.

PMSMs can be divided into two groups based on the rotor structure as salient and non-salient machines. While surface mounted permanent magnet synchronous motors (SPMs) are non-salient machines, interior mounted permanent magnet synchronous motors (IPMs) are known as salient brush-less AC machines. SPMs are motors designed by mounting permanent magnets on the rotor surface and do not contain saliency in the rotor [5]. Therefore, it has the capacity to generate only the magnet based electromagnetic torque. However, in IPMs, magnets are mounted in the rotor and there is a saliency in the rotor structure. When motor modelled with coordinate transformations in d- and q- rotary axes, inductance values in d- and q- axes are different.

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While there is a difference between inductance values in d- and q- axes in IPMs, d- and q- axes inductance values are the same in SPMs. Saliency ratio in PMSMs refers to the ratio of L_q to L_d. Since IPMs have saliency, they have the ability to produce reluctance torque as well as magnet-based torque. Thus, the torque output that can be obtained from IPMs is higher than that of SPMs [6].

There are scalar and vector approaches in control methods used in motor drive systems. Although the scalar control technique is a low-cost method, it is only effective in steady state because it exhibits very poor dynamic performance. Vector control approach has advantages over standard techniques such as full torque capacity at low speed, better dynamic performance, higher efficiency for each operating point in a wide speed range [7]. Vector control techniques are basically divided into two categories as Field Oriented Control (FOC) and Direct Torque Control (DTC). FOC and DTC are widely used in both PMSM and induction motor drive systems [8-11]. In the FOC control technique, the current errors are driven to zero while the torque and the stator flux magnitude errors are driven to zero in DTC drives [12]. Since DTC drives rely on observer accuracy and the current limits cannot be posed directly, the machine is controlled with FOC strategy in the case study in which the current limits can directly be posed and the drive is exempt from flux and torque observers.

After adopting the motor control with coordinate transformations in the drive systems, d- and q-axis reference voltage components are obtained. Although the reference voltages in d- and q- axis can be transformed into three phase components to directly being applied to the machine by the use of coordinate transformations in the simulation environment, this is not feasible in real life since a modulation strategy for an inverter is a must in practice. Therefore, the inverter structure and pulse width modulation technique has been modelled and employed in the simulated drives to better represent the drives as in real world. Sinusoidal pulse width modulation (SPWM) [13] and space vector pulse width modulation (SVPWM) are commonly used in motor drive systems [14-16]. The SVPWM technique is superior to SPWM with its features such as 15% more output voltage, lower total harmonic distortion, and low switching losses [17-18]. Hence, SVPWM switching technique is employed to trigger the inverter gates in this study.

Efficient torque control systems have been developed for two IPMs with different saliency ratios for the purpose of comparing the two machines. Since the available battery voltage is finite, SVPWM technique is limited by the over-modulation block in the simulation. Two IPM drives with different saliency ratios have been compared broadly in terms of torque output capabilities and overall system efficiencies. From the realistic simulation results, it has been validated that the IPM machine with a high saliency ratio has higher output torque capability and the drive achieves higher efficient operation.

2. MATHEMATICAL EXPRESSIONS

2.1. Coordinate transformations and IPM model

In order to control three-phase PMSMs like a DC motor, equations in the abc reference system are expressed in d- and q- rotary frames with the help of coordinate transformations. Firstly, Clarke matrix in (1) is applied to the equations in the abc reference system and defined in the stationary frame. The equations defined in the stationary frame are defined by the Park transformations given in (2) in the d- and q- axes according to the rotor angle θ_e. By taking the inverse of the matrices given in (1) and (2), I_{abc} currents at the inverter output to be used in the control system are transformed into d- and q- axes with the matrix in (3).

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} \cos\theta & \cos\theta - \frac{2*\pi}{3} & \cos\theta + \frac{2*\pi}{3} \\ -\sin\theta & -\sin\theta - \frac{2*\pi}{3} & -\sin\theta + \frac{2*\pi}{3} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3)$$

When the coordinate transformations are applied to the three phase equations of the motor, the voltage equations in the d- and q- axis of the IPM are as in (4) and (5).

$$V_d = R_s * I_d + L_d * \frac{dI_d}{dt} - L_q * \omega_e * I_q \quad (4)$$

$$V_q = R_s * I_q + L_q * \frac{dI_q}{dt} + L_d * \omega_e * I_d + \Psi_m * \omega_e \quad (5)$$

IPM torque and mechanical equations are given by (6) and (7). In (8) and (9), torque components are separated as torque due to magnets and reluctance torque. As can be seen from (8) and (9), the magnet-based torque depends on the magnetic flux linkage, and the reluctance torque depends on the difference of the d- and q- axis inductances.

$$T_e = \frac{3*p}{2}\left[\Psi_m * i_q + (L_d - L_q) * i_d * i_q\right] \quad (6)$$

$$\omega_m = \int \frac{T_e - T_m - B * \omega_m}{J} * dt \quad (7)$$

$$T_e^{Magnet} = \frac{3*p}{2}\left[\Psi_m * i_q\right] \quad (8)$$

$$T_e^{Reluctance} = \frac{3*p}{2}\left[(L_d - L_q) * i_d * i_q\right] \quad (9)$$

V_d,V_q are voltage magnitudes (Volt) and I_d, I_q are current magnitudes in dq- frame, ω_e and ω_m are the electrical and mechanical speed in rad/s, respectively, p is the pole-pair number, L_d and L_q are the inductance values of d- and q- axis, respectively, Ψ_m is the permanent magnet flux linkage (Weber) and R_s is the stator resistance (ohm). T_e is the electromagnetic torque in N.m. The saliency ratio of the motor is defined as the ratio of the q- axis inductance to the d- axis inductance and it is expressed by (10) [19].

$$\rho = \frac{L_q}{L_d} \quad (10)$$

In this study, it is aimed to analyse the torque production capability and the system efficiency of two IPM machines with different saliency ratios. In Figure 1, the schematic of the proposed control system for both motors is given.

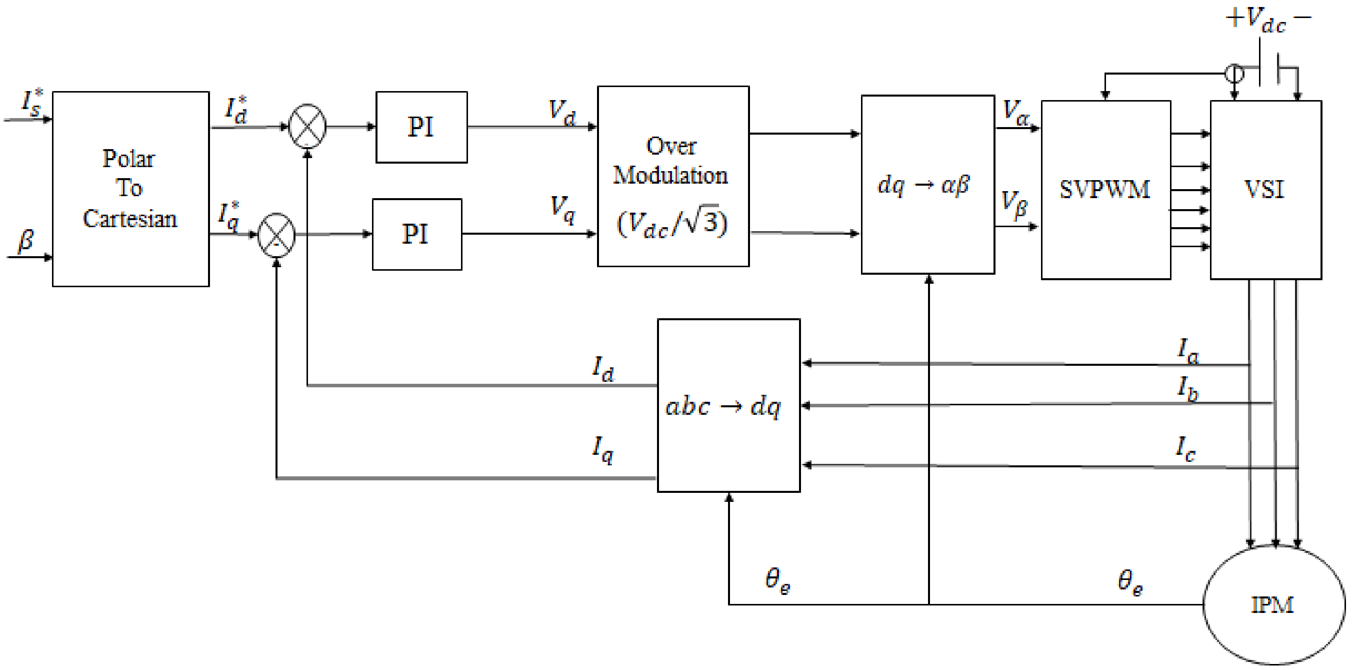

Figure 1 The proposed drive system schematic for both motors

2.2. Inverter and SVPWM technique

In (11-13), the function of the output phase voltages of the ideal inverter depending on the switching states are given. S_1, S_2 and S_3 represent the switching states.

$$V_a = \frac{V_{dc}}{3} * (2S_1 - S_2 - S_3) \quad (11)$$

$$V_b = \frac{V_{dc}}{3} * (2S_1 - S_2 - S_3) \quad (12)$$

$$V_c = \frac{V_{dc}}{3} * (2S_1 - S_2 - S_3) \quad (13)$$

After the control process is performed with PI controllers, voltage values are obtained in the d - and q- axes. For the application of the SVPWM technique, the voltage values in the d- and q- axes are transformed into the $\alpha\beta$ frame by inverse Park transformation. The angle of the voltage vector in the axes of the $\alpha\beta$ lies in the hexagonal structure in Figure 2. Sectors are determined according to the angle of the reference vector by dividing the 360º rotation path into 6 equal parts.

Switching times are calculated according to sector information through equation (14-16).

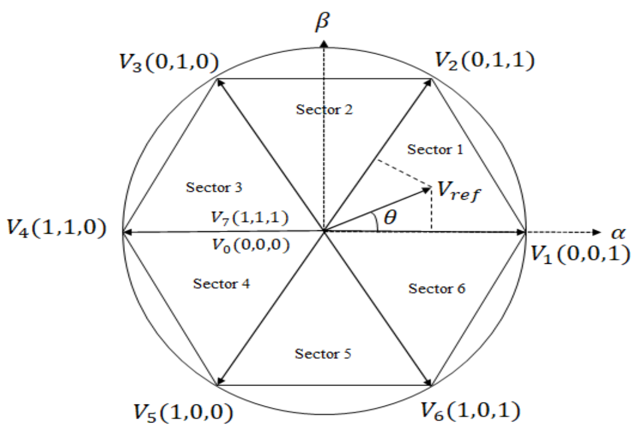

Figure 2 Hexagonal structure where the reference vector lies in

$$T_1 = \frac{\sqrt{3} * V_{ref}}{V_{DC}} * T_s * \sin((n * \frac{\pi}{3}) - \theta) \quad (14)$$

$$T_2 = \frac{\sqrt{3} * V_{ref}}{V_{DC}} * T_s * \sin((n * \frac{\pi}{3}) - \theta) \quad (15)$$

$$T_0 = T_s - (T_1 + T_2) \quad (16)$$

where, V_{dc} represents the battery voltage, V_{ref} is the magnitude of the reference vector, n is the sector information, T_S is the switching period, and θ is the angle of the reference vector.

3. SIMULATION RESULTS

The improved system performance with the increased saliency ratio is validated through the simulation studies in this section. The specifications of the two IPM motors are listed in Table 1. Two drives to be compared are implemented as shown in Figure 1. The two motors are operated at the 1000 rpm speed and the inverter switching frequency is set to 5 kHz. The motors with low and high saliency ratios are compared based on torque capability and the system efficiency in the following sections.

Table 1 The specifications of the two IPM motors

Motor Type	IPM Machine 1	IPM Machine 2
Phase Number/ Pole Number	3/8	
Nominal Speed	2500 rpm @120V DC	
Continuous Torque	15.7 Nm @51.6 Arms	
Continuous Power	4.1 kW @120V DC	
Input Voltage Range	12V-600 V	
Nominal d- Axes Inductance	0.282 mH	
Nominal q- Axes Inductance	0.828 mH	1.656 mH
Nominal PM Flux Linkage	0.0182 Weber	
Nominal Phase Resistance	0.0463 ohm	
Inertia	0.0072 $kg.m^2$	
Saliency Ratio	2.936	5.872

3.1. Torque production capabilities of the two motors

The two motors are operated at the same stator current magnitude values and the maximum produced electromagnetic torque with the two machines are presented in Figure 3. As can be seen from the Figure 3, the motor model with high saliency ratio is capable to generate higher output torque in the drive system.

In the motor drive system with low saliency ratio, 8.3 N.m average torque output is obtained when machine operates at 30 A, while the average torque production achieved by the higher salient machine is approximately 12.5 N.m. This implies that the twice the increase of the saliency ratio increases the torque production capability of the machine at the rate of 33.6% for the 30 A stator current magnitude operation.

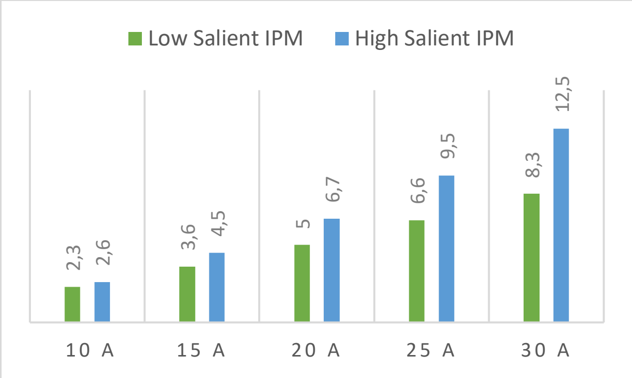

Figure 3 Torque production capabilities of the two machines (N.m)

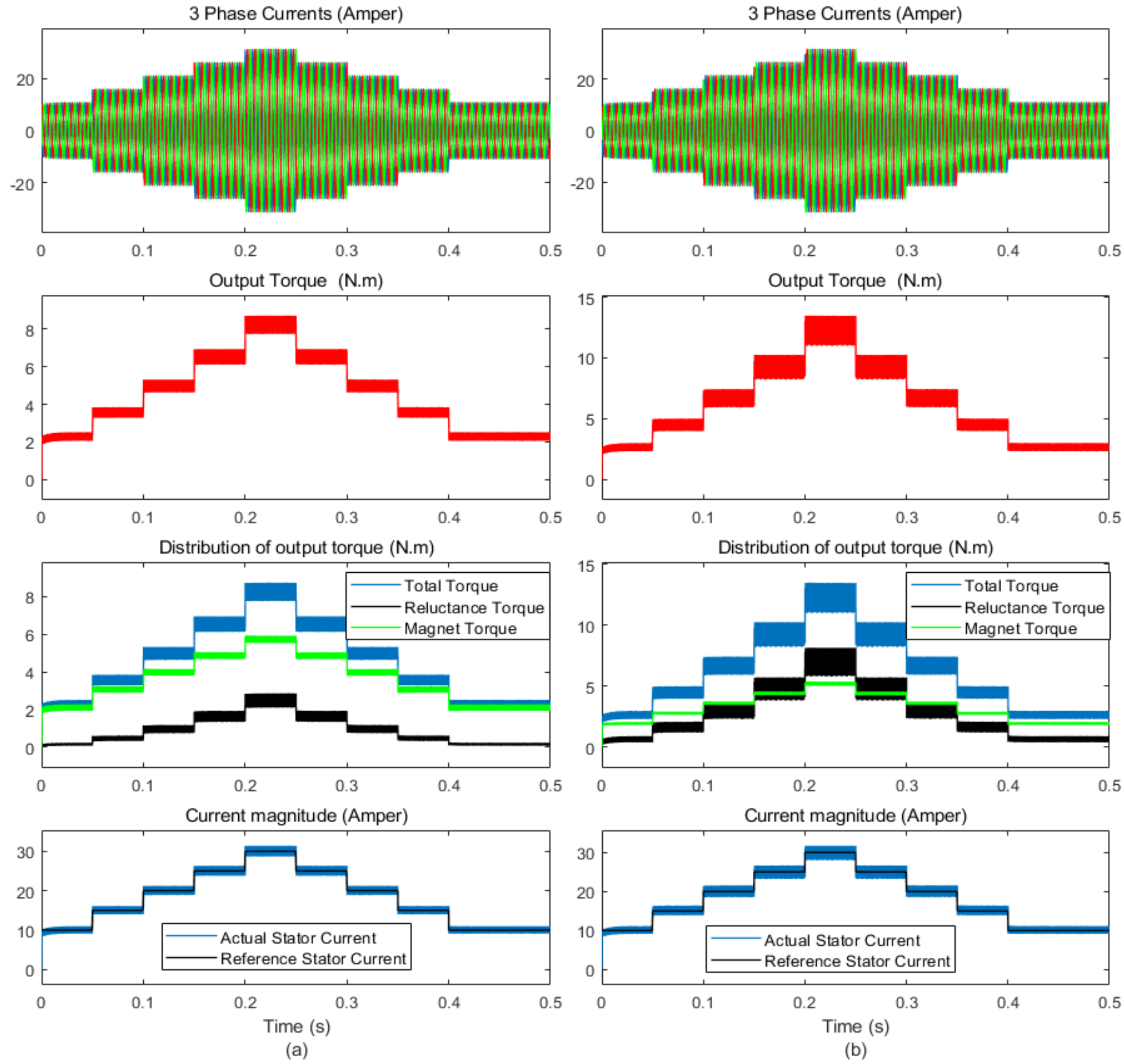

Figure 4 Maximum electromagnetic torque production with the two machines. (a) Low salient IPM (b) High salient IPM

The two machines have been operated to generate the maximum electromagnetic torque for given stator current magnitude commands and the results are illustrated in Figure 4. It is evident that the maximum electromagnetic torque production is higher in high salient machine than that of low salient machine since the utilization from the reluctance torque component increases in high salient machines while the magnet-based torque production slightly reduces. This implies that the achievement of the increased saliency ratio in IPM machines is a desired machine design criteria as the total torque can be increased by the utilization of the reluctance torque.

3.2. Efficiency analysis

Input and output powers of IPM machines are given in (17) and (18), respectively [20].

$$P_{input} = \frac{3}{2} * (V_d * I_d + V_q * I_q) \quad (17)$$

$$P_{output} = w_m * T_e \quad (18)$$

$$\eta(\%) = \frac{P_{output}}{P_{input}} * 100 \quad (19)$$

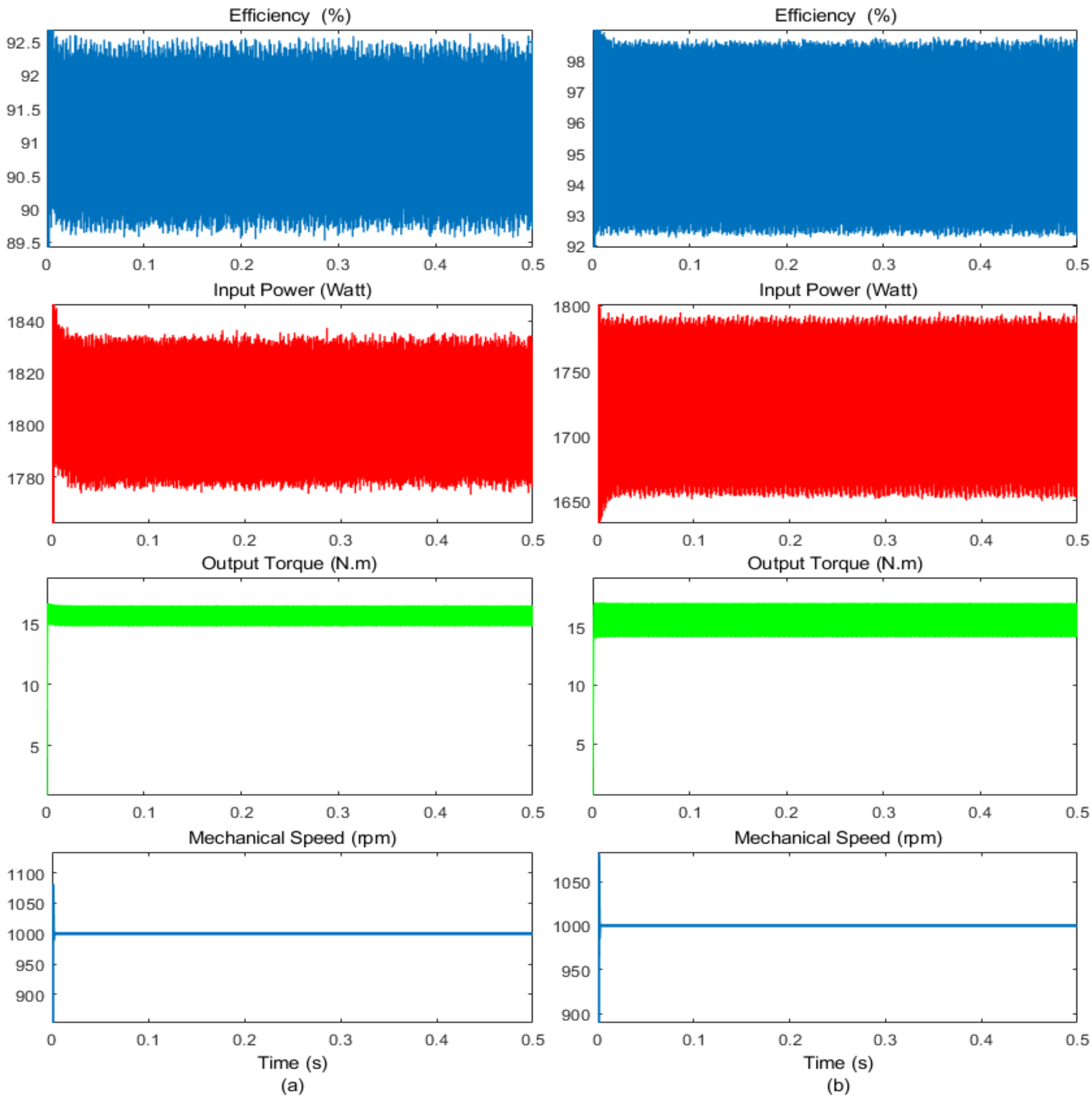

Figure 5 (a)Results with IPM Machine 1 (b) Results with IPM Machine 2

Figure 5 shows the efficiency results by operating the drive systems implemented for two different IPM models at continuous torque output (15.7 N.m) and 1000 rpm mechanical speed. Output powers of the two machines are the same based on (18) since the two drives are operated at the same speed and the same electromagnetic torque. On the other hand, the input powers of the two system show significant difference at the same certain operating point. While the average input power of the system is 1810 W for low salient drive, it is 1730 W for high salient machine. In the light of these results, the efficiency of the drive systems are 91% and 96% for low and high salient machines, respectively. Hence, 5% increase in the efficiency would be a significant improvement for high salient machines. Considering the two drive systems generate the same output torque production continuously at 1000 rpm, a battery pack of capacity 10 kWh would be consumed at 5 hours 31.5 minutes for low salient machines whereas it would be consumed at 5 hours 46.8 minutes for high salient machines. This implies that the high salient machine drive achieves the same output torque production 15.3 minutes longer than that of the low salient machine for the case study. Overall, the results validate how important it is to achieve the increased saliency ratio during machine design process.

4. CONCLUSION

The two IPM machines with a saliency ratio of 2.93 and 5.86 have been compared and its effect on output torque production and on the efficiencies of the drive systems have been analysed comprehensively. The comparisons are made by realistic high performance IPM drives and the results have been discussed in detail. It has been validated that the increase of the saliency ratio increases the torque production capability of the drive system while the operation speed and the stator current magnitude are the same. Accordingly, the system efficiency increases dramatically by the increase of the saliency ratio. It has been shown that the torque production capability of the machine would increase 33.6% while the machine operates at 30 A stator current magnitude. Also, system efficiency increased by 5% when tested at 1000 rpm speed and continuous torque (15.7 N.m). The results validate how significant it is to achieve the increased saliency ratio as an attractive design criterion.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The authors contributed equally to the study.

The Declaration of Ethics Committee Approval

The authors declare that this document does not require an ethics committee approval or any special permission.

The Declaration of Research and Publication Ethics

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