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Maximum Torque per Ampere Strategy in IPM Drives for Electric Vehicles

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Abstract: Permanent magnet synchronous motors (PMSM) are generally known for their type whose magnets are located on the rotor surface and this motor type, which is called surface mounted permanent magnet synchronous motors (SPM), produces magnet based torque. Based on torque equations, since there is only q- axis current and value of magnetic flux linkage, the d- axis current is kept at 0 and the torque is maximized and controlled, which is called $I_d = 0$ control technique. However, reluctance torque is produced in interior mounted permanent magnet synchronous motors (IPM) due to the inductance difference caused by the saliency in the rotors and by controlling the reluctance torque correctly, the efficiency of motor increases. For this reason, maximum torque per ampere (MTPA) strategy is applied to perform torque control efficiently in IPMs. In this study, the difference between the efficiency values was observed by simulating torque control in IPMs with the MTPA strategy instead of the conventionally used $I_d = 0$ control technique. As a result of the simulations, using the MTPA strategy instead of the conventional vector control technique in the drivers of the IPMs used in electric vehicle applications increases the efficiency of the system and extends drive range capacity by using the battery more efficiently.

Keywords: IPM, MTPA, Torque Control

Elektrikli Araçlar İçin GMSM Sürücülerinde Akım Başına Maksimum Tork Stratejisi

Öz: Kalıcı mıknatıslı senkron motorlar (KMSM), genellikle mıknatısları rotor yüzeyinde bulunan çeşidi ile bilinir ve yüzey mıknatıslı senkron motorlar (YMSM) olarak adlandırılan bu motor çeşidi rotor yüzeyinde bulunan mıknatıs tabanlı tork üretirler. Tork eşitliklerinde sadece q-eksen akımının ve sabit mıknatıslardaki akı değerinin olmasından dolayı d-eksen akımı 0 değerinde tutularak tork maksimize edilir ve kontrolü sağlanır ki bu kontrol tekniğine $I_d = 0$ kontrol tekniği denir. Fakat gömülü mıknatıslı senkron motorlarda (GMSM) rotorlarındaki çıkıntıdan kaynaklanan endüktans farkından dolayı relüktans tork üretilir ve relüktans torkunun doğru bir şekilde kontrol edilmesiyle motor verimi yükselmektedir. Bu sebeple GMSM'lerde tork kontrolünün verimli şekilde gerçekleştirilebilmesi için akım başına maksimum tork (ABMT) stratejisi uygulanmaktadır. Bu çalışmada GMSM'lerde tork kontrolünün konvansiyonel olarak kullanılan $I_d = 0$ kontrol tekniği yerine ABMT stratejisi ile simülasyonu gerçekleştirilerek verim değerleri arasındaki fark gözlenmiştir. Baz hızın altındaki hız değerlerinde tork kontrolünün verimli bir şekilde gerçekleştirildiği simülasyon sonuçları ile doğrulanmıştır. Simülasyonlar sonucunda elektrikli araç uygulamalarında kullanılan GMSM'lerin sürücülerinde konvansiyonel vektör kontrol tekniği yerine ABMT stratejisinin kullanılması sistemin verimini artırmakta ve bataryayı daha verimli kullanarak daha uzun menzil kapasitesi sağlamaktadır.

Anahtar Kelimeler: ABMT, GMSM, Tork Kontrolü

1. Introduction

Environmental problems such as global warming, acid rain, depletion of the ozone layer have revealed the necessity of reducing the carbon dioxide emissions in the world. The carbon dioxide emission rates in commercial, residential, transportation and industry are %15, %19, %32 and %34, respectively [1]. To overcome these problems, it is necessary to increase the use of renewable energy sources worldwide. The carbon dioxide emission in the transportation is at a considerable level, and its level can be reduced by increasing the use of electric vehicles as they can use renewable energy sources [2-4].

Permanent magnet synchronous motors (PMSM) are commonly used at different application area due to their superior features such as high efficiency, low acoustic noise, and small volume [5]. For these reasons, PMSMs have been preferred commonly in electric vehicle technology since 2010 [6]. In addition, from the results of [7], the authors conclude that PMSMs are more suitable for electric and hybrid vehicles. Hence, PMSMs and their control systems are an extremely important research subject for electric vehicle technology.

PMSMs can be divided into two groups as surface mounted permanent magnet (SPM) and interior mounted permanent magnet (IPM) according to the magnet placement in the rotors [8]. Due to the non-salient rotor structure of SPMs, when the motor is modelled in d- and q- axes, there is no inductance difference between the two axes. For this reason, they only produce the torque that the permanent magnets in the rotor can produce according to the magnetic flux linkage value, and when the motor is controlled using the field-oriented control (FOC) technique, torque control can be performed with only the q-axis current so this control technique is commonly known as $I_d = 0$ control technique [9-11]. However, since the inductance values in the d- and q- axes are different from each other in IPMs, they can produce reluctance torque as well as the torque production based on the magnets [12]. The torque production can be increased with the correct utilization of the reluctance torque, and the motor capacity can be used more efficiently. The correct use of the reluctance torque is achieved by producing the appropriate current values to determine the optimum operating point for the system from the reference torque value. The control strategy in which the reluctance torque is controlled correctly is called as the maximum torque per ampere (MTPA) strategy.

Since there is no reluctance torque in SPMs, the d-axis current has no effect on the torque generation and the $I_d = 0$ control technique is the realization of torque control with the q-axis current, which corresponds to the armature current in DC motors. In $I_d = 0$ control technique, the d-axis current is kept at 0 to maximize the torque production. In fact, the use of the $I_d = 0$ control technique means that the MTPA strategy is applied to SPMs [11], as the torque value changes proportionally to the q-axis current, so the control operation is provided on an axis and it is a simpler system compared to the MTPA strategy of IPMs. In the MTPA strategy for IPM drives, the reference current values generated from the torque depend on both axes, so it is more complicated than the $I_d = 0$ control technique.

The purpose of applying the MTPA strategy is to produce the current values that will provide the optimum operating point of the IPMs from the torque value requested from the system. There are various methods to find the MTPA trajectory in the literature [13], by testing the motor in suitable test environments and obtaining the current values required to operate at the optimum point according to the reference torque value, using pre-prepared look-up tables [14-16], signal processing methods through real signal injection [17], virtual signal injection due to the fact that real signal injection brings extra losses to the system [18, 19], and trajectory is obtained by solving non-linear equations in order to generate reference currents from the torque value requested from the system with

mathematical equations [20-22]. In this paper, MTPA points will be determined by the solution of non-linear equations with mathematical method and will be applied to the drive system.

In this study, it has been shown that the commonly used $I_d = 0$ control technique, due to its simplicity, is not suitable for each type of PMSM and does not provide maximum efficiency. Although the $I_d = 0$ control technique for SPMs is the most appropriate control technique in the constant torque region, the efficiency value increases considerably by using the MTPA strategy for IPMs. With the use of the MTPA strategy in IPM drives for electric vehicle applications, it has been confirmed by the simulation results that the stored energy in the battery can be used more efficiently. The demanded torque value can be produced with a minimized current magnitude.

2. Mathematical Expressions

2.1. IPM Model and MTPA Equations

The motor model and control algorithm are expressed in dq-axes using coordinate transformations. After applying Clarke and Park transformations to three phase motor equations, the motor voltage equations in the dq-axis are given by (1) and (2). IPM torque equation is given by (3). The reluctance torque and torque produced by the magnets are given by (4) and (5).

$$V_d = R_s * I_d + L_d * \frac{dI_d}{dt} - w_e * L_q * I_q \tag{1}$$

$$V_q = R_s * I_q + L_q * \frac{dI_q}{dt} + w_e * L_d * I_d + w_e * \Psi_m \tag{2}$$

$$T_e = \frac{3*p}{2} * (I_q * \Psi_m + (L_d\text{-}L_q)* I_d*I_q) \tag{3}$$

$$T_e^{Magnet} = \frac{3*p}{2} * (I_q * \Psi_m) \tag{4}$$

$$T_e^{Reluctance} = \frac{3*p}{2} *(L_d\text{ -}L_q)* I_d*I_q) \tag{5}$$

V_d and V_q are the direct and quadrature axis voltages, I_d and I_q are the direct and quadrature axis currents, w_e are the electrical speed in rad/s, p is the pole-pair number, L_d and L_q are the inductance values of the direct and quadrature axes, Ψ_m is the permanent magnet flux linkage and R_s is the stator resistance.

d- and q- axis currents can be written by (6-8).

$$I_d = -I_s * \sin \beta \tag{6}$$

$$I_q = I_s * \cos \beta \tag{7}$$

$$|I_s| = \sqrt{I_d{}^2 + I_q{}^2} \tag{8}$$

Substituting (3) into (6-8) one obtains;

$$\frac{dT_e}{d\beta} = \frac{3*p}{2}\left[-\Psi_m * I_s * \sin\beta + \left(L_q - L_d\right) * I_s^2 * \cos 2\beta\right] \tag{9}$$

The MTPA point is the point where the derivative of the torque value with respect to β is 0. The β derivative of the (9) assuming that the machine parameters are constant is given as;

$$\beta = \sin^{-1}\left(\frac{-\Psi_m + \sqrt{\Psi_m^2 + 8 * \left(L_q - L_d\right)^2 * I_s^2}}{4 * \left(L_q - L_d\right) * I_s}\right) \tag{10}$$

Substituting (10) into (6-8) and solving for the d- axis current for MTPA point, (11) is obtained;

$$I_d = \frac{\Psi_m}{2 * \left(L_q - L_d\right)} - \sqrt{\frac{\Psi_m^2}{4 * \left(L_q - L_d\right)^2} + I_q^2} \tag{11}$$

Substituting (11) into torque equation [20] ;

$$I_q^{MTPA} = \left(L_q - L_d\right)^2 * I_q^4 + \frac{2 * T_e}{3 * p} * \Psi_m * I_q - \left(\frac{2 * T_e}{3 * p}\right)^2 \tag{12}$$

When the current I_q is solved for the MTPA point, a 4th order non-linear equation is obtained. Newton Raphson method can be used to solve the higher order equation. Equations of the Newton Raphson method are given in (13) and (14).

$$I_q^{MTPA}(n + 1) = I_q^{MTPA}(n) - \frac{Function\ of\ I_q^{MTPA}\ (I_q^{MTPA}(n))}{Derivative\ Function\ of\ I_q^{MTPA}\ (I_q^{MTPA}(n))} \tag{13}$$

$$Derivative\ Function\ of\ I_q^{MTPA} = 4 * \left(L_q - L_d\right)^2 * I_q^3 + \frac{2 * T_e}{3 * p} * \Psi_m \tag{14}$$
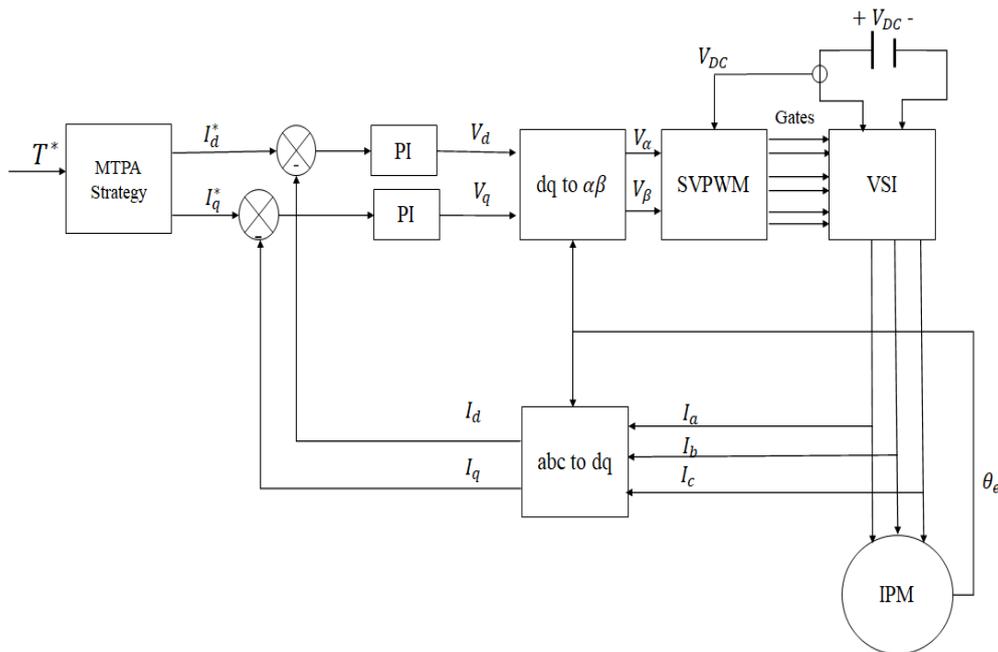
Figure 1. The Proposed Drive System Schematic

To start the iteration, the initial value of the I_q^{MTPA} must be determined. Since the magnet torque is effective at the beginning, the initial current value is as in (15).

$$I_q^{MTPA}(0) = \frac{2 * T_e}{3 * p * \Psi_m} \tag{15}$$

Substituting the value of I_q^{MTPA} in the torque equation produces the reference value I_d for MTPA operation.

$$I_d^{MTPA} = \frac{2 * T_e}{3 * p * I_q^{MTPA} * (L_d - L_q)} - \frac{\Psi_m}{(L_d - L_q)} \tag{16}$$

The proposed block diagram for the torque control of the IPM is shown in Figure 1. Since the comparison of $I_d = 0$ control technique and MTPA is the subject of the study, in $I_d = 0$ control technique, the reference current is 0 for the d-axis and the reference current for the q- axis is proportionally produced from the reference torque with the constant in (17).

$$K_t = \frac{2}{3 * p * \varphi_M} \tag{17}$$

It is important to note that (10)-(16) is correct under the assumption that the machine parameters are constant. The efficiency in practical applications may deviate slightly from the optimum, however, precise torque control can be achieved with the use of Newton-Raphson technique.

2.2. Space Vector Pulse Width Modulation (SVPWM)

Generally, two different PWM methods are commonly preferred in motor drive systems, namely, sinusoidal PWM (SPWM) and space vector PWM (SVPWM) [23, 24]. The first is SPWM technique and it is simple to implement. The second is the SVPWM technique, which is a good alternative to be used in motor drives with its superior features such as producing ~15% more output voltage compared to SPWM technique, having less harmonics, and less switching losses [25]. In this study, SVPWM technique has been employed as it is superior.

Accordingly, as can be seen from Figure 1, demanded dq- axis voltages are transformed into the αβ frame through the inverse Clarke transformation. Then the amplitude and angle of the reference vector consisting of voltage components in αβ axis are determined. Considering the 360° rotation angle, 6 sectors of each 60° are formed. The sector in which the reference voltage vector lies is obtained from the angle value of the reference vector. Switching durations of the switches are determined according to the time expressions given by (18-20).

$$T_1 = M * T_s * \sin((n * \frac{\pi}{3}) - \theta) \tag{18}$$

$$T_2 = M * T_s * \sin(\theta - (n - 1) * \frac{\pi}{3}) \tag{19}$$

$$T_0 = T_s - (T_1 + T_2) \tag{20}$$

θ, n, M and T_s are the angle of reference vector, sector number, modulation index and sampling time, respectively. Modulation index is given by (21) [26].

$$M = \frac{\sqrt{3} * V_{ref}}{V_{DC}} \tag{21}$$

3.   Simulation Results

In the control system, which is created by mathematical models, the switching frequency of the SVPWM technique is 5 kHz in both $I_d = 0$ control technique and the MTPA strategy. The results were obtained by running the simulation for 0.5 second. The limitation of using the battery capacity of 0.577 ratio, brought about by the SVPWM technique, is applied in the simulation in a way to prevent over-modulation. At speeds lower than the base speed, torque command value is changed with step functions up to the continuous torque value of the motor, and the accuracy of the control system is investigated. The front and rear image of the motor whose parameters are used in the simulations are given in Figure 2 and parameters of motor are listed in Table 1.

Figure 2. Motor view used in simulation

Table 1. Motor Parameters

Motor Type	Interior Permanent Magnet Synchronous Motor	
Phase Number/ Pole Number	3/8	
Nominal Speed	2500 rpm	@120 V DC
Continuous Torque	15.7 N.m	@51.6 A rms
Continuous Power	4.1 kW	@120 V DC
Input Voltage Range	12V- 600V	
Nominal d-Axes Inductance	0.282 mH	
Nominal q-Axes Inductance	0.0828 mH	
Nominal Stator Flux Magnitude	0.0182 Weber	
Nominal Phase Resistance	0.0463 ohm	
Inertia	0.0072 kg.m^2	

Case 1: Variable Torque and Constant Speed Comparison

By keeping the speed value at 1000 rpm, the torque value has been changed from 3 N.m with step functions up to the continuous torque value of the motor (15.7 N.m) as shown in Figure 3. Control systems created with both the $I_d = 0$ control technique and the MTPA strategy can follow the torque. However, the required current magnitude to produce commanded torque in the control system operating with the $I_d = 0$ control technique is significantly higher than the current value in the control system controlled by the MTPA strategy. In other words, $I_d = 0$ control technique consumes more power by drawing more current from the battery to track the reference torque. As can be seen from Figure 3, when 15.7 N.m torque is demanded from the system, MTPA strategy produces

reference torque with 48 A current magnitude, while the control system operating with $I_d = 0$ control technique requires 72 A current magnitude.
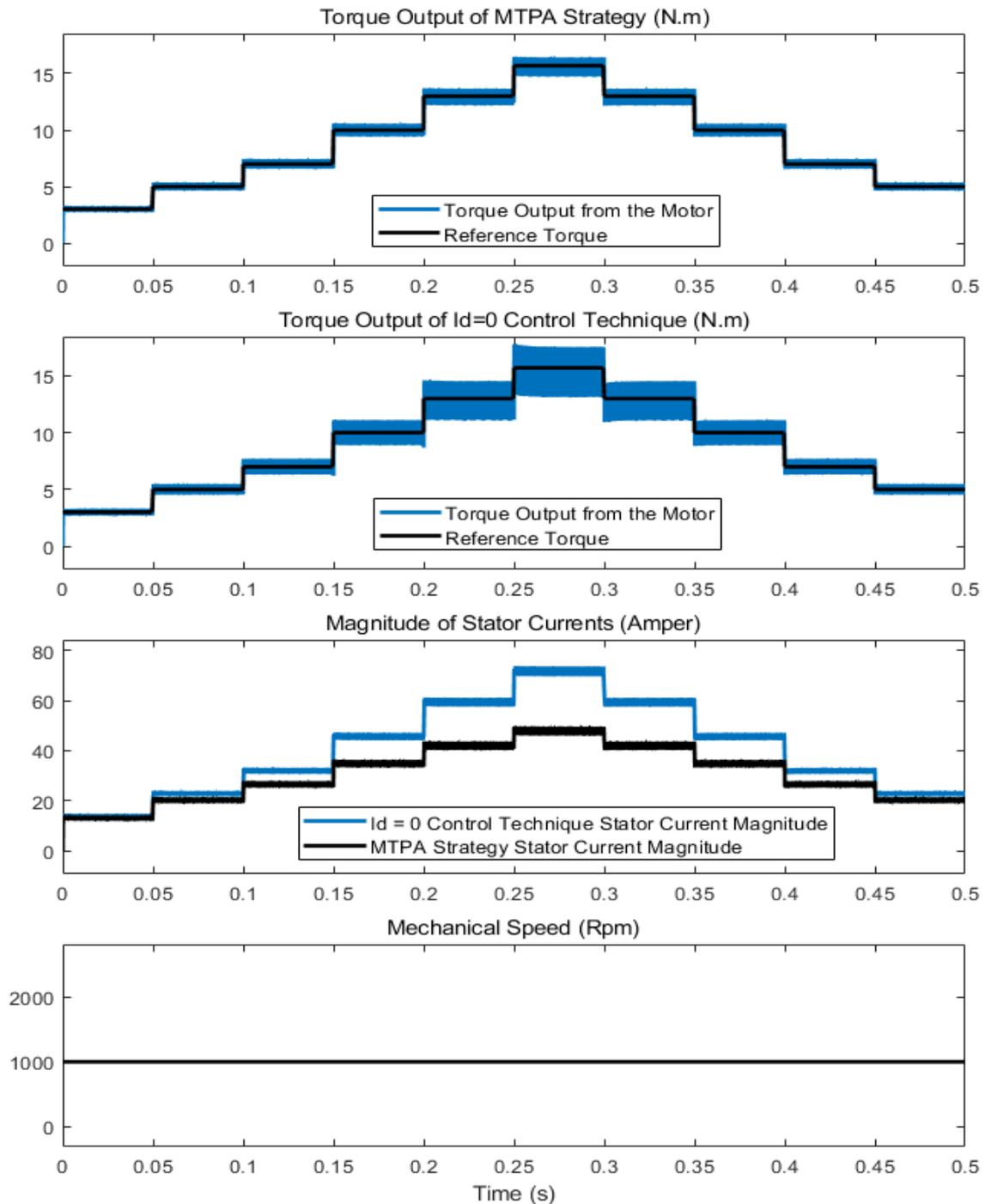
Figure 3. Torque and Current Outputs with the Two Control Strategies

Case 2: Variable Speed and Constant Torque Comparison

While demanding a constant torque value from the motor, the mechanical speed is increased with a ramp function from 0 rpm to 2000 rpm as shown in Figure 4. It is seen that the conventional $I_d = 0$ control technique is not able to generate demanded torque above 1340 rpm speed value while the torque production is successfully achieved with the MTPA control strategy.

$I_d = 0$ control technique reaches the system voltage limits at approximately 1340 rpm in the drive system applied. To generate the demanded torque from the motor as in MTPA drive system, the battery voltage level must be increased. As can be seen from Figure 5, when the 187 V battery voltage level is applied, the $I_d = 0$ controlled drive system can produce the command torque. One can deduce from the results that the torque ripple increases dramatically with the increasing stator current magnitude. Hence, accurate control strategy not only provides the demanded value but improves the output torque quality as well.
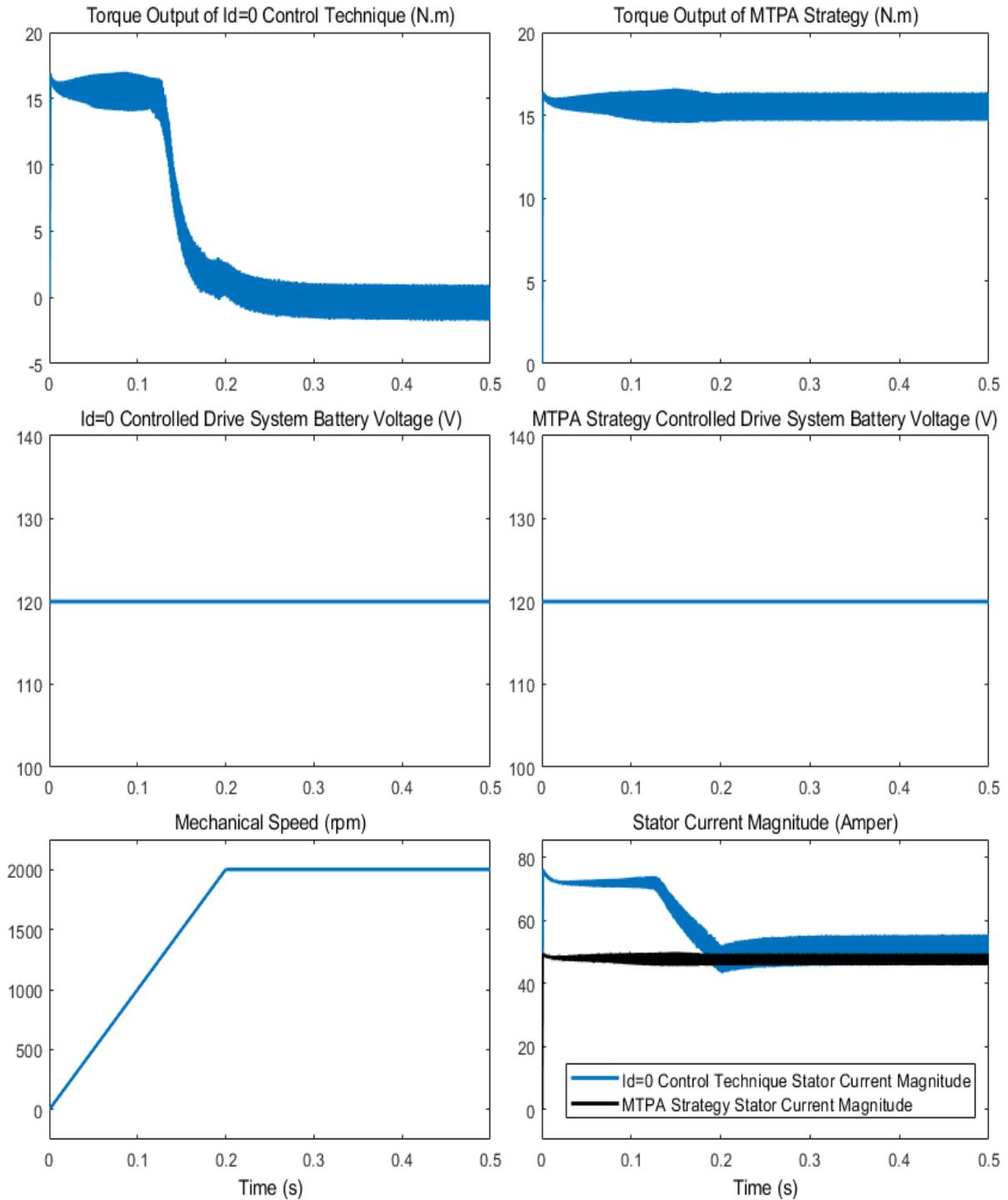
Figure 4. Variable Speed Comparison
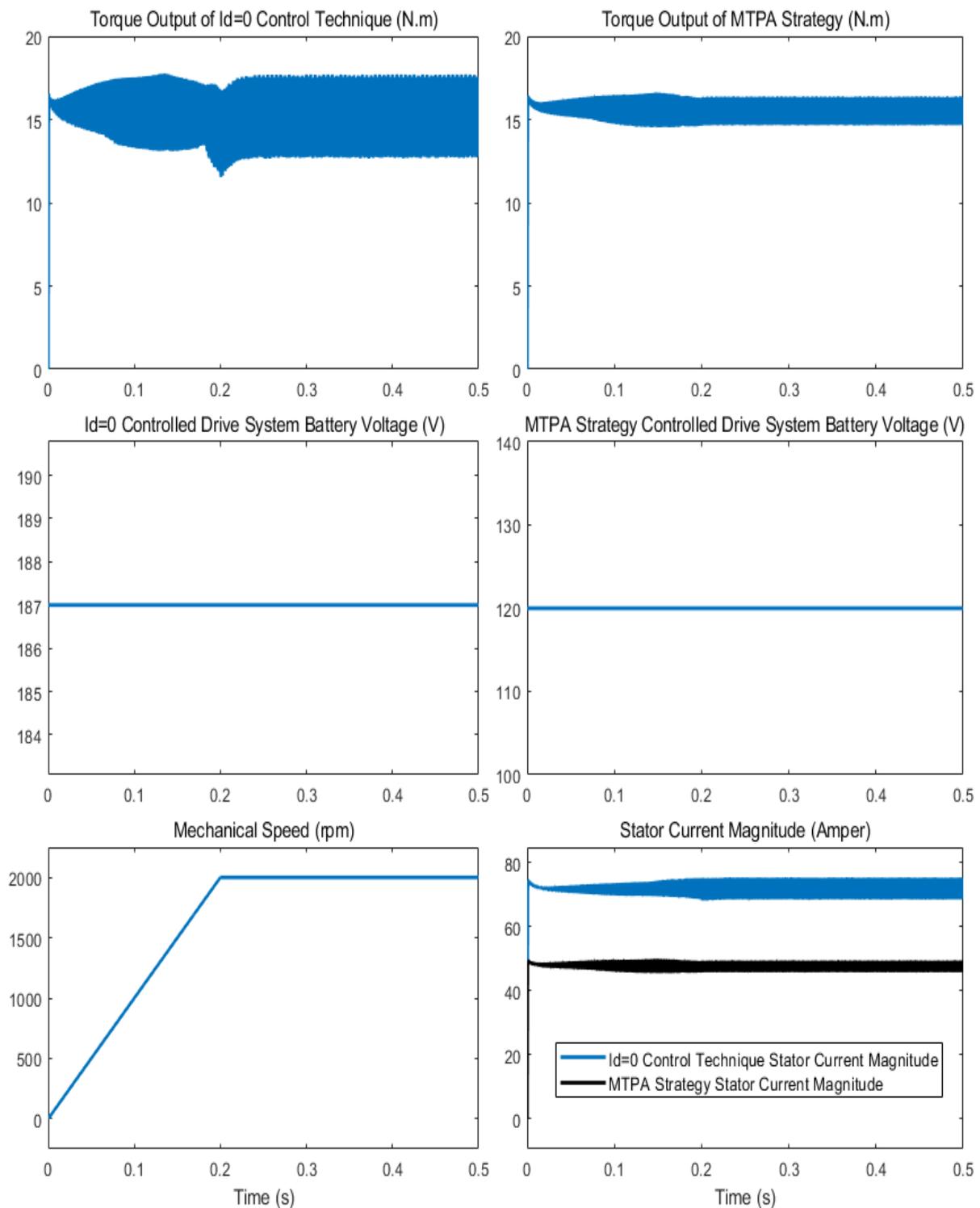
Figure 5. Outputs on Correction of Battery Voltage

4. Conclusion

It has been proven in this paper that the conventional $I_d = 0$ control technique does not provide optimum efficiency for each PMSM type due to the different rotor structures in the design of PMSMs. It has been shown that IPMs with saliency in their rotor are more efficient with the MTPA strategy compared to the $I_d = 0$ control technique. Additionally, since $I_d = 0$ controlled system does not produce the demanded torque with the minimized stator current magnitude, the system reaches the voltage limitation at a lower speed. Hence, rated torque production at the base speed can be obtained

with reduced battery voltage level if MTPA strategy is adopted. Moreover, the torque ripple with the MTPA control has been reduced significantly as the torque production can be achieved with the minimized stator current magnitude. All in all, accurate MTPA control adoption improves output torque quality, increases efficiency, extends drive range, and reduces the battery size for the traction applications. The two control strategies have been compared in the constant torque region (MTPA control) and the comparisons of the two strategies in the extended speed region (Constant Power Region, Field-Weakening control) would be further studied as future research.

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Authors' Contributions

This study was produced from the master's thesis prepared by Osman Emre ÖZÇİFLİKÇİ under the supervision of Serkan BAHÇECİ and Mikail KOÇ, in the Department of Electrical- Electronics Engineering at Erciyes University and Ahi Evran University, respectively. Serkan BAHÇECİ and Mikail KOÇ determined the main idea of the study and carried out paper revisions. Obtaining the simulation results and paper writing was carried out by Osman Emre ÖZÇİFLİKÇİ.

Competing Interests

The authors declare that they have no competing interests.

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