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# Extension of the Operating Region of an IPM Motor Utilizing Series Compensation

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# Extension of the Operating Region of an IPM Motor Utilizing Series Compensation

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*Abstract*—**This paper investigates the possibility of extending the operating region of a PM motor constrained by a given power supply voltage by using an open-winding motor drive configuration. A second inverter with a floating capacitor can be controlled to provide reactive power to the motor. A control method for the new open-winding PM machine drive employing FACTS concepts is proposed. Simulation and experimental studies on a lab scale IPM machine are presented. The results show that the proposed method is able to considerably improve the power capability of the motor beyond its base speed.**

## I. INTRODUCTION

Permanent magnet (PM) motors are presently widely used in applications like EV/HEV and construction equipments due to their high torque density and good efficiency. Because of their intrinsic properties, flux weakening control is usually needed to safely operate the motor in the constant power region beyond the base speed. The flux weakening capability of a PM motor drive is affected by both motor parameters and inverter ratings. A theoretical maximum speed limit is imposed by the power supply voltage when the characteristic current is higher than the rated current [1-4]. It is possible to extend the flux weakening region by insertng inductors in series with the motor. Instead of inductors, Lawler et al. have proposed to use SCRs to extend the flux weakening region of a BLDC motor drive [5]. El-Refaie et al. pointed out that the SCRs are fundamentally equivalent to inductors [6].

In flexible alternating current transmission systems (FACTS) applications, it is common to use power electronics converters to provide controllable reactive power for changing the power flow in the grid [7]. The FACTS type devices have also been employed in smaller single machine systems to improve the overall performance. For example, the static synchronous series compensator (SSSC) and the magnetic energy recovery switch (MERS) have been used to improve the generator power in diode rectifier based wind power systems [8-9]. The static synchronous compensator (STATCOM) has been used to regulate the load voltage in a single generator constant voltage variable frequency (CVVF) vehicular distribution system [10]. Similar to a MERS, series connected single phase H-bridges with floating capacitor has also been proposed as part of a hybrid multilevel converter (MLC) to provide reactive power to the load and to improve the output voltage waveform [11]. For this type of topology, the voltage applied to the motor terminal is increased. However the insulation of the motor windings usually does not need to be improved since the voltage change rate is not increased.

Traditionally, open-winding machine drives have been proposed for very high power AC drive applications where the power is divided equally into two inverters to reduce the size of each single inverter [12]. It is essentially a MLC in a different configuration compared to more traditional neutral point clamped (NPC) or cascaded H-bridge MLCs. Most of the research efforts in the field of open-winding motor drives are spent on PWM techniques [13-14]. Recently, open-winding PM machine drives have drawn attention from the field of EV/HEV [15-16]. Rossi et al. proposed a series hybrid powertrain based on open-winding machine drive configuration. An open-winding PM generator was coupled with the internal combustion engine (ICE). The generated power was split into two isolated DC buses through individual rectifiers. Two regular three-phase PM machine drives were attached to each of the DC bus and each of the drive powers an individual shaft [15]. Welchko proposed an open-winding PM motor drive system with two isolated DC buses for combined propulsion and energy management functions in hybrid vehicles. One of the DC buses was connected to an energy storage element, for instance a battery. Regenerative energy during braking could be stored in the battery and used later when needed. Three control methods were mentioned by the author: unity power factor control, voltage quadrature control and optimum inverter utilization control [16]. Kwak and Sul proposed a flux weakening control method for an open-winding SPM motor drive [17]. The torque capability at top speed was improved

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by 15%. However, a separate set of transformer and rectifier were used in the system which diminished the benefits. In addition, the authors did not analyze the advantages against the added cost of the drive.

In this paper, a new open-winding motor drive configuration and its control method are proposed. As shown in Fig. 1, INV1 is connected to a DC voltage source and INV2 is connected to a floating capacitor. The floating capacitor will charge from the main DC bus when needed. There is no extra pre-charge circuit or procedure required. The floating capacitor voltage can be controlled to be either higher or lower than the source voltage by INV2. This configuration can also be considered as a special condition in the HEV drive proposed in [16] when the energy storage is low. The function of INV2 is similar to that of the SSSC in FACTS [7]. It is used to provide the reactive power and to change the equivalent impedance seen by INV1. As will be shown in the later sections, by providing reactive power to the motor, the power capability of the motor can be considerably improved at high speed. When powered from the same supply voltage, the drive will be able to operate the motor under study at a higher maximum speed. The size of the inverter and the applicability of the proposed system to other motors will be discussed as well.

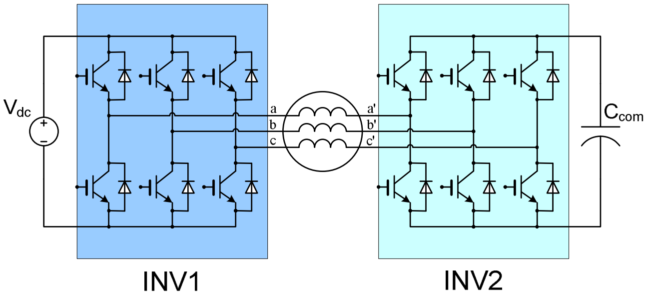


Fig. 1. Proposed series compensated open-winding PM motor drive

## II. SERIES COMPENSATION CONCEPT AND PROPOSED CONTROL METHOD

Flux weakening control is commonly used in PM motor drive beyond the base speed. The controller forces the inverter to increase d-axis current in the negative direction to prevent saturation of the current regulators at high speed. Ideally, the power of the motor is kept constant as the speed increases [1-4]. There are two basic types of flux weakening control strategies, feedforward style and feedback style. The feedforward style uses the machine parameters to calculate the current command based on the voltage and current limits. The implementation of this method is easy and straightforward. Also, the transient performance is superior. The feedback approach utilizes the output of the current regulators (voltage commands) as a feedback to modify the current command vector. The feedback approach for the flux weakening controller is less sensitive to machine parameter accuracy. But the dynamic performance of the feedback style of flux weakening is not as good as the feedforward style.

Current limit circle and voltage limit ellipses are often used to study flux weakening and the power capability of PM motor drives [1]. The current vector must lie within the intersection of the current limit circle and voltage limit ellipses. The center of the voltage ellipses is located at the negative characteristic current on the d-axis of the rotor reference frame. The characteristic current $I_{ch}$ is an important parameter in determining the flux weakening capability of a PM motor. Theoretically, a PM motor drive will have infinite constant power speed ratio (CPSR) given the characteristic current is equal to the rated current. When $I_{ch}$ is smaller than the rated current, the PM motor drive is only capable of delivering a reduced power beyond the base speed. If $I_{ch}$ is larger than the rated current, the motor will have a finite maximum speed imposed by the voltage of the power supply and rating of the drive [1]. Like mentioned above, the maximum speed of such a motor can be increased by adding external inductors in series with the motor.

Similar to the SSSC [7], INV2 in the proposed system can be controlled as inductors in series with the PM motor to enhance the drive's flux weakening capability. The equivalent impedance of INV2 can be varied by controlling the voltage injected by INV2 according to the machine current. The compensation voltage can be calculated as in (1) given the desired compensation impedance and machine current are known. $\tilde{Z}_{com}$ is complex compensation impedance. $r_{com}$ and $X_{com}$ are the real and imaginary parts of the compensation impedance. The real part implies the real power flow between the motor and INV2.

$$\tilde{V}_{com} = \tilde{Z}_{com}\tilde{I}_s = (r_{com} + jX_{com})\tilde{I}_s \tag{1}$$

Assuming purely inductive compensation, the voltage limit can be modified as (2) for an ideal lossless motor.

$$\left(i_d + \frac{\lambda_m}{L_d + L_{com}}\right)^2 + \left(\frac{L_q + L_{com}}{L_d + L_{com}}\right)^2 i_q^2 = \frac{V_{max}^2}{(L_d + L_{com})^2}\frac{1}{\omega_r^2} \tag{2}$$

Ideally, the compensation inductance for infinite CPSR will require the center of the voltage limit ellipses locating on the edge of the current limit circle. The optimal compensation inductance can be calculated via (3).

$$L_{opt} = \frac{\lambda_m}{I_r} - L_d \tag{3}$$

An example of current limit circle and voltage limit ellipses with and without INV2 compensation for a motor of high characteristic current are shown in Fig. 2. The dashed ellipses are the voltage limits without compensation and solid ellipses are the new voltage limits for optimal compensation inductance. It is clear that the center of the ellipses is moved towards the origin of the current vector plane and the shape of the ellipses also changes slightly. A salient IPM motor is used here for this study. However, the topology and control method can be applied to SPM motor or synchronous reluctance motor as well.

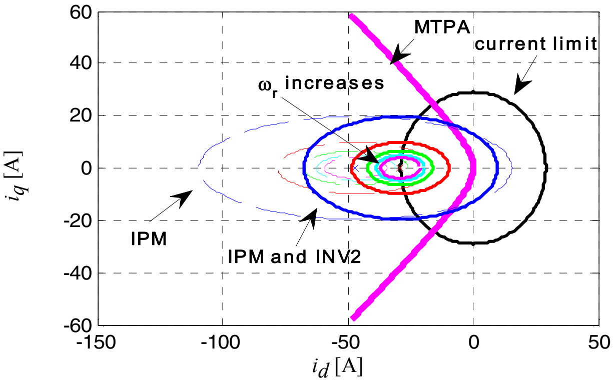


Fig. 2. IPM operating limit on current vector plane

The power-speed and torque-speed curve for the same motor when INV2 is controlled at different inductance are plotted in Fig. 3 and 4.

By purely inductive compensation, the ideal CPSR of an open-winding motor drive could be extended to infinity ignoring the voltage limit of INV2. Moreover, the power capability can be improved considerably at high speed. However, the added inductance would initiate the flux weakening at a lower speed resulting in reduced power capability of the drive around the corner speed. Unlike physical inductors, INV2 can be controlled to be a variable inductance or even be capacitive when needed. In the controller, reactive part of the voltage can be directly used as the command of INV2 instead of compensation impedance. By decomposing the voltage command vector into real and imaginary components using the current phase angle, the drive will be able to operate within the envelope of all power-speed curves shown in Fig. 3.

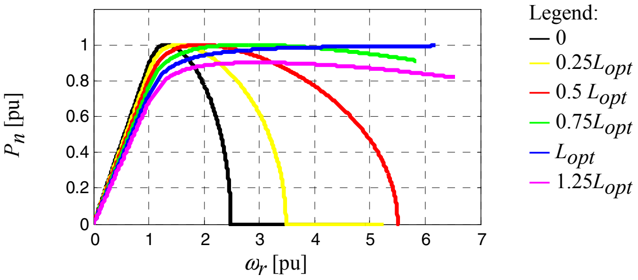


Fig. 3. Power-speed curves under different compensation inductance

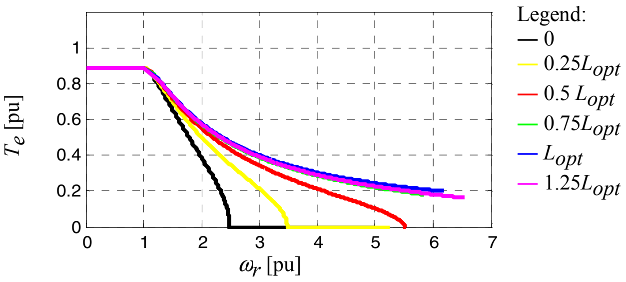


Fig. 4. Torque-speed curve under different compensation inductance

The overall speed controller is shown in Fig. 5. A common field oriented controller (FOC) is used for the proposed system. The voltage command from the current regulator is distributed between the two inverters by (4) and (5). INV2 is controlled to provide the reactive part of the voltage up to its limits. INV1 provides the remaining part of the voltage. The quantities $\gamma$ and $\beta$ are the voltage and current phase angles with respect to the q-axis. $T$ is the reference frame transformation. The voltage of the floating capacitor $v_{dc2}$ is controlled through the real part of INV2 voltage. The floating capacitor voltage is only raised to its nominal value when needed to keep the switching losses of INV2 minimal. A feedback style flux weakening controller is then used to avoid saturation of current regulators. The amplitude of INV1 voltage reference is used as the input of the outer voltage loop for flux weakening.

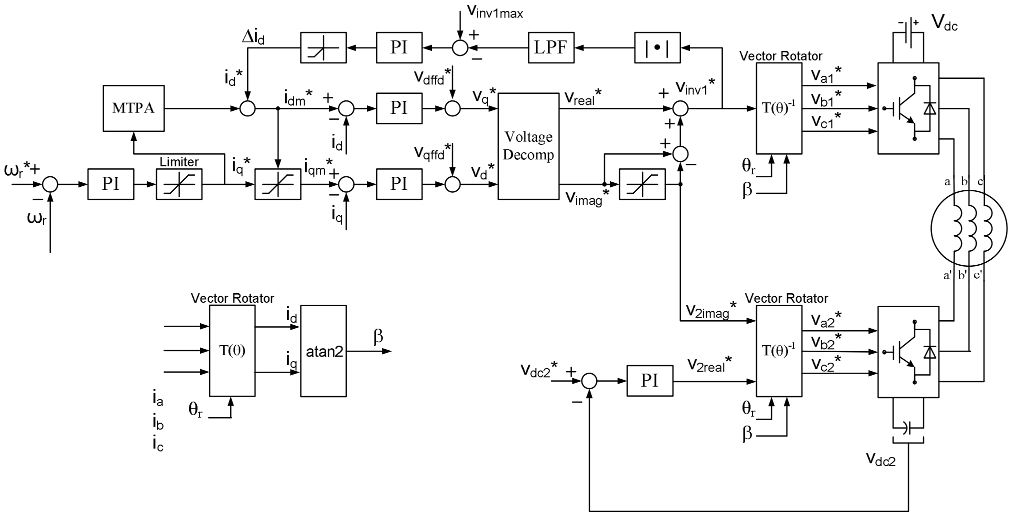


Fig. 5. Block diagram of the proposed open-winding PM motor drive control method

$$v^*_{inv1} = \left\{ |v^*_{dq}|\cos(\gamma-\beta) + j\left[ |v^*_{dq}|\sin(\gamma-\beta) - sgn(\sin(\gamma-\beta))\ min\left(\left||v^*_{dq}|\sin(\gamma-\beta)\right|, v2max\right)\right]\right\} T^{-1}(\theta_r - \beta) \quad (4)$$

$$v^*_{inv2} = \left[ v^*_{real2} + j\ sgn(\sin(\gamma-\beta))min\left(\left||v^*_{dq}|\sin(\gamma-\beta)\right|, v2max\right)\right] T^{-1}(\theta_r - \beta) \quad (5)$$

## III. INVERTER SIZE AND APPLICABILITY CONSIDERATIONS

Conceptually, the CPSR of a PM motor with large characteristic current would become infinite when INV2 is controlled as inductors in series. In practice though, INV2 would reach its voltage limit as the speed of the rotor increases. Since INV2 is connected in series with the motor, the current rating has to be the same as the main inverter. Nevertheless, the voltage rating of INV2 can be sized differently according to requirements of the application. Comparisons of the power-speed curves and torque-speed curves when INV2 is sized differently are shown in Fig. 6 and 7. It can be seen that even a small size INV2 is able to improve the power capability at high speed considerably.

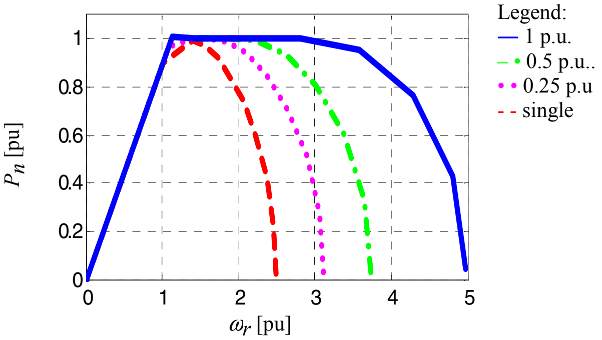


Fig. 6. Power-speed curves for different INV2 rating

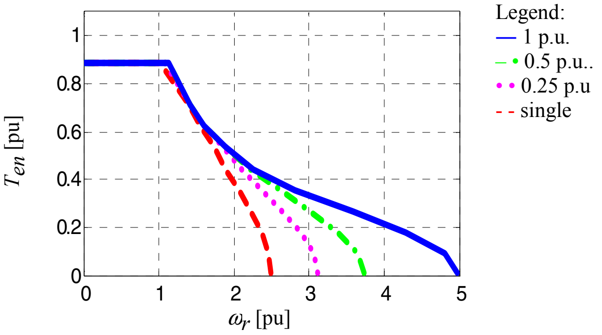


Fig. 7. Power- speed curves for different INV2 rating

When the power supply voltage is limited, a more conventional method to improve power capability at high speed is to use a DC/DC boost converter between the power supply and the inverter. If regeneration is required, a bidirectional boost converter will be needed. By using a boost converter, the corner speed is moved to a higher speed. The drive is able to deliver power that is larger than 1 per unit. However, the CPSR of the drive remains constant. On the other hand, INV2 in the proposed system is only able to supply reactive power to the motor. Therefore, the proposed system is not able to deliver power that is higher than 1 per unit. Instead, the CPSR of the drive is increased. For the same maximum speed, the motor terminal voltage will be the same for the two topologies. As a result, the inverter rating of the drive with a boost converter is the same as the sum of the two inverters of the proposed system. An extra full power rating boost converter and an inductor will add significant cost to the system for the boost converter topology. In addition motor winding insulations may need to be improved due to the increased DC bus voltage. In short, if power higher than 1 per unit is not required by the application, the proposed system could be a cost effective alternative to the conventional drive with a boost converter. It is also worth noting that an open-winding motor drive that has two independent power sources will be able to supply power higher than 1 per unit as well.

The size of the floating capacitor is another important factor when considering the overall cost of the proposed system. Like in most switching converters, the capacitance can be determined by desired voltage ripple, peak motor current and capacitor parameters like capacitance and equivalent series resistance (ESR). In practice, the ripple current rms value may play a more important role in sizing the floating capacitor.

The motor considered above has a high characteristic current. The designs of PM motor can vary significantly. It is worth to consider how the proposed system would work with other motors. In the proposed system, INV2 is only supplying reactive power to the motor. Therefore, the amount of reactive power required by the motor will affect the performance of the proposed system. The proposed topology will only be able to improve the power capability of the drive in the part of operating space where the motor needs reactive power. Since the proposed system is used to improve the power capability of the motor drive beyond the base speed, the power factor of the motor at the rated condition will help determine how much the power capability can be improved using series compensation. Ignoring the losses in the machine, the power factor is only determined by the current vector for a given machine. The power factor of an ideal lossless machine can be calculated as:

$$pf = \frac{\lambda_m\cos(\beta) - \frac{1}{2}I_s^2\sin(2\beta)(L_d - L_q)}{\sqrt{(L_q I_s\cos(\beta))^2 + (L_d I_s\sin(\beta) + \lambda_m)^2}} \quad (3)$$

In general, PM motors have very good power factor. However, depending on the specific machine designs, the power factor of a PM motor could become worse at certain operating conditions. For instance, with a motor that is designed for high power factor operation at the rated condition, the power factor would deteriorate rapidly beyond the base speed. The motor used in this study belongs to this category. Usually, the characteristic current is much higher than the rated current for this kind of motor. INV2 is controlled for inductive compensation in this case. An auxiliary inverter of the same size of the main inverter would be able to approximately double the maximum speed limit.

In contrast, a PM motor that is designed for a wide CPSR would have a power factor in the vicinity of 0.7 at the rated condition. For this kind of motor, the power factor will approach unity in deep flux weakening region. For these motors, the start of the flux weakening can be postponed by using series compensation. The motor is able to deliver rated torque beyond the corner speed. INV2 is mostly controlled for capacitive compensation. The start of flux weakening can be postponed to 30~40% higher than the original corner speed.

It is worth to note that there is no need to change inductive or capacitive compensation for different motors. The proposed control method will automatically handle this issue. However, for synchronous reluctance or PM assisted reluctance motors which have zero or low characteristic current, the proposed control method needs to be modified to cover the operating region where the current amplitude is reduced due to the voltage limit [18].

The normalized motor parameter plane has been commonly used to study the flux weakening capability of PM motors [2].The same concept can be used here to study the applicability of the proposed topology. On the motor parameter plane, the horizontal axis represents the amount of magnets used in the motor. The vertical axis shows the saliency ratio. A motor on the horizontal axis is a non-salient SPM motor. On the other hand, a motor on the vertical axis corresponds to a synchronous reluctance motor. The power-speed and torque-speed curves of the sample motors when driving by a conventional 2-level inverter are shown on the motor parameter plane in Fig. 8. Fig. 9 shows the power-speed and torque-speed curves when the auxiliary inverter INV2 is added to the system. INV2 is sized to be the same as INV1 in the comparison.

## IV. SIMULATION RESULTS

The proposed system was simulated using parameters of a lab scale motor. The parameters of the motor and inverters are given in Table. I. It should be pointed out that due to the mechanical limit of the setup, the rated current of the motor is decreased so that the maximum speed limit is at a safe level for experiment verification.

The inverter phase voltage references are plotted with the motor current of the same phase in Fig. 10. Two operating conditions in steady state are shown. Low speed loaded operation is shown in Fig. 10 (a). INV1 voltage reference is in phase with current, indicating that INV1 is only supplying real power to the motor. INV2 voltage reference is lagging the current by 90 degrees. INV2 is acting as a three-phase capacitor in this case. In Fig. 10 (b), the motor is operated at high speed with no applied load torque. The motor is operated at a leading power factor. INV2 is controlled as a three-phase inductor.

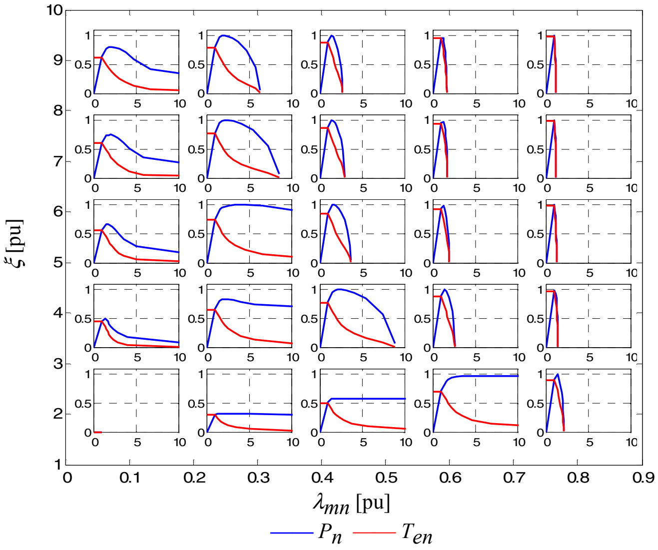


Fig. 8. Power-speed and torque-speed curves of different machines on the normalized machine parameter plane, driven by single inverter drive

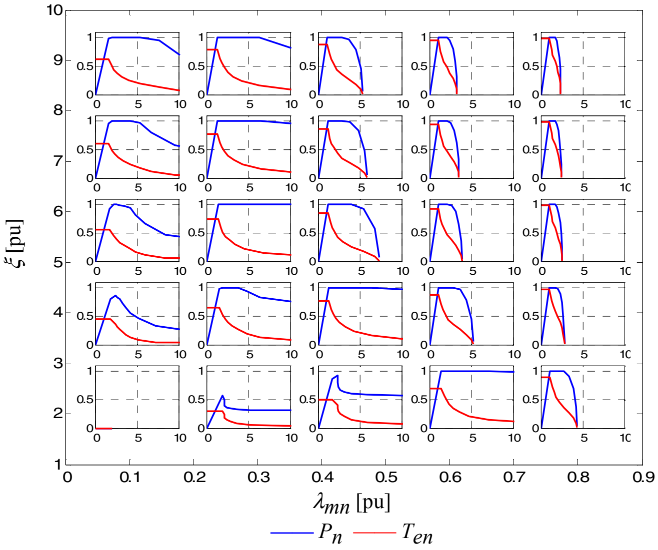
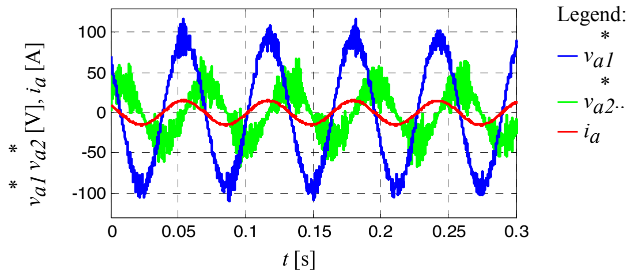


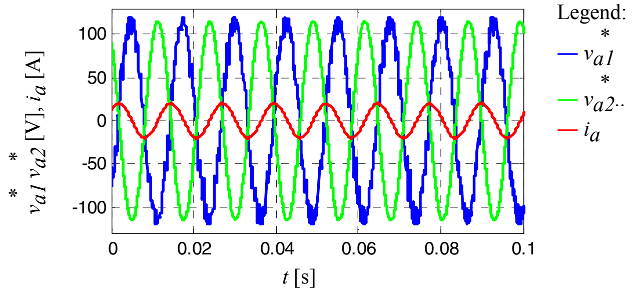
Fig. 9. Power-speed and torque-speed curves of different machines on the normalized machine parameter plane, driven by open-winding drive

TABLE I. MOTOR AND DRIVE PARAMETERS

| **Symbol** | **Parameters** | **Value** |
|---|---|---|
| $r_s$ | stator resistance | 0.315 Ohm |
| $L_d$ | d-axis inductance | 16 mH |
| $L_q$ | q-axis inductance | 51 mH |
| $\lambda_m$ | permanent flux linkage | 0.75 wb |
| $P$ | number of poles | 4 |
| $I_r$ | rated peak current | 21.6 A |
| $V_{dc}$ | DC bus voltage | 200 V |
| $V_{dc2}$ | floating capacitor voltage | 200 V |
| $C_{com}$ | Floating capacitor capacitance | 800 µF |
| $f_s$ | switching frequency | 8 kHz |



(a) low speed, loaded



(b) high speed, no load

Fig. 10. Simulated nverter voltage references and motor current

Fig. 11 (a) shows the speed during acceleration. The velocity reference is ramped up. The motor accelerates until the inverters reach the voltage limit. The amplitude of INV1 voltage reference is shown in Fig. 11 (b). The floating capacitor is charged during the transient as shown in Fig. 11 (c).

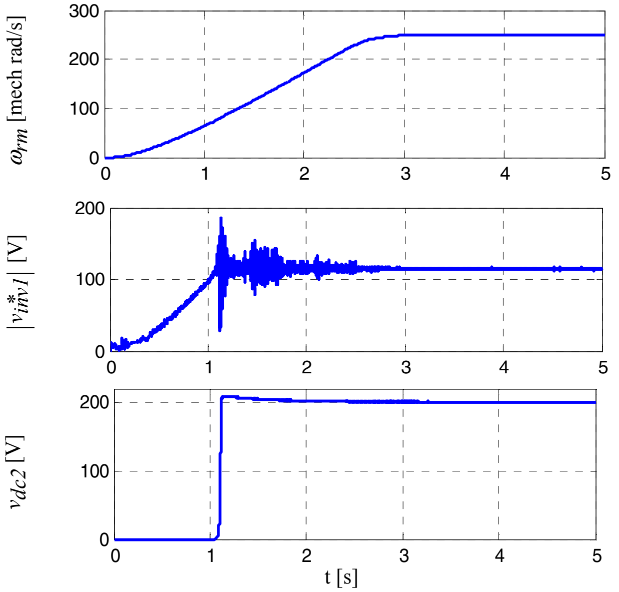
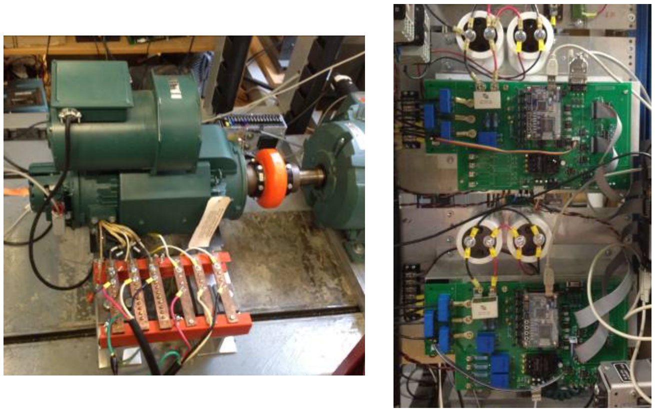


Fig. 11. Simulated transient during acceleration

## V. EXPERIMENTAL RESULTS

A lab scale motor has been modified as an open-winding motor and the proposed system has been built in the lab for experimental study. Fig. 12 shows the pictures of the open-winding motor and the inverters.



(a) open-winding IPM motor (b) inverters

Fig. 12. Experiment setup

The transient during acceleration is shown in Fig. 13. It is shown that the flux weakening controller is able to keep the amplitude of INV1 voltage reference within its limit.

The floating capacitor can be charged during normal operation. Fig. 14 shows the transient during a load change. The capacitor is charged only when the current exceeds a threshold value. Also, the floating capacitor voltage can be controlled very well during a load change.

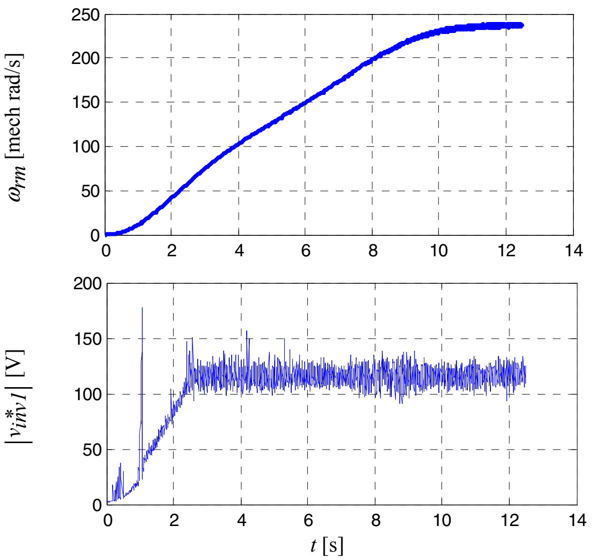


Fig. 13. Measured transient during acceleration

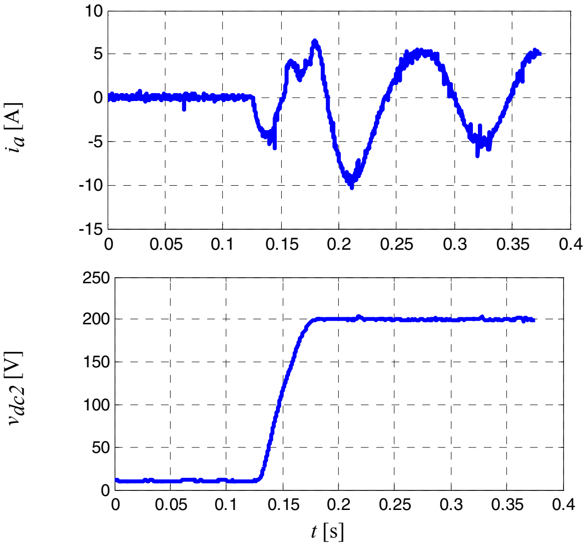


Fig. 14. Measured charge of floating capacitor during transient

The power-speed and torque-speed curves when INV2 is sized differently have been obtained by experimental methods as well. Each of the point on the curves is a steady state operating point. The results are compared with the single 2-level inverter drive in Fig. 15 and 16. As predicted, the power capability of the motor is improved considerably in the high speed region.

The transient responses during acceleration are also compared for different INV2 sizes. The motor accelerates until the drives reach their limits. Fig. 17 gives the comparison. The results show that the maximum speed is about twice comparing to the single 2-level inverter drive when INV2 is sized to be 1 per unit.

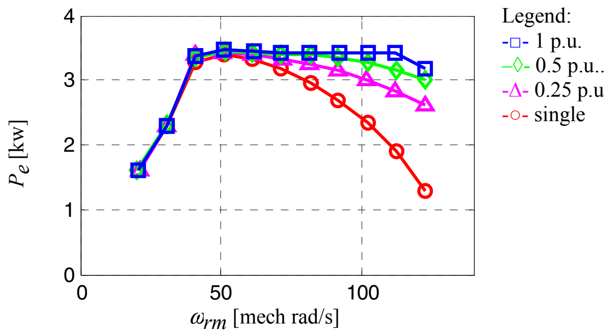


Fig. 15. Measured power-speed curve for different INV2 ratings

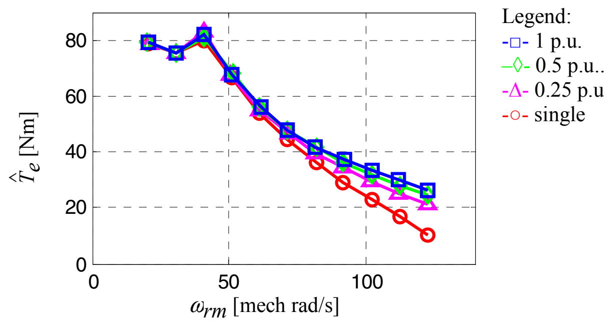


Fig. 16. Measured torque-speed curve for different INV2 ratings

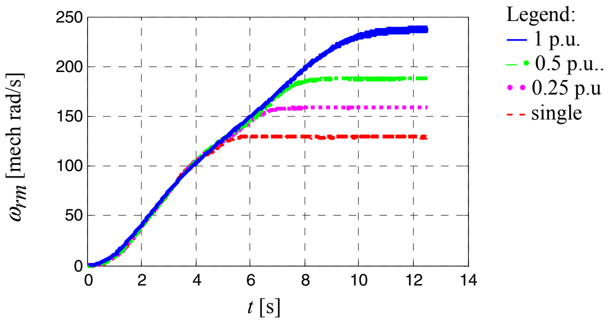


Fig. 17 Comparison of measured ramp speed response in experiment for different INV2 ratings

## VI. CONCLUSIONS

A new open-winding PM motor drive and its control method have been proposed in this paper. A floating capacitor is used at the DC bus of the auxiliary inverter. The power capability of the drive can be improved by supplying controlled reactive power to the motor using the auxiliary inverter. The size of the auxiliary inverter against the improvement of power capability is discussed. It has been shown that the proposed topology and control method can be applied to other types of PM motors. Simulation and experimental results are provided to show the validity of the proposed topology and control method.

# REFERENCES

[1] Schiferl, R. and Lipo, T.A.,, "Power Capability of Salient Pole Permanent Magnet Synchronous Motors in Variable Speed Drive Applications," IEEE Trans. on Industry Applications, Vol. 26, No. 1, January/February 1990, pp. 115-123.

[2] Soong, W.L., Miller, T.J.E., "Field-weakening performance of brushless synchronous AC motor drives," *Electric Power Applications, IEE Proceedings* - , vol.141, no.6, pp.331-340, Nov 1994

[3] Jahns, Thomas M., "Flux-Weakening Regime Operation of an Interior Permanent-Magnet Synchronous Motor Drive," *Industry Applications, IEEE Transactions on* , vol.IA-23, no.4, pp.681-689, July 1987

[4] Morimoto, S., Sanada, M., Takeda, Y., "Wide-speed operation of interior permanent magnet synchronous motors with high-performance current regulator," *Industry Applications, IEEE Transactions on* , vol.30, no.4, pp.920-926, Jul/Aug 1994

[5] Lawler, J.S., Bailey, J.M., McKeever, J.W., Pinto,J., "Extending the constant power speed range of the brushless DC motor through dual-mode inverter control," *Power Electronics, IEEE Transactions on* , vol.19, no.3, pp. 783- 793, May 2004

[6] EL-Refaie, A.M., Novotny, D.W., Jahns, T.M., "A simple model for flux weakening in surface PM synchronous machines using back-to-back thyristors," *Power Electronics Letters, IEEE* , vol.2, no.2, pp. 54- 57, June 2004

[7] Gyugyi, L., Schauder, C.D, Sen, K.K., "Static Synchronous Series Compensator: A Solid-State Approach to the Series Compensation of Transmission Lines," *Power Engineering Review, IEEE* , vol.17, no.1, pp.62, January 1997

[8] Singer, A., Hofmann, W.;"Static synchronous series compensation applied to small wind energy conversion system," *Power Electronics and Applications, 2007 European Conference on* , pp.1-9, 2-5 Sept. 2007

[9] Takaku, T.; Homma, G.; Isober, T.; Igarashi, S.; Uchida, Y.; Shimada, R.; "Improved wind power conversion system using magnetic energy recovery switch (MERS)," *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005* , vol.3, , pp. 2007- 2012 Vol. 3, 2-6 Oct. 2005

[10] Clements, N.; Venkataramanan, G.; Jahns, T.M.; , "Regulation of permanent magnet generators using angle control of stator-connected voltage source inverters," *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE* , vol., no., pp.1166-1172, 12-16 Sept. 2010

[11] Steimer, P.K.; Manjrekar, M.D.; , "Practical medium voltage converter topologies for high power applications," *Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE* , vol.3, no., pp.1723-1730 vol.3, Sept. 30 2001-Oct. 4 2001

[12] Stemmler, H., Guggenbach, P., "Configurations of high-power voltage source inverter drives," *Power Electronics and Applications, 1993., Fifth European Conference on* , vol., no., pp.7-14 vol.5, 13-16 Sep 1993

[13] Shivakumar, E.G.; Gopakumar, K.; Sinha, S.K.; Pittet, A.; Ranganathan, V.T.; , "Space vector PWM control of dual inverter fed open-end winding induction motor drive," Applied Power Electronics Conference and Exposition, 2001. APEC 2001. Sixteenth Annual IEEE , vol.1, no., pp.399-405 vol.1, 2001

[14] Shiny, G.; Baiju, M.R.; , "Space Vector PWM scheme without sector identification for an open-end winding induction motor based 3-level inverter," Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE , vol., no., pp.1310-1315, 3-5 Nov. 2009

[15] Rossi, C., Grandi, G.., Corbelli, P., "Series hybrid powertrain based on the dual two-level inverter," *Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference on* , vol., no., pp.277-286, 22-24 May 2008

[16] Welchko, B.A., "A double-ended inverter system for the combined propulsion and energy management functions in hybrid vehicles with energy storage," *Industrial Electronics Society, 2005. IECON 2005. 31st Annual Conference of IEEE* , vol., no., pp.6 pp., 6-6 Nov. 2005

[17] Kwak, M-S, Sul, S-K , "Flux Weakening Control of an Open Winding Machine with Isolated Dual Inverters," *Industry Applications Conference, 2007. 42nd IAS Annual Meeting. Conference Record of the 2007 IEEE* , vol., no., pp.251-255, 23-27 Sept. 2007

[18] Liu, H.; Zhu, Z.Q.; Mohamed, E.; Fu, Y.,; Qi, X.; , "Flux-Weakening Control of Nonsalient Pole PMSM Having Large Winding Inductance, Accounting for Resistive Voltage Drop and Inverter Nonlinearities," *Power Electronics, IEEE Transactions on* , vol.27, no.2, pp.942-952, Feb. 2012