A Review of Flux-weakening Control in Permanent Magnet Synchronous Machines

Dongyun Lu[1], *Student Member, IEEE* and Narayan C. Kar[2], *Senior Member, IEEE*
Department of Electrical & Computer Engineering
University of Windsor, Windsor, ON, N9B 3P4 Canada
[1]lu1y@uwindsor.ca; [2]nkar@uwindsor.ca

***Abstract*—Permanent magnet synchronous machines (PMSMs) are the most popular motors being used as traction motors in the electric drive-train due to their high torque-per-ampere characteristics and potential for wide flux-weakening operation to extend the constant power range. This paper classifies and overviews the state-of-the-art flux-weakening control strategies for PMSMs. The advantages and disadvantages of each approach are discussed. The benefits of this research work are to lay down a foundation for future improvements, and help researchers choose the appropriate flux-weakening control algorithm for traction application.**

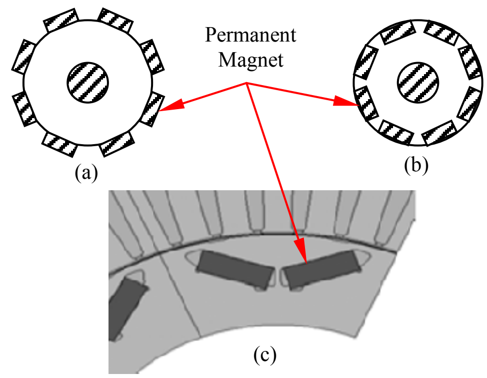

Fig. 1. Permanent magnet synchronous machines. (a) Surface-mounted. (b) Inset. (c) Interior [2].

I. Introduction

With an increasing consumer expectation for improved electric vehicle (EV) performance, auto manufacturers are recognizing that the design of next generation electric propulsion systems will heavily rely on the development of high performance motor drives specific to electric vehicle application. Due to the use of high-energy permanent magnets as the field excitation mechanism, permanent magnet synchronous motor (PMSM) drives can be potentially designed with high power density, high speed, and high operation efficiency, which make them the primary choice of leading automakers such as Nissan.

PMSMs are classified according to the position and shape of the permanent magnets in the rotors. Three common groups are known as: surface, inset, and interior or buried PMSM as shown in Fig. 1. The surface-mounted and inset rotor PMSMs are often collectively called the surface-mounted PMSMs where the permanent magnets are exposed to the air gap [1]. The interior PMSM (IPMSM) has its magnets buried inside the rotor with a higher capability for flux-weakening due to the fact that the *q*-axis inductance can be much higher than the *d*-axis inductance.

One of the primary limiting features of PMSM drives is the limited excitation control. The internal EMF of the motor rises in proportion to the motor speed. Such behavior is desirable in the so-called constant torque range, since it is consistent with the constant volts-per-hertz control, which is normally used during this mode of operation. However, when the speed continues to rise, the voltage limit of the associated frequency converter is reached. The motor is then said to enter the flux-weakening operation. The internal voltage must now be adjusted to be compatible with the applied converter voltage which increases as speed increases. As a result, the motor power factor becomes leading and the current to be commutated by the inverter continues to increase as speed increases. However, the voltage is limited by the rating of the converter and the current is also limited by the rating of the machine. To achieve an extended constant power range for traction application, to eliminate the use of multiple gear ratios, and to reduce the power inverter volt-ampere rating, flux-weakening operation is one of the most applicable solutions.

There are primarily two approaches for implementing flux-weakening of PMSMs. One method is to improve the magnetic design of the motor, while the other is to use sophisticated electronic control techniques. The machine designers are able to improve the flux-weakening capability by changing the motor structures or excitation method like in [3]-[8]. [3] used annular iron mounted on the surface of the magnets and eight flux barriers to alter the path of flux to reduce the flux from the PM linked by the armature winding. A hybrid excitation was applied in [8] to combine the permanent magnet excitation with wound field excitation to improve the flux-weakening capability of the machines. While the flux-weakening capability of an IPM motor drive depends on the machine design, the proper control strategy is needed to obtain the maximum output torque given the inverter rating [9]. The electronic control approach is generally based on the control of the stator current components: *d*- and *q*-axis currents, to counter the fixed-amplitude magnetic air-gap flux generated by the rotor magnets which performs a role similar to the field weakening in a separately excited dc motor.

This paper classifies and overviews the main proposed electronic control approaches to apply flux-weakening operation on the PMSMs. The advantages and disadvantages of each method are explained. So far, based on the method to acquire the demagnetization current, the control algorithms dealing with the problem have been divided into four categories: feed-back,

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

feed-forward, hybrid and non-linear control theory based flux-weakening technologies. In section II, some basics of flux-weakening techniques will be discussed. Four different classes of control strategies such as feed-back, feed-forward, hybrid and non-linear control theory based approaches will be discussed in section III.

II. Basics for Flux-weakening Operation

A. PMSM Model

The following mathematical model of PMSMs and all variables are in normalized units and established in the *d-q* rotor reference frame. The stator voltage equations in the rotor reference frame are given as follows:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega L_q \\ \omega L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix} \tag{1}$$

where,

v_d and v_q : normalized *d*- and *q*-axis terminal voltages
i_d and i_q : normalized *d*- and *q*-axis armature currents
R_s : normalized stator resistance
L_d and L_q : normalized *d*- and *q*-axis stator inductances
ω : electrical angular velocity in per-unit
λ : permanent magnet flux linkage
p : derivative operator

For motor drives, the maximum current and voltage must be limited within the system limits. Considering both motor and inverter ratings, they can be expressed as follows:

$$\left(i_d^2 + i_q^2\right) \le I_{\max}^2 \tag{2}$$

$$\left(v_d^2 + v_q^2\right) \le V_{\max}^2 \tag{3}$$

where $I_{\max}$ and $V_{\max}$ are the normalized maximum current of PMSM and maximum DC-link voltage, respectively. The voltage and current limits affect the maximum-speed-with-rated-torque capability and the maximum torque-producing capability of the motor drive system, respectively. For the application like electric vehicle drive-train, it is desirable for the motor drive to possess a wide constant-power operating region by means of flux weakening.

B. Flux-weakening Operation

Based on equations (1) to (3), the steady-state voltage constraints can be rewritten as follows:

$$\left[\left(\frac{R_s i_q}{\omega} + L_d i_d + \lambda\right)^2 + \left(\frac{R_s i_d}{\omega} - L_q i_q\right)^2\right] \le \frac{V_{\max}^2}{\omega^2}. \tag{4}$$

The electromagnetic torque T_e can be noted as follows:

$$T_e = \frac{3}{2}\frac{P}{2} i_q \left[K + \left(L_d - L_q\right) i_d\right] \tag{5}$$

where P is the number of poles and K is the flux linkage constant. The rotor speed of the motor can be expressed as:

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - T_l - B\omega) \tag{6}$$

where T_l is the external load torque and B is the viscous frictional coefficient of the motor and load.

Equation (4) shows that the voltage limit constraint defines

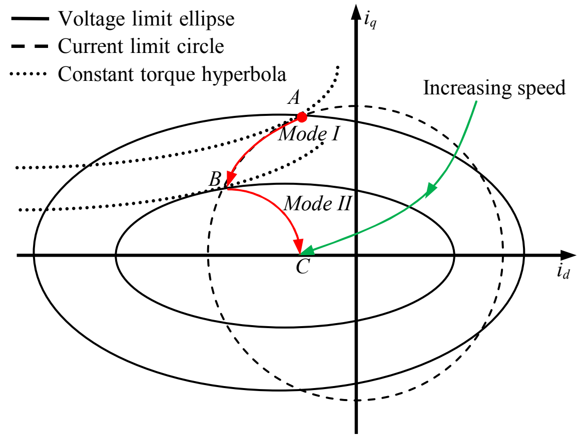

Fig. 2 Diagram showing the maximum torque flux-weakening trajectory.

an ellipse, whose size is inversely proportional to speed. The centre of the ellipse is termed as the infinite-speed operating point where the operating point must converge towards at high speed. A given operating point will not exceed the voltage or current limit constraints if it lies within the intersection of the voltage limit ellipse and the current limit circle, or inside the current limit circle and the voltage limit ellipse.

However, to achieve maximum torque in the flux-weakened region, the machine must be operated in both voltage and current limited modes simultaneously [10], which can be determined by using the circle diagram [10]–[13] as shown in Fig. 2. Based on the operation condition, the two flux-weakening operating modes can be divided into:

Mode I: Current and voltage limited region. As the speed goes up or the DC-link voltage drops, the voltage ellipse shrinks, and the motor drive is running in current and voltage limited region, where the drive is operated with rated current and rated terminal voltage along line AB, i.e. at the intersection of the voltage and current-limit curves.

Mode II: Voltage limited region. As the speed increases further, the drive operates to give maximum torque with limited voltage along line BC, i.e. from the point where the torque hyperbolas are tangent to the voltage limit ellipse to the center of the ellipse.

For the flux-weakening control, the motor is excited within the current and voltage limits. To obtain the excitation currents, various control algorithms have been investigated.

III. Controls Based Flux-weakening

PMSMs can operate in a wide constant power operating region for traction application by means of flux-weakening [14], and both *d*- and *q*-axis armature currents have to be varied according to the speed and torque requirements. Based on the ways to acquire the *d*- and *q*-axis armature currents, the flux-weakening control methods can be classified into four categories: feed-forward, feed-back, hybrid technique and non-linear control theory based strategy.

A. Feed-forward Technique

Feed-forward solutions presented in [15]—[22] employ analytically or experimentally evaluated control characteristics, which are computed to exploit the maximum motor performance in the assumed feeding voltage and current limits. The q-axis current command is determined from the torque command or the d-axis current, while the demagnetizing d-axis current is obtained from flux-weakening characteristics as a function of the operating speed.

In [15], a feed-forward flux-weakening control algorithm is proposed as shown in Fig. 3. For the flux-weakening operation, the V_{max} and I_{max} are considered to be constant which can be obtained from the inverter operation. When neglecting the resistance voltage drop, the motor d-axis stator current request at rotor speed ω can be derived as:

$$i_d{}^* = \frac{-2L_d + \sqrt{4L_d^2 - 4\left(L_d^2 - L_q^2\right)\left(1 + L_q^2 I_{\max}^2 - \frac{V_{\max}^2}{\omega^2}\right)}}{2\left(L_d^2 - L_q^2\right)} \qquad (7)$$

$$i_q = \sqrt{I_{\max}^2 - i_d^{*\,2}}\,. \qquad (8)$$

The maximum torque T_{ef} can be calculated by using (5), which is then compared with the torque command T_{ec} generated from speed error in the drive system. The final torque request T_e^* used to calculate the q-axis current is then determined by the following logic to enable maximum torque production per unit current:

$$T_{ec} \rangle T_{ef}\text{, then } T_e^* = T_{ef}$$

$$T_{ec} \langle T_{ef}\text{, then } T_e^* = T_{ec}\,.$$

Then the q-axis current is adjusted by using:

$$i_q^* = \frac{T_e^*}{1 + \left(L_d - L_q\right) i_d^*}\,. \qquad (9)$$

Feed-forward methods generally have good stability and transient responses, but they are strongly dependent on the motor parameters and the accuracy of the motor model. Parameter variation of the machine associated with either temperature, changing of the material characteristics with the time, and saturation effects will affect the performance of the controller, or even deteriorate the controller response.

B. Feed-back Technique

In feed-back approaches [23]—[31], on the other hand, the motor voltage and/or speed are measured and the demagnetizing current (d-axis component of the current) is adjusted in order to track the voltage limit at increasing speed. The demagnetizing current vector can be adjusted by tracking the voltage error [28] or the speed error [29].

To achieve minimum copper-loss operation, [29] proposed a voltage constraint tracking based flux weakening control method to adjust the demagnetization current based on the location of the voltage vector. As shown in Fig. 4, by using the output u^* from the speed controller as the initial value for the q-axis current, if the required voltage vector is not reaching the maximum DC-link voltage, the d-axis current can be

$$i_d^*(t) = i_d^*(t0) + \int_{t0}^{t} K_a \left|\omega^* - \omega\right| dt \qquad (10)$$

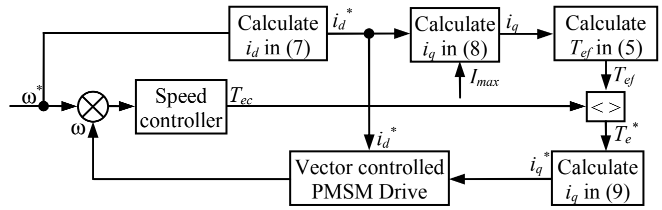

Fig. 3. Block diagram of feed-forward technique.

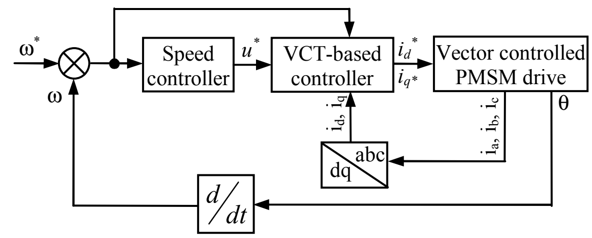

Fig. 4. Block diagram of one feed-back control technique.

Or else it could be

$$i_d^*(t) = i_d^*(t0) - \int_{t0}^{t} K_b \left|\omega^* - \omega\right| dt \qquad (11)$$

where K_a and K_b are positive integration constants.

If the $i_d^*(t)$ is within the current limit, then

$$i_q^*(t) = sign(u^*) \times \sqrt{I_{\max}^2 - i_d^*(t)} \qquad (12)$$

where u^* is the output of the PI speed controller.

The aforementioned methods are robust to the variation of the motor parameters, resulting in no steady-state error. And since these methods utilize the DC-link voltage more efficiently, the motor drive using these methods usually has higher power efficiency than the conventional anti-windup or flux-weakening control methods under the same voltage and current limitation. However, the transient performance of closed-loop voltage controllers is usually not good enough and the gain setup of the regulators is difficult, owing to the operation in the proximity of the voltage saturation region [8].

C. Hybrid Technique

Hybrid techniques [32]-[37] have also been proposed in an attempt to utilize the advantages of both the feed-back and feed-forward solutions. The pre-computed d-axis current command for maximum torque per ampere (MTPA) is adjusted by the optimization objectives, while the q-axis current command is determined from the torque command and d-axis current feed-back. The other way is that the feed-forward current references determined from MTPA are modified through the feedback flux obtained from the output of the integrator in the current controller.

The flowchart of Fig. 5 illustrates the online optimal flux-weakening control principle of PM Brushless AC drives stated in [32]. When the motor speed changed significantly, to improve the dynamic response, the feed-forward control method has been used. The control algorithm adjusts the stator d- and q-axis currents based on the optimal current profiles for maximum power operation. When the motor returns to steady-state operation, the previous d- and q-axis currents are used as initial values, while the DC-link current, q-axis current error and the motor speed are used as optimization objectives to optimize the flux-weakening control online. When the q-axis current error is less than the appropriate value, or there is an increase in the motor speed, or the DC-link current is increased, the tuning of Δi_d will ensure the achievement of maximum inherent power capability and hence improvement of the motor efficiency, and the tuning of Δi_d will continue at the same direction. Otherwise, the polarity of Δi_d has to be changed.

In the hybrid technique proposed in [36] as shown in Fig. 6, to obtain quasi-six-step operation, the feed-forward path consists of 1-D look-up table to generate the base flux $|\lambda|_{\mathrm{BASE}}$ of the constant torque region for the MTPA operation with the commanded torque T_e^*. When the motor is running in the flux-weakening region, the IPMSM can be operated by decreasing the flux from the $|\lambda|_{\mathrm{BASE}}$ at a quantity of $\Delta\lambda$ which is determined by the feed-back path.

The feed-back loop is used to obtain $\Delta\lambda$ based on the difference between the reference voltage updated by current regulator and the output voltage limited by the overmodulation. There are two low-pass filters (LPFs) in this path to smooth out the ripples of the voltage difference, one is used for d-axis voltage and the other one is for q-axis voltage. The filtered voltage differences e_d and e_q are used to calculate the feed-back $\Delta\lambda$ by

$$\Delta\lambda = \frac{\sqrt{e_d^2 + e_q^2}}{K_\omega} \tag{13}$$

where K_ω is a gain which can be designed as

$$\omega_{BASE} \le K_\omega \le \omega_{MAX}$$

where ω_{BASE} is the base electrical angular speed of the IPMSM, and the ω_{MAX} is the maximum speed of the machine. The higher K_ω would result in more torque for a poorer transient response, which should be carefully chosen according to the request from different applications.

The demanded flux $|\lambda|^*$ to excite the motor in flux-weakening region is then adjusted by

$$|\lambda|^* = |\lambda|_{BASE} - \Delta\lambda. \tag{14}$$

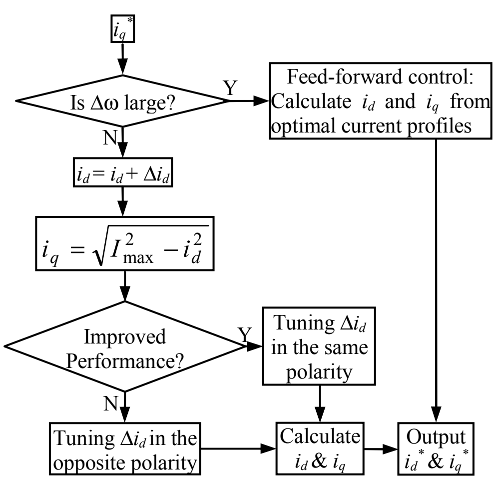

Fig. 5. Flowchart of online optimal control strategy.

To take the magnetic saturation and the parameter uncertainties into consideration, the 2-D look-up tables are then used to generate the current references i_d^{r*} and i_q^{r*} by taking the torque reference and the demanded flux $|\lambda|^*$ as two input data.

When the motor is working in the flux-weakening region, the necessary voltage to excite the motor due to the high back-EMF forces the inverter to go into overmodulation, and the current regulator has to work in saturation, overmodulation module has to be used to ensure the inverter working under voltage limitation.

The hybrid control techniques usually use look-up tables to obtain the excitation current commands for MTPA, and then use feed-back technique to adjust the current commands for flux-weakening operation, which is very robust to the variation of the motor parameter and model uncertainty. However, in order to acquire the look-up tables, extensive experiments have to be conducted. Due to the step-by-step tuning of the excitation currents, sometimes, the transient response can be slow.

D. Non-linear Control Theory Based Technique

[38]-[41] applied non-linear control theory to the flux-weakening control of the IPMSM which is different from the previously discussed method. By using the control theory, speed and current controllers are combined together instead of keeping the conventional cascade structure, and the system parameters and controller parameters are tuned on-line.

Based on the motor model including the various machine parameters, an adaptive back-stepping speed controller is proposed in [38]. To achieve the speed control tracking, the d- and q-axis currents can be calculated as [42],

$$i_d^* = \alpha\left|J\frac{d}{dt}\omega^* + B\omega + T_l + K_s e\right| \tag{15}$$

$$i_q^* = \frac{J\frac{d}{dt}\omega^* + B\omega + T_l + K_s e}{\frac{3}{4}P\lambda_m + \frac{3}{4}P(L_d - L_q)\alpha\left|J\frac{d}{dt}\omega^* + B\omega + T_l + K_s e\right|} \tag{16}$$

where K_s is a positive coefficient, and α is an adjustable parameter with a negative value that will be calculated in each sampling interval.

Considering that the inertia J and load torque T_l can be varied abruptly by the external load, to tune J and T_l on-line, i_d^* and i_q^* can be:

$$i_d^* = \alpha\left|c_1\frac{d\omega^*}{dt} + c_2\omega + c_3 + K_s e\right| \tag{17}$$

$$i_q^* = \frac{c_1\frac{d\omega^*}{dt} + c_2\omega + c_3 + K_s e}{\frac{3}{4}P\lambda_m + \frac{3}{4}P(L_d - L_q)\alpha\left|c_1\frac{d\omega^*}{dt} + c_2\omega + c_3 + K_s e\right|} \tag{18}$$

where c_1, c_2, and c_3 will be adjusted on-line, and the speed error is defined as:

$$e = \omega^* - \omega. \tag{19}$$

The Lyapunov function can be defined:

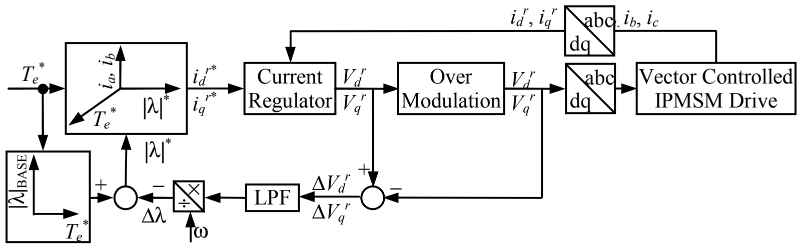

Fig. 6. Hybrid flux-weakening method of IPMSM.

$$V = \frac{1}{2} J e^2 \quad (20)$$

where J is the inertia coefficient of the motor and load. To consider the influence of the tuned-parameter error, and assuming that the variations of the inertia, viscosity and load are very slow, the differentiation of V can be written as:

$$\frac{d}{dt}V = (J - c_1)\left(e\frac{d}{dt}\omega^* - \frac{1}{\gamma_1}\frac{d}{dt}c_1\right) + (B - c_2) \times\left(e\omega - \frac{1}{\gamma_2}\frac{d}{dt}c_2\right) + (T_L - c_3)\left(e - \frac{1}{\gamma_3}\frac{d}{dt}c_3\right) - K_s e^2 \quad (21)$$

Finally, to achieve ${dV}/{dt} = 0$, the parameter adaption laws can be set as follows:

$$\frac{dc_1}{dt} = \gamma_1 e \frac{d\omega^*}{dt} \quad (22)$$

$$\frac{dc_2}{dt} = \gamma_2 e\omega \quad (23)$$

$$\frac{dc_3}{dt} = \gamma_3 e \quad (24)$$

$$\alpha = \frac{L_d i_d^*}{\left[\frac{3}{4}P\lambda_m + \frac{3}{4}P\left(L_d - L_q\right)i_d^*\right] \times \sqrt{\left(\frac{2V_{om}}{P\omega_r}\right)^2 - \left(L_d i_d^* + \lambda_m\right)^2}} \quad (25)$$

From the equations [17]—[18], [22]—[25], we can see that the algorithm of the adaptive controller is iterative in nature. The parameter α calculated in the previous sampling interval is used to compute i_d* and i_q* of the current sampling interval, and then, i_d* and i_q* in the current sampling time interval are used to compute α for the next sampling interval.

The control theory based technique simplifies the controller structure, and is also robust to the variation of the motor parameters. However, the computational complexity is higher than the control algorithms in the other three categories.

IV. CONCLUSION

The flux-weakening operation of PMSM is vital in widening the constant power range for vehicle traction application, which can be handled from both design and control points of view. Various control algorithms have been investigated in the literature, however, every control algorithms have their own advantages and disadvantages. In order to compare these methods, robustness, computational complexity and dynamic response have been used. The findings of this research work can be summarized as follows:

(1). Robustness to parameter variation and model uncertainty: Since the derivation of the feed-forward methods is based on the parameters and model of the motor, any parameter variation or inaccuracy in the motor model would definitely affect the performance of the controller. On the other hand, the other three methods that apply on-line tuning to the excitation currents are inherently robust to such uncertainties.

(2). Computational complexity: The computational burden of control theory based methods is more substantial in comparison with the other methods; however, with the improvement in the micro-controller, more robust and predictive control theory can be investigated.

(3). Dynamics response: If fast response is required for some application, feed-forward controllers would be superior over the other three approaches. To compensate the parameter and model uncertainty, experimentally obtained flux-weakening characteristics can be employed by using look-up tables.

ACKNOWLEDGMENT

The work reported in this paper is supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under Canada Research Chair program.

REFERENCES

Motor Theory, Design and Circle Diagram of Flux Weakening Method

[1] I. Husain, *Electric and Hybrid Vehicles: Design Fundamentals*, 1st ed., New York: CRC Press, 2003, p.150.

[2] A. Takasaki, T. Mizutani, K. Kitagawa, T. Yamahana, K. Odaka, T. Kuzuya, Y. Mizuno, and Y. Nishikawa, "Development of new hybrid transmission for 2009 Prius," in *EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, pp. 1-6, 2009.

[3] L. Xu, L. Ye, and A. El-Antably, "A new design concept of permanent magnet machine for flux weakening operation," *IEEE Transactions on Industry Applications*, vol. 31, pp. 373-378, 1995.

[4] W. L. Soong, D. A. Staton, and T. J. E. Miller, "Design of a new axially-laminated interior permanent magnet motor," *IEEE Transactionson Industry Applications*, vol. 31, pp. 358-367, 1995.

[5] A. Shakal, Y. Liao and T. A. Lipo, "A permanent magnet ac machine structure with true field weakening capability," in *1993 IEEE International Symposium on Industrial Electronics*, pp. 19-24, 1993.

[6] B. J. Chalmers, L. Musaba, and D. F. Gosden, "Variable-Frequency synchronous motor drives for electric vehicles," *IEEE Transactions on Industry Applications*, vol. 32, no. 4, pp. 896-903, 1996.

[7] C. Deak, A. Binder, B. Funieru, and M. Mirzaei, "Extended field weakening and overloading of high-torque density permanent magnet motors," in *2009 Energy Conversion Congress and Exposition,* pp. 2347-2353, 2009.

[8] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. B. Ahmed, and M. Lécrivain, "Hybrid excitation synchronous machines: energy-efficient solution for vehicles propulsion," *IEEE Transactions On Vehicular Technology*, vol. 58, no. 5,2137-2149, pp. 2009.

[9] G. Pellegrino, E. Armando and P. Guglielmi, "Direct flux field-oriented control of IPM drives with variable DC link in the field-weakening region," *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1619-1627, 2009.

[10] S. Morimoto, Y. Takeda, T. Hirasa, and K. Taniguchi, "Expansion of operating limits for permanent magnet by current vector control cnsidering inverter capacity," *IEEE Transactions on Industry Applications*, vol. 26, pp. 866–871, 1990.

[11] T. M. Jahns, "Flux-weakening regime opeation of an interior permanent magnet synchronous motor drive, " *IEEE Transactions on Industry Applications*, vol. IA-23, pp. 681-689, 1987.

[12] W. L. Soong and T. J. E. Miller, "Field-weakening performance of brushless synchronous AC motor drives," *IEE Proc-Electr.* Power *Appl.,* Vol. 141, pp. 331-340, 1994.

[13] R. F. Schiferl and T. A. Lipo, "Power capability of salient pole permanent magnet synchronous motors in variable speed drive applications," *IEEE Trans. Ind. Appl.*, vol. 26, no. 1, pp. 115–123, 1990.

[14] J. Simanek, J. Novak, O. Cerny, and R. Dolecek, "FOC and flux weakening for traction drive with permanent magnet synchronous motor," in *Proceeding of IEEE Symp. on Int. Electronics*, pp. 753-758, 2008.

Feed-forward Control Method

[15] R. Krishnan, "Control and operation of PM synchronous motor drives in the field-weakening region," in *International conference on Industrial Electronics, Control, and Instrumentation*, vol. 2, pp.745-750, 1993.

[16] A. Verl and M. Bodson, "Torque maximization for permanent magnet synchronous motors," *IEEE Transactions on Control System Technology*, vol. 6, pp740–745, 1998.

[17] M. M. Bech, T. S. Frederiksen, and P. Sandholdt, "Accurate torque control of saturated interior permanent magnet synchronous motors in the field-weakening region," in *2005 Industry applications conference*, vol. 4, pp. 2526-2532, 2005.

[18] M. Tursini, E. Chiricozzi and R. Petrella, "Feedforward flux-weakening control of surface-mounted permanent-magnet synchronous motors accounting for resistive voltage drop," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 1, pp. 440-448, Jan. 2010.

[19] G. Pellegrino, E. Armando and P. Guglielmi, "Direct flux field-oriented control of IPM drives with variable DC link in the field-weakening region," *IEEE Transactions on Industry Applications*, vol. 45, no. 5, pp. 1619-1627, 2009.

[20] T. M. Jahns, G. B. Kliman, and T. W. Neumann, "Interior permanent magnet synchronous motors for adjustable-speed drives," *IEEE Transactions on Industrial Applications*, vol. IA-22, pp. 738-747, 1986.

[21] M. N. Uddin, and M. A. Rahman, "High-speed control of IPMSM drives using improved fuzzy logic algorithyms," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 1, pp. 190-199, 2007.

[22] S. R. Macminn and T. M. Jahns, "Control techniques for improved high-speed performance of interior PM synchronous motor drives," *IEEE Trans. Ind. Appl.*, vol. 27, no. 5, pp. 997-1004, 1991.

Feed-back Control Method

[23] H. Song, J. M. Kim, and S. K. Sul, "A new robust SPMSM control to parameter variations in flux weakening region," in *Proceedings of IEEE Industiral Electronics Society Annual Conference*, pp. 1193–1198, 1996.

[24] J. Kim and S. Sul, "Speed control of interior permanent magnet synchronous motor drive for the flux weakening operation," *IEEE Transactions on Industry Applications*, vol. 33, no. 1, pp. 43–48, 1997.

[25] B.-H. Bae, N. Patel, S. Schulz, and S.-K. Sul, "New Field Weakening Technique for High Saliency Interior Permanent Magnet Motor, " in *Industry Appications Society Annual Meeting*, vol. 2, pp. 898-905, 2003.

[26] R. U. Lenke, R. W. De Doncker, M.-S. Kwak, and S.-K. Sul, "Field Weakening Control of Interior Permanent Magnet Machine using Improved Current Interpolation," in *IEEE Power Electronics Specialists Conference*, pp. 1-5, 2006.

[27] G. Y. Choi, M. S. Kwak, T.S. Kwon and S. K. Sul, "Novel Flux-Weakening Control of a PMSM for Quasi Six-Step Operation," in *IEEE Industry Appications Society Annual Meeting*, pp. 1315-1321, 2007.

[28] T. Kwon, and S. Sul, "Novel antiwindup of a current regulator of a surface-mounted permanent-magnet motor for flux-weakening control," *IEEE Trans. Ind.. Appl.*, vol. 42, no. 5, pp. 1293-1300, 2006.

[29] S. Sue and C. Pan, "Voltage-constraint-tracking-based field-weakening control of IPM synchronous motor drives," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 340-347, 2008.

[30] N. V. Olarescu, M. Weinmann, S. Zeh and S. Musuroi, "Novel flux weakening control algorithm for PMSMS," in 2009 *Power Engineering, Energy and Electrical Drives*, pp. 123-127, 2009.

[31] R. Doleček, J. Šimánek, J. Novák and O. Černý, "Dynamics of a feed-back optimal-current-vector flux-weakening strategy for traction permanent-magnet synchronous motors," in 2009 *ELECTROMOTION*, pp. 1-6, 2009.

Hybrid Based Technology

[32] Z. Q. Zhu, Y. S. Chen, and D. Howe, "Online optimal flux-weakening control of permanent-magnet brushless AC drives," *IEEE Transactions on Industry Applications*, vol. 36, no. 6, pp. 1661–1668, 2000.

[33] J. J. Chen and K. P. Chin, "Minimum copper loss flux-weakening control of surface mounted permanent magnet synchronous motors," *IEEE Trans.Power Electron.*, vol. 18, no. 4, pp. 929–936, 2003.

[34] G. Gallegos-Lopez, F. S. Gunawan, and J. E. Walters, "Optimum torque control of permanent-magnet AC machines in the field-weakened region," *IEEE Trans. Ind. Appl.*, vol. 41, no. 4, pp. 1020–1028, 2005.

[35] G. Gallegos-López, F. S. Gunawan, and J. E. Walters, "optimum torque control of permanent-magnet AC machines in the field-weakened region," *IEEE Transactions on Industry Applications*, vol. 41, no. 4, pp. 1020-1028, 2005.

[36] T. Kwon, G. Choi, M. Kwak, and S. Sul, "Novel flux-weakening control of an IPMSM for quasi-six-step operation," *IEEE Transactions on Industry Applications*, vol, 44, no. 6, pp. 1722-1731, 2008.

[37] T. Kwon, S. Sul, L. Alberti, and N. Bianchi, "Design and control of an axial-flux machine for a wide flux-weakening operation region," *IEEE Trans. Ind. Appl.*, vol, 45, no. 4, pp. 1258-1266, 2009.

Control Therory Based Technique

[38] J. Chen and K. Chin, "Automatic flux-weakening control of permanent magnet synchronous motors using a reduced-order controller," *IEEE Transactions on Power Electronics*, vol. 15, no. 5, pp. 881-890, 2000.

[39] J. L. Shi, T. H. Liu and S. H. Yang, "Nonlinear-controller design for an interior-permanent-magnet synchronous motor including field-weakening operatioin, " *IET Electric Power Appl*. vol, 1, no. 1 pp.119-126, 2007.

[40] S. Bolognani, S. Bolognani, L. Peretti and M. Zigliotto, "Combined speed and current model predictive control with inherent field-weakening features for PMSM drives," in 2008 *IEEE Electrotechnical conference*, pp. 472-478, 2008.

[41] P. Vaclavek and P. Blaha, "Interior permanent magnet synchronous machine field weakening control strategy – the analytical solution, " *The University Electro-communications*, pp. 753-757, 2008.

[42] M. F. Rahman, D. M. Wilathgamuwa, M. N. Uddin, and K. J. Tseng, "Nonlinear control of interior permanent-magnet synchronous motor," *IEEE Trans. on Industry Applications*, vol. 39, no. 2, pp. 408-416, 2003.

BIOGRAPHIES

Dongyun Lu (S'09) received the B.Sc.in electrical engineering from Sichuan University, Chengdu, China, in 1991. Currently, she is a PhD. candidate in the Electrical and Computer Engineering Department at the University of Windsor, Windsor, ON, Canada. She has been conducting research in the area of torque control of switched reluctance motor for hybrid electric vehicle propulsion application. Her research interests include power electronics, motor design and control. She is a student member of IEEE.

Narayan C. Kar (S'95-M'00-SM'07) received the B.Sc. degree in electrical engineering from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, in 1992 and the M.Sc. and Ph.D. degrees in electrical engineering from Kitami Institute of Technology, Hokkaido, Japan, in 1997 and 2000, respectively.

He is an associate professor in the Electrical and Computer Engineering Department at the University of Windsor, Canada where he holds the Canada Research Chair position in hybrid drivetrain systems. His research presently focuses on the analysis, design and control of permanent magnet synchronous, induction and switched reluctance machines for hybrid electric vehicle and wind power applications, testing and performance analysis of batteries and development of optimization techniques for hybrid energy management system. He is a Senior Member of the IEEE.