Field-Weakening Control Strategy for an Interior Permanent Magnet Synchronous Motor Drive

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***Abstract*—In this paper a durable flux-weakening control strategy is introduced. Based on this control strategy a vector control of an interior permanent magnet synchronous motor drive is implemented. The new field-weakening control scheme is introduced based on the space-vector modulation technique, that deals with the problem of the dc-link voltage not being fully utilized. The switching of field-weakening is decided using the duty-time of the zero-voltage vector that is set as a feedback signal. A Matlab/Simulink is used to generate the new control scheme. The results show that the proposed scheme is attainable. Since the motor operates in two modes the proposed control scheme has shown a smooth transition between the constant-torque region which is below the base speed and the constant-power region that is above the base speed.**

***Keywords*—:** Maximum torque per ampere, Field-Weakening control, control system, Space-Vector modulation, Interior Permanent Magnet Synchronous Motor.

I. INTRODUCTION

It has been seen that in the past few years the permanent magnets synchronous motors are extensively used in different applications starting from the simple ones like pumps or fans to high performance drives like machine-tools servos and applications that require high level of speed regulation like hybrid electric vehicles. This is all due to the fact that this type of motors contains special characteristics like high power density, high torque to inertia ratio [1] and easiness to achieve field-oriented control compared with the induction motor [2]. It is well known that a permanent magnet synchronous can operate in two modes the constant-torque mode and the constant-power mode. When the motor operates at a speed below the base speed the constant torque mode is activated. There are basically different techniques that are employed to control the operation of the motor in this mode, $i_d = 0$ control [3], maximum torque per ampere control [4-5] or any other control strategy [6]. The main concern is that when the motor reaches the base speed the terminal voltage of the inverter reaches its limit value, this can cause the current regulators to go through saturation and the stator current will no longer be able to track the desired output value. it has been seen that the motor cannot operate at a speed higher than the base by increasing the voltage. Thus, to obtain higher acceleration, flux-weakening algorithm is required control strategy that can make the motor run at higher speeds while keeping the voltage in a perfect balance [7-8].

The main idea of the field-weakening is to reduce the d-axis flux by reducing the effect of the permanent magnet flux. And from that principle large number of scholars worked on achieving this goal and they have developed many methods. CT pan, along with many other academicians came out with a method that works based on the analysis of the mathematical model. The method proposed a mathematical relationship between the two current components and the rotor speed in which the values of the direct and quadrature current components are calculated when the motor is working in the field-weakening mode [9]. But it has been seen that this method contains some draw backs it's sensitivity to motor parameters and inability to achieve fast dynamic response made this method only reasonable in theoretical analysis. While RU Lenke along with his colleagues, introduced the look-up table method in order to carry out the field-weakening control. This control technique generates the values of the reference currents both direct and quadrature from a look-up table which coincides to the reference value of the stator flux and torque [10]. Even though this method achieves real-time performance but it's still sensitive to the changes of the motor parameters. And the precision of this algorithm depends on large experiment data. The Gradient descent method that is presented by YD Yoon, generates field-weakening making adjustments to the current reference value. The region of the field-weakening is assigned by finding the angle between the voltage decreasing direction and constant-torque direction. By comparing this method with the look-up table method, it can be seen that the Gradient descent method is more suitable but the main drawback is that its calculation is too complex [11-13]. ZB Zeng introduced the outer loop voltage control method, in this method the field-weakening can be switched automatically by using the differentials between the threshold value and the given voltage value [14-16]. The algorithm is quite simple and reliable but it suffers from a drawback that the dc bus voltage is not fully utilized.

In this paper a new field-weakening control technique is introduced this technique works based on space vector modulation technology and it is employed to find the switching of the field-weakening controller. During the field-weakening operation a lag might occur caused by the quadrature axis current regulation and for that reason a lead-angle technique is introduced to avoid this problem. The simulation results show how this technique is efficient as it assures a smooth transition between the constant torque region and the constant power region not to mention the efficiency of the inverter.

II. MATHEMATICAL MODEL OF IPMSM

For an IPMSM the direct and quadrature axis inductances are not equal and the voltage equations are given as the following:

$$V_{sd} = R_s . i_{sd} + \frac{d\psi_d}{dt} - \omega_e . \psi_q . \quad (1)$$

$$V_{sq} = R_s . i_{sq} + \frac{d\psi_q}{dt} + \omega_e . \psi_d . \quad (2)$$

To which: $\psi_d = L_d . i_{sd} + \psi_m$ (3)

$\psi_q = L_q . i_{sq}$ (4)

And The motor torque is calculated using the following equation [17]:

$$T_e = \frac{3}{2} P_b (\psi_d . i_{sq} - \psi_q i_{sd}) \quad (5)$$

Substituting equation (3) and (4) the electromagnetic torque equation becomes as the following:

$$T_e = \frac{3}{2} . P_b .(\psi_m . i_{sq}) + \frac{3}{2} . P_b .(L_d - L_q) . i_{sd} \, i_{sq} . \quad (6)$$

Where i_{sd} , i_{sq} d-and q-axis currents V_{sd}, V_{sq} d-and q-axis voltages R_s stator resistance ω_e synchronous electrical speed ψ_q, ψ_d d-and q-axis flux linkages ψ_m flux linkage of the permanent magnet, P_b pole pair . The electromagnetic torque has two terms, the first term Is called the torque produced by the intersection between the stator current and the permanent magnet flux linkage this term is called the reluctance torque. The second term is caused by the saliency of the motor. in this paper the effect of the magnetic saturation is not considered and hence both (L_d) and (L_q) are both considered to be constant.

III. SPACE VECTOR PULSE WIDTH MODULATION

Space vector modulation is a technique used to provide pulses to the inverter that is connected to the permanent magnet motor. This technique is used extensively for its low switching loss, high flexibility and low computational complexity [18]. PWM technique finds the average variation of voltage space vector.

Eight switching states where there are six active states and two zero states, and they can be represented as a hexagonal shape in a two dimensional plane. the hexagon is divided into six sectors the radius is equal to the voltage space vector of the three phase inverter as shown in Fig (1).

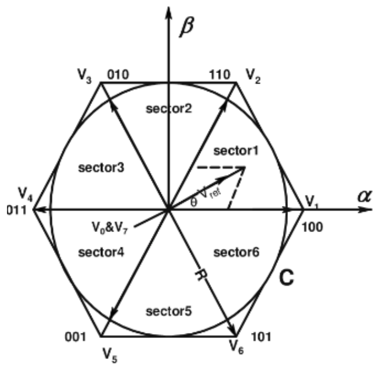


Fig. 1. Eight switching states of the inverter

The main objective of the space vector modulation is to approximate the reference vector. And this can be done using the switching combination, the approximation is done by switching between any two adjacent active vectors and the zero or null vector. Based on that the following equations are represented:

$$T_1 V_1 + T_2 V_2 + T_0 V_{0,7} = T_S \, V_{ref} \quad (7)$$

$$T_1 + T_2 + T_0 = T_s \quad (8)$$

In which T_1, T_2 and T_0 are the duty-times for the active voltage vector V_1, V_2 and the zero-voltage vector $V_{0,7}$ in the one PWM period. And T_s is the switching time. In the space vector PWM a rotating voltage vector is used as a reference and this vector is sampled once in every sub cycle T_s. Based on the equations above there are two operating conditions for the inverter that is if $T_1 + T_2 < T_s, T_0 > 0$ then the inverter is said to be in the linear modulation mode and this mode contains sufficient modulation margin to pursue the reference vector. When $T_1 + T_2 > T_s, T_0 < 0$ this is known as the over modulation mode that is when the user tries to get output voltage with magnitude more than of that allocated inside the cotangent circle of hexagon as shown in Fig.2 [19].

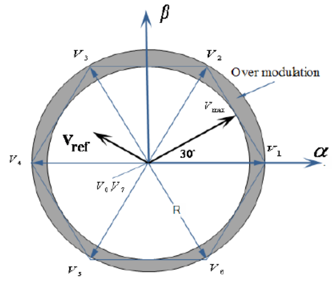


Fig.2 Overmodulation region

IV. FIELD-WEAKENING PRINCIPLE

In a permanent magnet synchronous motor, a constant torque can be delivered as long as the inverter voltage value does not reach its limit, and the motor is said to be operating at a speed below the base. Once the motor reaches the base speed the induced back-EMF reaches the maximum available voltage and it can be seen that the torque will drop rapidly when the speed increases. In order to increase the operating range of the motor that is to make it operate at speeds beyond the base a field-weakening algorithm is introduced. The inverter provides two constraints, the maximum available voltage and the maximum available current and these are given by the following equations [20]:

$$i_{sd}^2 + i_{sq}^2 \leq I_{max}^2 \quad (9)$$

$$V_{sd}^2 + V_{sq}^2 \leq V_{max}^2 \quad (10)$$

In which: I_{max}^2 is the maximum current provided by the inverter. V_{max}^2 is the maximum voltage provided by the inverter. Using the voltage equations and flux equations given in section two of this paper the dq voltage equations are written as the following:

$$V_{sd} = R_s . i_{sd} - \omega_e L_q i_{sq} . \quad (11)$$

$$V_{sq} = R_s . i_{sq} + \omega_e (L_d . i_{sd} + \psi_m) \quad (12)$$

By substituting Eq. (11) and Eq. (12) into Eq. (10) the following equation is formulated:

$$\left(\frac{V_{max}}{\omega_e}\right)^2 \geq L_d^2\left(\frac{\psi_m}{L_d}+i_{sd}\right)^2+\left(L_q.i_{sq}\right)^2 \qquad (13)$$

Eq. (13) can be represented in the dq plane as an ellipse as shown in Fig. 3.

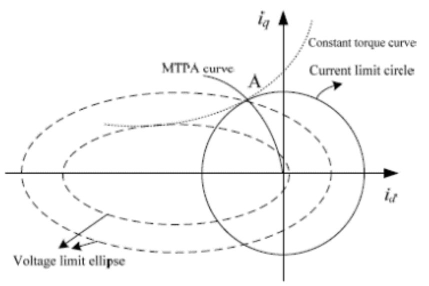


Fig. 3. inverter voltage and current limitation

As seen in Fig. 3, the voltage ellipse shrinks as the motor speed increases. Starting from zero over the MTPA curve the motor is working at a speed below the base. When the motor reaches the rated speed given by point (A) in the graph the maximum values of voltage and current are reached and current regulators get saturated for that the motor cannot increase its speed any way further because the motor will be out of control. In order to make the motor operate at a wide ranges of speed the field-weakening technique should get in the service. The main idea of the field-weakening is that the current should move from point A and move along the circumference of the circle in a direction where i_{sd} increases more into the negative side and i_{sq} decreases, and this will reduce the value of the stator voltage below the max value and the current regulators shall breakaway from saturation which will allow the motor to operate at higher speeds. The following equation is used to give a clear understanding to the idea:

$$\psi_d = L_d.i_{sd} + \psi_m \qquad (14)$$

By making the direct axis current component goes more into the negative the resulting flux ψ_d is lowered and by lowering the resultant flux the motor shall operate at speeds above the base speed and hence increasing its speed range.

When going into the field-weakening mode there is a risk of saturation of the (PI) current regulators. Using the new proposed method, the saturation of the current regulators can be overcomed, also this method provides a better utilization of the dc bus voltage. The new proposed field-weakening algorithm uses the switching time of the zero voltage vector as a feedback in order to switch to the field-weakening controller. As it has been seen that the duty-time of the zero voltage vector gives a status about the output of the inverter. When $T_0 < 0$ the value of the reference voltage V_{ref} has gone beyond the inverter's capability and that means the system need to go into the field-weakening mode. This method also focuses on preventing the current from exceeding the limit during this mode of operation that's why a lead-angle control is introduced. This method works on separating the magnitude of the stator current from its angle and keeps the magnitude of the current within the required limits using the limiter. The construction of the field-weakening block [21] is shown in Figure 6.

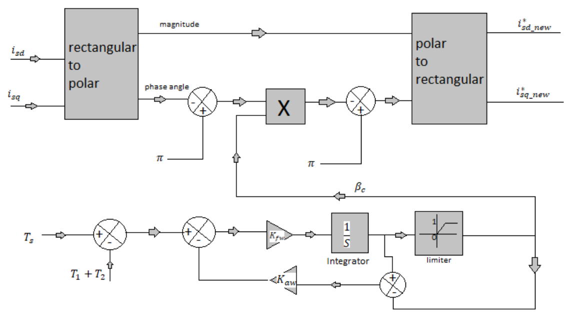


Fig. 4 Block diagram of flux weakening

In which: β_c Field-weakening coefficient (0….1) k_{aw} Gain of the field-weakening integrator, k_{fw} Anti-windup gain , The field-weakening coefficient is given by the following equation:

$$\beta_c = k \int T_0 \, dt \qquad (15)$$

In the above equation k, a positive constant and it represents the rate of change of the field-weakening coefficient. β_c makes modifications on the lead-angle of the stator current, new values of the stator currents will be generated based on the modified angle. When the motor is operating at a speed below the base T_0 is greater than 0 and the field-weakening coefficient β_c is equal to 1. But when the motor reaches the base speed T_0 go to zero. The angle gets modified and the new stator currents will be given by the following equations:

$$i^*_{sd\ new} = i_s \cos\left[\pi - \beta_c(\pi - \emptyset_i)\right] \qquad (16)$$

$$i^*_{sq\ new} = i_s \sin\left[\pi - \beta_c(\pi - \emptyset_i)\right] \qquad (17)$$

And through that process the d-axis current is increasing towards the negative and the q-axis current is decreasing as shown in Fig. 5.

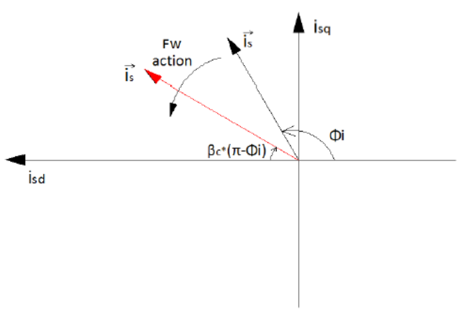


Fig. 5 Field weakening action

V. Simulation Results

For a clear understanding the field-weakening has been represented in Matlab/Simulink and the simulation model is shown in the Fig. 6. The motor parameters are given as the following: $R_s = 9.62m\Omega$, direct axis inductance $L_d = 28.7\mu H$, quadrature axis inductance

$L_q = 47.2\mu H$, number of pole pair $P_b = 6$, moment of inertia J=20.17 kg. m^2 , permanent magnet flux-linkage $\psi_m = 9.71mwb$ and viscous friction coefficient B=0 N.m.s . the drive system uses a space vector PWM inverter with a switching frequency of 5KHZ and dc-bus voltage of 24V.

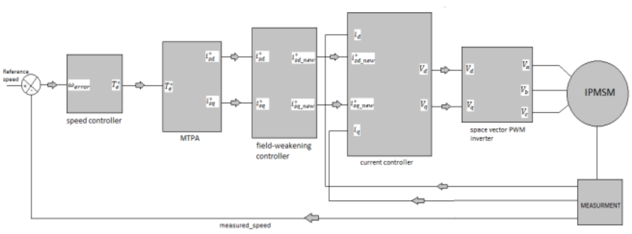


Fig. 6 Simulation model of MTPA for IPMSM drive

It can be observed from Fig. 7 that the speed response of the IPMSM motor when the reference speed is 2500 r/min when including the field weakening control. In Fig. 8, the direct and quadrature current response. Fig. 9 a and b showed the torque response without and with the field weakening respectively.

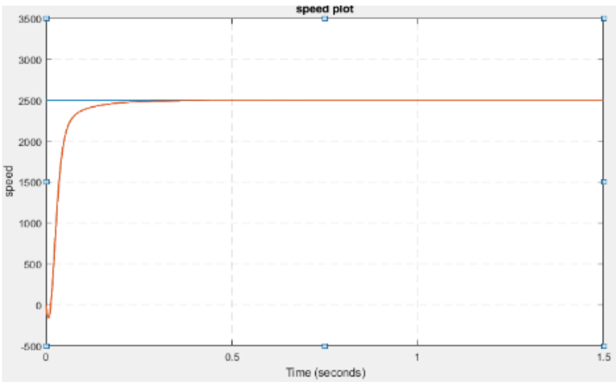


Fig. 7 Speed response

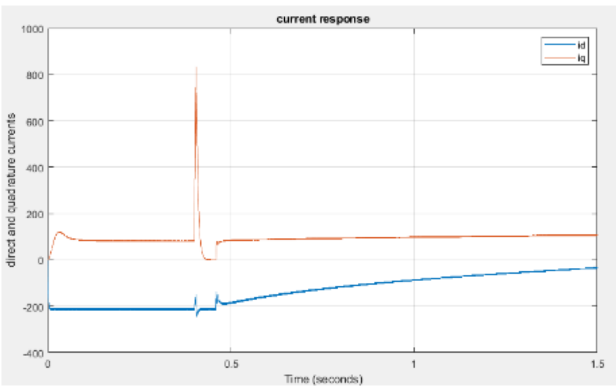
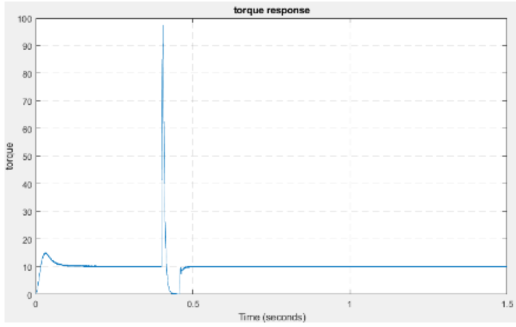
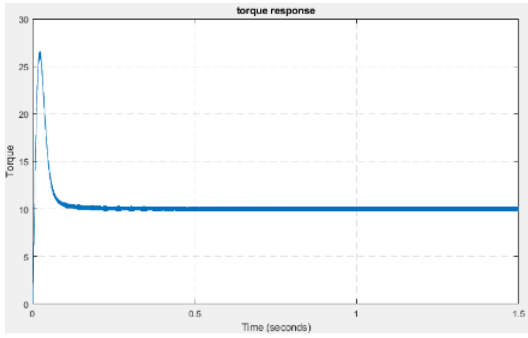


Fig. 8 d and q current components



a



b

Fig. 9 Torque response

It can be illustrated from Fig. 9 that the ripple in the dynamic torque is reduced when including the effect of the flux weakening.

VI. CONCLUSION

The main goal of the field-weakening is to expand the operating range of an IPMSM in order to increase the number of applications that this motor can contribute in. A field-weakening control technique along with the space vector PWM is represented. A Matlab/Simulink was carried out and it shows how the field-weakening is carried out. It has been seen that the drive system can go into the field-weakening with a good torque dynamic. This method is also capable of preventing the current saturation in the PI controllers by using the lead-angle control method. The results have shown an improved utilization of the dc-bus voltage and for different values of speeds, still the overshoot is a bit high in all the plots but it can be fixed but the system has proven its effectiveness and it can be used in different applications such as electric vehicles.

REFERENCES

[1] S. Morimoto, Y. Takeda, “Expansion of Operating Limits for Permanent Magnet Motor by Current Vector Control Considering Inverter Capacity”, IEEE Transactions on Industry Applications, Vol.26, No.5, Sept/Oct1990.

[2] Yuan Zhang, Longya Xu, Gu ven M.K, Song Chi, Illindala M, "Experimental verification of deep field weakening operation of a 50-kW IPM machine by using single current regulator", IEEE Trans. Industry Applications, vol. 47, no. 1, pp. 128-133, 2011.

[3] Tingting Liu, Yu Tan, Gang Wu, Shumao Wang, "Simulation of PMSM vector control system based on matlab/simulik", In Proceedings of ICMTMA on Measuring Technology and Mechatronics Automation, IEEE, pp. 343-346, 2009.

[4] T.M.Jahns G.B.Kliman, “Interior Permanent-Magnet Synchronous Motors for Adjustable-Speed Drives” , EE Transactions On Industry Applications, Vol. IA-22, No.4, Jul/Aug 1986.

[5] P.D.Chandana Perera, “Sensorless Control of Permanent-Magnet Synchronous Motor Drives”, IET Aalborg University, Ph.D. Thesis, Dec. 2002.

[6] Zhihong Wu, Gensheng Li, Yuan Zhu, "Efficient Optimization Control of Permanent Magnet Synchronous Motor Using Artificial Neural Network", AISS: Advances in Information Sciences and Service Sciences, Vol. 3, No. 7, pp. 260-267, 2011.

[7] Gaolin Li, Derong Luo, Sheng Ye, Rongyao Li, "Flux-weakening control of permanent magnet synchronous motor used in electric Vehicles", Power Electronics, vol. 44, no. 6, pp. 88-89, 2010.

[8] J.Ottosson, M.Alakula, “Compact Field Weakening Controller Implementation” ,SPEEDAM 2006 International Symposium on Power Electronics, Electrica Drives,Automation and Motion.

[9] Ching-Tsai Pan, Sue Shinn-Ming, "A linear maximum torque per ampere control for IPMSM drives over full-speed range", IEEE Transactions on Energy Conversion, vol. 20, no. 2, pp. 359-366, 2005.

[10] Lenke R.U., De Doncker, R.W., Mu-Shin Kwak, Tae-Suk Kwon, Seung-Ki Sul, "Field weakening control of interior permanent magnet machine using improved current interpolation technique", In Proceedings of the 37th IEEE Power Electronics Specialists Conference, IEEE, pp. 1-5, 2005.

[11] Qiang Ding, "Study of the flux weakening control strategy for PMSM vector control system",Central South University, China, 2010.

[12] Young-Doo Yoon, Seung-Ki Sul, "New flux weakening control for surface mounted permanent magnet synchronous machine using gradient descent method", In Proceedings of the 7th International Conference on Power Electronics, pp. 1208-1212, 2007.

[13] Kai Sun, Qi-fang Shu, "Field weakening operation control strategies of interior permanent magnet synchronous motor for electric vehicles", In Proceedings of the 30th Chinese Control Conference, pp. 3640-3643, 2011.

[14] N Bianchi, S Bolognani, M. Zigliotto, "High-performance PM synchronous motor drive for an electrical scooter", IEEE Trans. on industry applications, vol. 37, no. 5, pp. 1348-1355, 2001.

[15] Zhaohui Tang, Qiang Ding, Shouyi Yu, Weihua Gui, Yonggang Li, "Research of flux weakening strategy of interior permanent magnet synchronous motor", Electric machines and Control, vol. 14, no. 5, pp. 68-72, 2010.

[16] Derong Luo, Zhibo Zeng, Shoudao Huang, Ziqiang Chen, Jianye Li, "A leading angle field weakening control method for permanent magnet synchronous motor on electric vehicles", Journal of Hunan University (Natural Sciences), vol. 38, no. 3, pp. 40-44, 2011.

[17] I.Boldea, S.A.Nasar “Electric Drives”, CRC Press 1999.

[18] Sayali S. Raut, A. S. Sindekar, “Modelling and Simulation of FOC based Permanent Magnet Synchronous Motor Drive using SVPWM Technique” , IOSR Journal of Electrical and Electronics Engineering, vol. 14, no. 2, PP. 58-63, 2019.

[19] M. Kubeitari, A. Alhusayn, M. Alnahar, “Space Vector PWM Simulation for Three Phase DC/AC Inverter”, International Journal of Electrical and Computer Engineering, Vol.6, No.12, 2012.

[20] B-H Bae, S-K Sul, “New Field Weakening Technique for High Saliency Interior Permanent Magnet Motor”, Industry Applications Conference, Oct.2003.

[21] J.Wai, T.M.Jahns, “ A New Control Technique for Achieving Wide Constant Power Speed Operation with an Interior PM Alternator Machine”, IEEE, 2001.