Maximum Torque of IPMSM in Wide Speed Range Based on Current Angle Approach

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***Abstract*—This paper presents a novel control scheme for interior permanent magnet synchronous machine (IPMSM) to operate in wide speed range based on current angle approach. Below base speed, maximum torque per ampere (MTPA) strategy is employed and for above that, field weakening (FW) is utilized based on current angle. Motor can work continuously by choosing maximum angle between MTPA and FW strategies. Furthermore, it realizes maximum torque per flux (MTPF) strategy based on the torque angle control to operate above critical speed. The proposed algorithm could enter FW region (II) automatically. Compared to other methods, the algorithm of the proposed scheme is simple and d- and q-axis currents are generated separately. It is also capable of operating for both motoring and regenerating mode while achieving maximum torque. Besides, there is a smooth transition between constant torque and field weakening region in both modes. The simulation results show the validity of the proposed control scheme.**

Keywords—Interior permanent magnet synchronous machine (IPMSM), Current angle, Field weakening, Maximum torque

I. INTRODUCTION

Permanent magnet synchronous machine is one kind of the synchronous machines which field circuit is replaced with PMs. Due to elimination of field circuit, there is no need to maintain the field circuit and rotor copper losses are cancelled. Hence, efficiency of PMSM is higher than induction and conventional synchronous machines. Generally, depending on the placement of magnet, PMSM's are divided into two classification: SPMSM and IPMSM. As saliency ratio of SPMSM is equal to 1, IPMSM is more commonly used in wide speed range. In other words, the IPMSM has higher reluctance torque in FW region. Therefore, it is essential to utilize reluctance torque in field weakening (FW) region [1]. To exploit maximum torque, FW schemes can be generally classified into two categories (i) independent of model (ii) based on model. The first scheme adopts a voltage control loop, which is based on the difference between actual voltage and maximum attainable voltage, to recognize the operating condition. There are two ways to do this: one is adaptive control and the other is six-step control. Since inverter mode changes to overmodulation in six-step control, the utilization of DC-link voltage is improved in FW region. However, this mode causes torque ripple which can lead to noise increasing [2]. In [3,4], proposed scheme is based on current angle control which increases with voltage control loop. As motor requests more voltage to reach higher speed, this loop is enabled and increases the current angle. Besides, In [3], proposed control scheme is implemented in motor which is used for electric vehicle application. These schemes, which has been discussed so far, can be applied to any type of motor to operate in FW region and is insensitive to motor parameters. However, free-model schemes have a poor dynamic performance, weak tracking and may be unstable against unpredictable changing [2]. On the other hand, the second scheme depends on motor parameters and this type can be divided in two approach: direct control of flux and indirect control of flux. The former is controlled by flux directly in wide speed range and the latter is controlled by d-axis current, which is a representative of flux, indirectly. In [5], d-axis current is derived as function of q-axis current, speed and iron resistance to minimize efficiency in wide speed range. By differentiating sum of core loss and copper loss with respect to d-axis current gives the optimal d-axis. In [6], off-line method is used to generate d and q-axis currents in both regions. Depending on which region, a coefficient was proposed to adjust stator flux linkage. In [7,8], DTC based PI-controllers was employed to operate in wide speed range. For below rated speed, MTPA based on lockup table (LUT) is utilized to generate corresponding flux. Besides, MTPV strategy is implemented above critical speed. In [9,10], a different approach was presented to implement MTPF strategy above critical speed considering the stable area. Although DTC scheme is slightly dependent of motor parameters, torque ripple is significant at high speed which can cause noise [11]. This paper presents a novel scheme to achieve maximum torque in wide speed range both motoring and regenerating mode based on current angle approach.

The reminder of this paper is classified as follows: section II describes the strategy used in the proposed scheme and considered limitations for above base speed. In section III, the proposed control scheme is investigated; then, in section IV the simulation results are provided to confirm the proposed scheme and eventually the conclusions are highlighted in section V.

II. OPERATION TRAJECTORY OF IPMSM

A. Current and Voltage Limit

In the rotor (d-q) reference frame. The model of IPMSM can be expressed as:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega \lambda_q \tag{1}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega \lambda_d \tag{2}$$

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{4}$$

$$T_e = \frac{3p}{2}\left(\lambda_m i_q + \left(L_d - L_q\right) i_d i_q\right) \tag{5}$$

where

R_s	stator resistance
p	number of pole pairs
L_d,L_q	inductances of d-q axis
λ_m	flux of permanent magnet
T_e	electromagnetic torque

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The machine faces current and voltage limitations in order to operate above the base speed and these limitations must be taken into account. Equations (6) and (7) represent current and voltage limitations, respectively.

$$i_d^2 + i_q^2 \leq I_{max}^2 \quad (6)$$

$$v_d^2 + v_q^2 \leq V_{max}^2 \quad (7)$$

Equation (6) is a representative of a current limit circle (CLC) with radius of I_{max} in the id-iq plane as exhibited in Fig 1. I_{max} is the maximum current which is determined by rated current of the inverter.

Equation (7) represents the voltage limitation which constrained by voltage of DC-link.

where V_{max} can be stated as:

$$V_{max} = KV_{dc} - R_s I_m \quad (8)$$

In (8), K stands for the modulation index which is determined by table I.

Neglecting the resistance and derivative terms in (1) and (2), the voltage limit can be plotted in id-iq plane by substituting (1) and (2) into (7) to give:

$$\left(L_q i_q\right)^2 + \left(L_d i_d + \lambda_m\right)^2 \leq \frac{V_{max}^2}{\omega_e^2} \quad (9)$$

Equation (9) is a representative of voltage limit ellipse (VLE) in id-iq plane centered at $\left(-\frac{\lambda_m}{L_d}, 0\right)$ and $\frac{\lambda_m}{L_d}$ is also the current of motor characteristic. As illustrated in Fig.1, VLE will shrink with increasing speed. It is proved that the size of ellipse depends on the saliency ratio [1]. Also, operating point of machine should be located within the CLC and VLE in order to work sustainably.

B. MTPA Strategy for Below Base Speed

For below base speed, the maximum torque per ampere (MTPA) strategy is accomplished in order to achieve maximum torque under constant current constraint. As illustrated in Fig. 2, d- and q-axis current components can be expressed in terms of magnitude and angle of current:

$$i_d = |I_s| \cos\beta \quad (10)$$

$$i_q = |I_s| \sin\beta \quad (11)$$

where β is the current angle. By substituting (8) and (9) into (3) to give electromagnetic torque in terms of magnitude and angle of current:

$$T_e = \frac{3p}{2}\lambda_m |I_s| \sin\beta + \frac{3p}{4}\left(L_d - L_q\right)|I_s|^2 \sin(2\beta) \quad (12)$$

The first term of (10) is the torque which is generated by the interaction of the permanent magnet and stator current and the second term is reluctance torque which is produced because of difference between L_d and L_q. The optimal current angle β, which generates current reference, can be found by differentiating T_e/I_s with respect to β:

$$\beta_{MTPA} = \cos^{-1}\left(\frac{-\lambda_m + \sqrt{\lambda_m^2 + 8\left(L_d - L_q\right)^2 |I_s|^2}}{4\left(L_d - L_q\right)|I_s|}\right) \quad (13)$$

The condition of MTPA is independent of speed and thus, (13) is constant until machine dose not enter the FW region.

TABLE I. MODULATION INDEX

M-index	Modulation Techniques		
	Sinusoidal PWM (SPWM)	*Space-vector PWM (SVM)*	*Six-step PWM*
K	$\frac{1}{2}$	$\frac{1}{\sqrt{3}}$	$\frac{2}{\pi}$

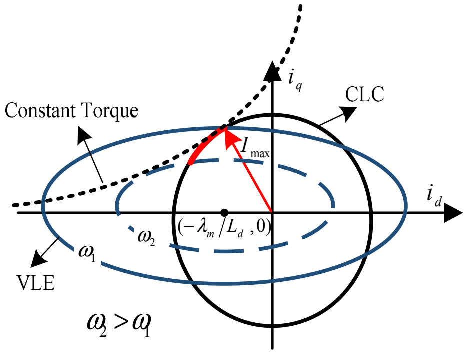

Fig. 1. Current and voltage trajectories for achieving maximum torque

It should be noted that current magnitude of (13) is its maximum in order to achieve maximum torque. Furthermore, (11) must be negative to produce maximum torque in regenerative mode. However, (10) must be negative in both motoring and regenerating mode. The reference currents are generated for below base speed. Also, according to (12), first term, which is called excitation torque, will reach its maximum when $\beta = 90$ and reluctance torque will reach its maximum as $\beta = 135$. Thereby, the answer of (13) is within $90 < \beta < 135$.

C. Field Weakening Strategy for Above base speed

As soon as motor enters into the FW region, current angle starts to vary with increasing speed. Besides, both I_s and V_s reach its maximum so that they are uncontrollable. Accordingly, the only mean of drive control is current angle or voltage angle in FW region. In order to achieve maximum torque, optimal current angle (β_{FW}) of FW can be obtained by substituting (10) and (11) into (9) as follows:

$$\left(-L_q |I_s| \sin(\beta)\right)^2 + \left(L_d |I_s| \cos(\beta) + \lambda_m\right)^2 = \frac{V_{max}^2}{\omega_e^2} \quad (14)$$

By solving (14), we have:

$$\beta_{FW} = \cos^{-1}\left(\frac{-B + \sqrt{(B)^2 - 4(A)(C)}}{2(A)}\right) \quad (15)$$

where $A = \left(L_d^2 - L_q^2\right)|I_s^2|$, $B = 2\lambda_m L_d |I_s|$, $C = L_q^2 |I_s^2| + \lambda_m^2 - \frac{V_{max}^2}{\omega_e^2}$.

Equation (15) is the function of speed which changes with speed variation. By substituting (15) into (10) and (11), the corresponding d-q currents of FW region are produced so that motor can operate above base speed.

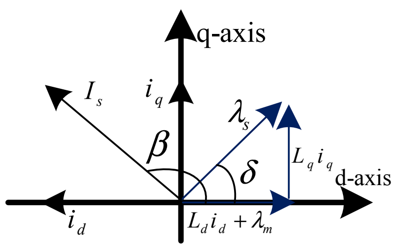

Fig. 2. Stator current and stator flux in d-q axis

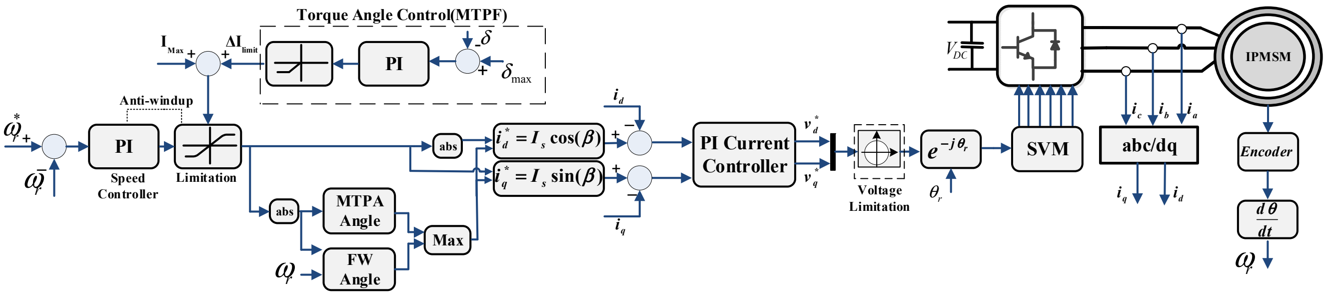

Fig. 3. Proposed Control Scheme of IPMSM Based on Current Angle Approach to operate in wide speed range

D. MTPF Strategy for Above Critical Speed

In FW region, the more the speed increases, so does the torque angle. However, there is a stability limit for torque angle which motor must not exceed. As depicted in Fig. 2, d- and q-axis stator flux components can be defined in terms of magnitude and angle of stator flux:

$$\lambda_d = |\lambda_s| \cos(\delta) \quad (16)$$

$$\lambda_q = |\lambda_s| \sin(\delta) \quad (17)$$

Therefore, the torque equation can be expressed in terms of magnitude and angle of stator flux by combining (3), (4), (16) and (17) into (5):

$$T_e = \frac{3p}{2L_dL_q} \times |\lambda_s|\big(\lambda_m L_q \sin(\delta) + 0.5(L_d - L_q)|\lambda_s| \sin(2\delta)\big) \quad (18)$$

The maximum torque angle can be computed by differentiating T_e/λ_s with respect to δ:

$$\delta_{max} = \frac{-\lambda_m L_q - \sqrt{\lambda_m^2 L_q^2 + 8(L_d - L_q)^2 |\lambda_s|^2}}{4(L_d - L_q)|\lambda_s|^2} \quad (19)$$

Above δ_{max}, motor enters into the FW region (II) and the maximum torque per flux (MTPF) should be employed to keep stability of motor. Therefore, control of torque angle leads to MTPF strategy. As torque angle reach its maximum, magnitude of current should decrease in order to track MTPF trajectory. Indeed, MTPF strategy is the approximation of maximum torque per voltage (MTPV) [12].

Hence, this paper proposes a new control scheme method to generate optimal current reference in FW region (II) based on current angle.

III. PROPOSED CONTROL SCHEME

The proposed control scheme is shown in Fig. 3. This scheme is able to work all four quadrants operation in wide speed range. Furthermore, it can also achieve maximum torque in both motoring and generating mode with auto switching structure. As seen in Fig. 3, PI speed controller has a anti-windup structure which compares speed reference to the current speed of machine and generates the command current magnitude. PI with anti-windup structure improves speed response in transient behavior and has a lower settle time in comparison to conventional PI. As far as motor operates below critical speed, the output of torque angle controller is zero and current limitation is in its maximum to produce maximum torque. As torque angle of motor reaches its maximum, current magnitude starts to decreases in order to keep torque angle in its maximum as (20):

$$|I_{limitation}| = I_{Max} + \Delta I_{limit} \quad (20)$$

As a result, motor enters into FW region (II) and current magnitude starts to decrease and therefore efficiency will improve. In this scheme, motor can also work in both region by selecting maximum current angle between FW and MTPA strategies. Selection of optimum current angle is simple because speed comparison and complex algorithm are not needed to determine the corresponding region. It should be noted that absolute of current is used to generate optimum current angle. Also, due to demagnetizing phenomena, d-axis current is lower than zero and therefore operating point is either in region 2 or 3 of d-q plane. Hence, absolute of current is also used to generate d-axis current.

IV. SIMULATION RESULTS

Table.2 shows the parameters of IPMSM which is simulated in PLECS to verify the operation of proposed scheme. MTPF strategy can be implemented in this motor, since λ_f/L_d is less than rated current of inverter. Fig.4 shows the speed response from zero to 4500 rpm under the load torque of 0.2 N.m. Also, torque characteristic is illustrated in Fig.5 to prove achieving maximum torque during acceleration in both regions. Below rated speed, MTPA strategy is followed and operating point is on the CLC because magnitude of current is its maximum. Both magnitude and angle of current are constant during this operation as shown in Figs.9,10. As motor enters into FW region, torque angle of IPMSM starts to increase as displayed in Fig.11. In this state, FW current angle is selected because it is greater than MTPA current angle. However, torque limit, flux and q-axis current decrease in FW region as shown. in Fig.5,6,7. As long as torque angle is less than maximum torque angle, motor operates in FW region (I). When torque angle reaches the maximum torque angle, the torque angle control loop is enabled so that magnitude of current starts to decrease to track MTPF trajectory as shown in Fig.9. However, magnitude of d-axis current decreases above critical speed as indicated in Fig.8. Torque-speed characteristic is also exhibited in Fig.12 and it demonstrates that there is a smooth transition among MTPA, FW and MTPF regions. It should be noted that control scheme operates automatically.

The second section of simulation confirms that proposed scheme can work in four quadrants operation. Fig.13 shows the speed response under different variation. Also, Fig.14 shows that maximum achievable torque is obtained during acceleration and deceleration under the load torque of 0.2 N.m. As depicted in Fig.13 and Fig.14, motor starts to accelerate from 0 to 1100 rpm with maximum torque below base speed. As soon as motor reaches reference speed, load torque is tracked. The second step at t=1.5, the reference speed is 2800rpm. Above rated speed, motor enters into FW region (I) so that the current angle starts to increase. Furthermore, torque characteristic will decrease with increasing speed.

TABLE II. THE PARAMETERS OF IPMSM USED IN SIMULATON

Parameter	Value, unit
Stator phase resistance (R_s)	18.6 Ω
Number of pole pairs	2
Magnet flux linkage	0.18 Wb
d-axis inductance (L_d)	238 mH
q-axis inductance (L_q)	512.8 mH
Moment of inertia	0.00117 Kg.m^2
Rated speed	1500 rpm
Rated current of inverter	1.28 A
Maximum phase voltage	178 V
Maximum torque	1.2 N.m
Switching frequency	20kHz
DC link voltage	310 V

However, maximum achievable torque is obtained during acceleration in FW region (I) as seen in Fig.14. The third step at t=3, motor accelerates to reach reference speed, which is selected 4000rpm. In this duration, motor enters into FW region (II) above critical speed. The forth step causes motor to work in second quadrants with generating negative torque to decrease speed. It is important to be noted that torque angle control loop is also activated in regenerative mode above critical speed. The next step, motor decelerates from 3500 to 2500 with maximum negative torque limit in FW region (I). And the final reference speed is selected 1200rpm to show maximum negative torque during decelerate mode below rated speed. In any mode of operation which has been discussed so far, the operating point returns to MTPA in steady-state.

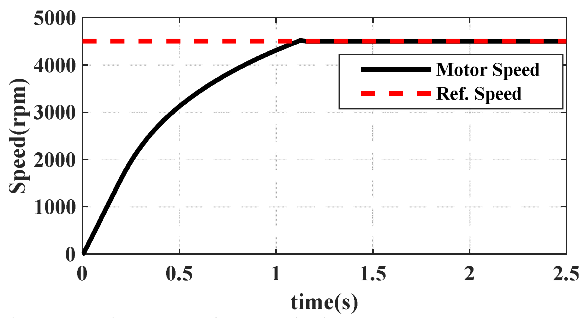

Fig. 4. Speed response of proposed scheme

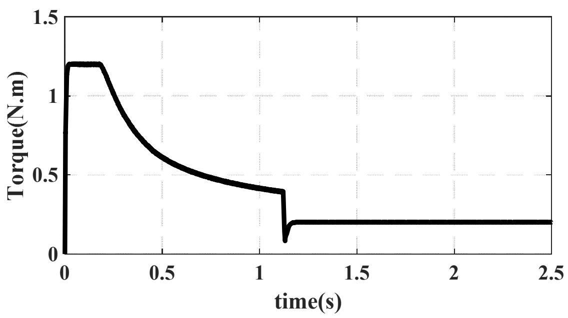

Fig. 5. Torque characteristic under the load torque of 0.2 N.m

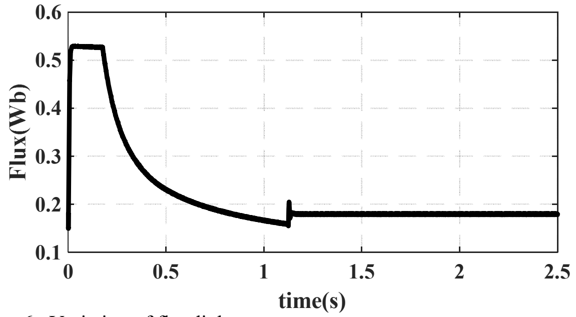

Fig. 6. Variation of flux linkage

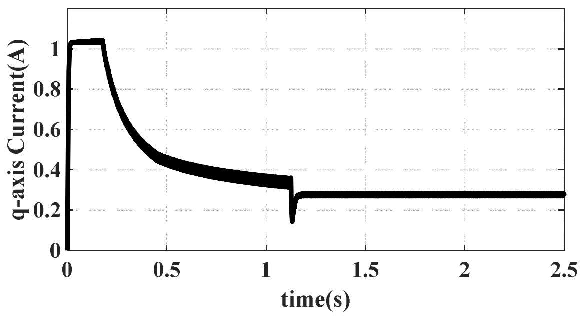

Fig. 7. The operating point of q-axis current

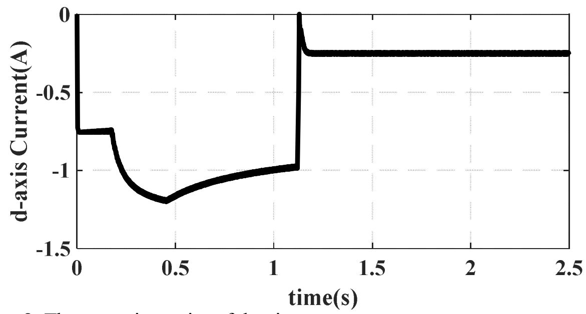

Fig. 8. The operating point of d-axis current

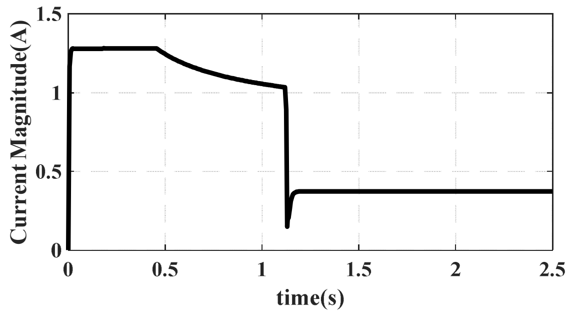

Fig. 9. Variation of current magnitude

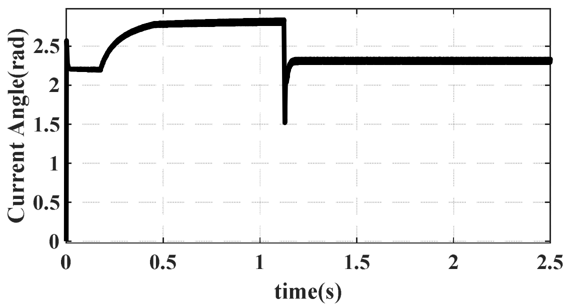

Fig. 10. Variations of current angle

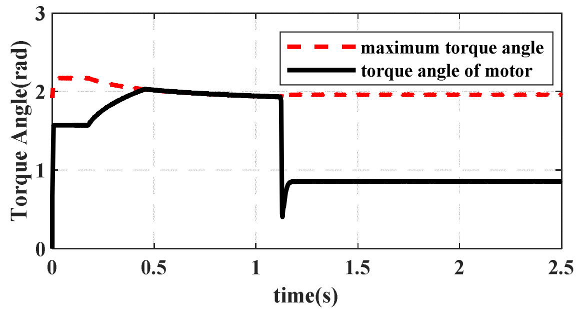

Fig. 11. Variation of torque angle

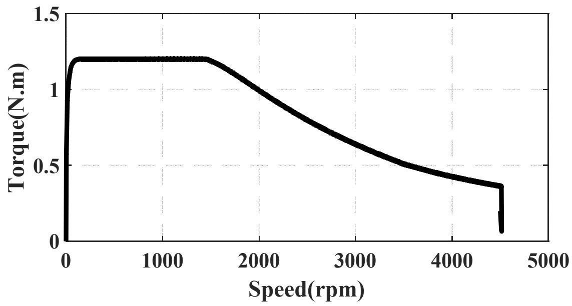

Fig. 12. Torque-speed characteristic of IPMSM under reference speed 4500rpm

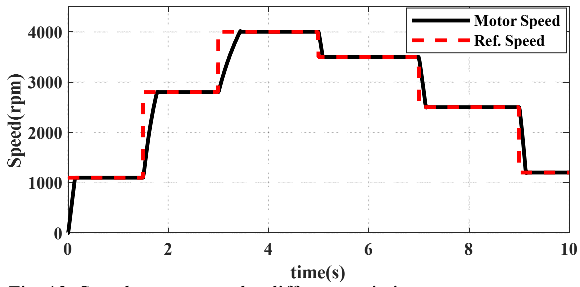

Fig. 13. Speed response under different variations

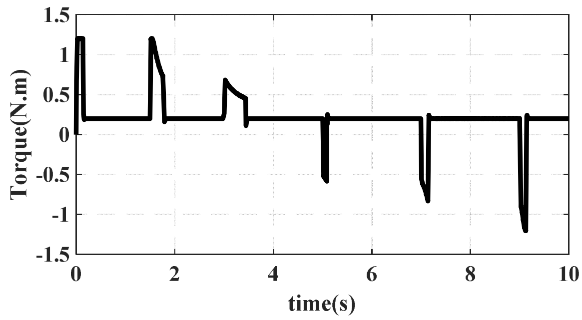

Fig. 14. Torque characteristic under different variations

V. CONCLUSION

This paper has investigated the operation of IPMSMs to achieve maximum torque in wide speed range and proposed a novel control scheme based on the current angle. This scheme could control IPMSMs above the critical speed with an auto-switching structure. Indeed, torque angle control has been used to operate the motor in FW region (II). In addition, the proposed scheme works in all four quadrants operating regions. Furthermore, there was no need to use LUTs and offline methods and it is able to work analytically. It is recommended to utilize parameter estimator in order to increase accuracy of parameter variations. The simulation results have confirmed the effectiveness of the proposed method.

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