Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles

Induction and switched-reluctance machines can provide the needed characteristics, but permanent magnet brushless machines offer a higher efficiency and torque density.

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ABSTRACT | This paper reviews the relative merits of induction, switched reluctance, and permanent-magnet (PM) brushless machines and drives for application in electric, hybrid, and fuel cell vehicles, with particular emphasis on PM brushless machines. The basic operational characteristics and design requirements, viz. a high torque/power density, high efficiency over a wide operating range, and a high maximum speed capability, as well as the latest developments, are described. Permanent-magnet brushless dc and ac machines and drives are compared in terms of their constant torque and constant power capabilities, and various PM machine topologies and their performance are reviewed. Finally, methods for enhancing the PM excitation torque and reluctance torque components and, thereby, improving the torque and power capability, are described.

KEYWORDS | Brushless drives; electric vehicles; electrical machines; hybrid vehicles; induction machines; permanent-magnet machines; switched reluctance machines

I. INTRODUCTION

Electrical machines and drives are a key enabling technology for electric, hybrid, and fuel cell vehicles. The basic characteristics which are required of an electrical machine for traction applications include the following [1]–[3].

- High torque density and power density.
- High torque for starting, at low speeds and hill climbing, and high power for high-speed cruising.
- Wide speed range, with a constant power operating range of around 3–4 times the base speed being a good compromise between the peak torque requirement of the machine and the volt-ampere rating of the inverter.
- High efficiency over wide speed and torque ranges, including low torque operation.
- Intermittent overload capability, typically twice the rated torque for short durations.
- High reliability and robustness appropriate to the vehicle environment.
- Acceptable cost.

In addition, low acoustic noise and low torque ripple are important design considerations. On an urban driving cycle, a traction machine operates most frequently at light loads around the base speed. Therefore, in general, it should be designed to operate at maximum efficiency and minimum acoustic noise in this region.

Typical torque/power-speed characteristics required for traction machines are illustrated in Fig. 1. Induction machines (IM), switched reluctance machines (SRMs), and permanent-magnet (PM) brushless machines (Fig. 2) have all been employed in traction applications, and can be designed to exhibit torque/power-speed characteristics having the form shown in Fig. 3. In the constant torque region I, the maximum torque capability is determined by the current rating of the inverter, while in the constant power region II, flux-weakening or commutation phase advance has to be employed due to the increasing influence of the back-electromotive force (back-EMF). However, the power capability and the maximum speed can be enhanced without sacrificing the low-speed torque capability by employing a dc–dc voltage booster [4], a technique which is employed in the Toyota...
hybrid system, or by employing series/parallel winding connections, i.e., series connection at low speed and parallel connection at high speed, as demonstrated in [5] and [6]. In general, however, the design considerations and control methods for the three machine technologies are significantly different, as will be discussed in this paper. Electrical machine design cannot be undertaken in isolation, but must account for the control strategy and the application requirements, both static and dynamic. Hence, a system-level design approach is essential.

This paper describes the basic operational characteristics and design features associated with the foregoing electrical machine technologies for traction applications, and reports the latest developments, with particular reference to PM brushless machines, for which there are various topologies.

II. INDUCTION MACHINES

Of the three electrical machine technologies under consideration, induction machines are the most mature. In this section, the basic characteristics of IMs are briefly reviewed and specific design features for traction applications are highlighted. Optimal flux, maximum efficiency, and low acoustic noise operation are then discussed.

A. Basic Characteristics

IMs are robust, relatively low cost, and have well-established manufacturing techniques. Good dynamic torque control performance can be achieved by either vector control or direct torque control. For conventional IMs, the constant power range typically extends to 2–3 times the base speed. However, for traction machines, this can be extended to 4–5 times the base speed, which is generally desirable [7].

The torque-speed characteristic of an IM is mainly characterized by the starting torque, the pull-out torque and the associated speed, and the maximum speed. The electromagnetic torque is given by

\[
T = \frac{mpV_s^2R_s}{2\pi f_s \left( R_s + \frac{R_0}{s} \right)^2 + X_k^2}
\] (1)

and the maximum torque, i.e., pull-out torque, is

\[
T_{\text{max}} \propto \frac{V_s^2}{f_kX_k} \propto \frac{V_s^2}{I_k}
\] (2)

while the starting torque and corresponding phase current are given by

\[
T_{st} = \frac{mpV_s^2R_0'}{2\pi f_s \left( R_s + R_0' \right)^2 + X_k^2}
\] (3)

\[
I_{st} = \frac{V_s}{\sqrt{(R_s + R_0')^2 + X_k^2}}
\] (4)
where $V_s$ and $f_s$ are the supply voltage and frequency, $\psi_s$ is the stator flux-linkage, $m$ is the number of phases, $p$ is the number of pole-pairs, $s$ is the slip, $R_s$ and $R_0^r$ are the stator winding resistance and effective rotor cage resistance per phase, respectively, $X_s = X_0 + X_0^r = 2\pi f_s L_k$ and $L_k$ are the short-circuit reactance and the total stator and effective rotor leakage inductance per phase, respectively. The pull-out torque is independent of the rotor resistance, approximately inversely proportional to the total stator and rotor leakage reactance, proportional to the square of the stator flux (or voltage), and inversely proportional to the square of the supply frequency. The starting torque is proportional to the square of the supply voltage, while the lower the stator and rotor leakage reactance and the lower the supply frequency, the higher will be the starting torque.

B. Design for Traction Applications

In addition to the general requirements cited in the introduction for traction machines, essential design parameters for IMs include the number of poles, the number of stator and rotor slots, the shape of the stator and rotor slots, and the winding disposition. The design process usually involves three stages:

1) making appropriate choices for the pole number and stator/rotor slot numbers;
2) dimensioning the machine and designing the stator winding to achieve a specified power at the base-speed within a specified volume envelope;
3) simulating the machine performance over the full operating speed range.

With an inverter fed machine, both a high starting torque and a low starting current can be achieved, since the supply voltage and frequency are variable. Thus, compared with machines designed for constant supply frequency operation certain restrictions, such as the need for a specific rotor slot shape to achieve the required starting torque, are removed. By appropriate choice of supply voltage and frequency, the starting torque can be almost as high as the maximum torque, while a high efficiency can be achieved by minimum slip control [8], [9].

The stator slot number and rotor slot number, and their shape and size should be optimized to minimize the total leakage inductance and resistance. Generally, this favors the use of wide and relatively shallow rotor slots and parallel sided teeth, as opposed to deep bars or double cages in conventional IMs. This results in a lower rotor leakage inductance, which, in turn, improves the power factor and increases the peak torque. In addition, the rotor slot area is more effectively utilized. When combined with the reduced rotor resistance, a lower leakage reactance is also beneficial in reducing the slip frequency at rated torque, and the variation of the slip frequency with load.

The speed range of an IM is limited by its pull-out torque at high speed. As will be evident from (2), the pull-out torque is proportional to the square of the flux-linkage and inversely proportional to the stator and rotor leakage inductances. In the flux-weakening region, the flux reduces with increasing frequency, the consequent reduction in the pull-out torque being exacerbated by the fall in the voltage across the magnetizing reactance due to the influence of the leakage reactance. Therefore, to obtain a wide speed range, it is again beneficial to minimize the leakage reactance. In [10], for example, this was achieved by:

a) increasing the width of the stator slot openings to reduce the stator slot leakage flux;
b) increasing the air-gap length to reduce the harmonic leakage flux;
c) employing relatively wide, open rotor slots to reduce the rotor slot leakage flux;
d) not employing skew so as to eliminate skew leakage;
e) employing a copper cage (Fig. 4).

A significant improvement in the available torque at maximum speed was then achieved (Fig. 5).

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**Fig. 4. IM traction machine [10]. Rating: 120 Nm, 11.5 kW at maximum speed of 7600 rpm, 26 kW at base-speed of 2020 rpm.**

**Fig. 5. Torque-speed curve of IM for traction drive [10].**
Over the maximum envelope of the torque/power-speed characteristic, encompassing both constant torque and constant power operating modes, the copper loss only varies slightly with speed. In contrast, initially the iron loss increases with speed and is a maximum at the base speed, after which it gradually reduces as the degree of flux-weakening is increased. It is well known that when the iron loss and copper loss are similar the efficiency will be maximized. Therefore, an IM for traction applications should be designed such that the iron loss is higher than the copper loss at around the base speed, and vice versa at low and high speeds [9]. In this way, a high efficiency can be maintained over the entire operating speed range by incorporating optimal flux control, i.e., by reducing the flux level at low torque, as will be discussed later, since the most frequent operating condition generally demands low torque around base speed.

C. Optimal Flux, Maximum Efficiency, and Minimum Acoustic Noise

High-efficiency operation is a very important issue for traction drives. The optimal flux level for maximum efficiency varies directly with the torque and inversely with the speed [11]. Thus, at low torque it is advantageous to reduce the flux in an optimal manner in order to reduce the iron loss and maximize the efficiency. However, as the torque level is increased the flux must be simultaneously increased until the rated flux level is attained; otherwise, the copper loss will increase excessively due to the low torque per ampere. If optimal flux control is employed, a significant efficiency improvement is achieved at all loads in both constant torque and constant power modes [11]–[13]. Above base speed, in the constant power mode, the flux naturally reduces since it is inversely proportional to the speed due to the limited inverter voltage.

Optimal flux control for maximum efficiency also results in lower acoustic noise [14], which, in general, increases with both the load and the flux. By way of example, Fig. 6 shows the variation of the sound pressure level with flux and load, for a constant stator fundamental frequency. It will be observed that:

1) under the same flux level, the sound pressure level increases with load;
2) at light loads, a reduction in the flux can significantly reduce the acoustic noise; however, as the load is increased the noise can increase as the flux is reduced;
3) the optimal flux level for the lowest noise emissions increases with the load.

Since both vector control and direct torque control, either indirectly or directly, control the flux and torque, optimal flux control can be readily exercised. However, the optimal flux level for each specific torque and speed usually has to be determined experimentally, since no general and simple analytical method is available [11].

III. SWITCHED RELUCTANCE MACHINES (SRMs)

A. Features of SRMs

The design and operational features of SRMs are well-documented [15], [16], and may be summarized as follows.

- Simple, robust rotor structure, without magnets or windings, which is desirable for high-temperature environment and high-speed operation. However, it can have a significant rotor iron loss.
- Potentially low cost, although relatively high manufacturing tolerances are required due to the need for a small air gap.
- Modest short-duration, peak torque capability as the magnetic circuit tends to be relatively highly saturated.
- Smooth operation at low rotational speeds requires relatively complex profiling of phase current waveforms and accurate measurement of rotor position.
- Unipolar operation requires nonstandard power electronic modules, but SR drives have an inherent degree of fault tolerance.
- Since their operating is based on the sequential excitation of diametrically opposite stator coils in machines having the basic 6/4 and 8/4 stator/rotor pole number combinations, the acoustic noise, vibration, and torque ripple tend to be relatively high.

The high-speed operating capability of SRMs, their relatively wide constant power capability, and the minimal effects of temperature variations offset, to some degree,
their relatively lower power factor. Thus, SRMs have significant potential for use in vehicle propulsion systems [7], [17]–[19].

Typical SRMs are shown in Fig. 7, together with one phase leg of the inverter. When a stator pole is aligned with a rotor pole, the phase inductance is a maximum, while in the unaligned position the inductance is a minimum. When operated as a motor, the phase windings are excited during the period when the inductance is increasing as the rotor rotates. When operated as a generator, the phases are commutated on and off during the period when the inductance is reduced as the rotor rotates. The higher the ratio of the aligned inductance to the unaligned inductance, the higher the torque/power capability. In general, it requires the rotor pole arc to be slightly wider than that of the stator poles. Comparatively, SRMs have relatively few feasible stator/rotor pole number combinations (6/4, 8/6, and integer multiples thereof being the most common). Further, the stator poles are generally parallel-sided and carry a concentrated coil, as illustrated in Fig. 7. However, several alternative SRM topologies have been proposed, of which the long-pitched winding SRM [20] which utilizes the variation of the winding mutual inductances, rather than the variation of the phase self-inductances, to produce torque, and the segmented rotor SRM [21] are arguably the most notable, since they may produce a similar torque density to that of conventional SRMs.

B. Operational Characteristics

SRMs are usually operated in the discontinuous current mode, although continuous current operation may be advantageous under certain operating conditions. As was shown in Fig. 3, three operational modes generally exist for traction drives. Thus, in the constant torque region I, the phase currents are controlled by PWM to produce the desired output torque, the peak torque capability depending on:

1) the allowable maximum current from the inverter;
2) the rate of rise of the current after a phase winding has been commutated on;
3) the degree of saturation in the magnetic circuit;
4) the allowable temperature rise.

Thus, a high overload capability requires thicker stator and rotor back-iron and appropriate thermal management. Above base speed in the constant power region, when the inverter supply voltage is limited, commutation advance is required. Thus, both the turn-on and turn-off angles are gradually advanced as the speed is increased, and the machine eventually enters the single pulse mode of operation. When the machine is motoring, the peak current is determined solely by the turn-on angle, while when generating, both the turn-on and turn-off angles influence the peak current [22]. At very high rotational speeds, i.e., region III of Fig. 3, further commutation advance is limited due to the influence of the back-EMF and the winding inductance, since the phase current waveforms become continuous. However, as will be described later, by employing two-phase overlapping excitation and continuous conduction the power capability at high rotational speeds can be enhanced. Clearly, the foregoing operational characteristics of an SRM are appropriate for traction applications.

C. Constant Power Operation

An SRM is capable of extended constant power operation, typically up to 3–7 times the base speed [23]. This is usually achieved by phase advancing the excitation until overlap between successive phase currents occurs.

The high-speed performance of an SRM depends heavily on the rotor pole design, and in general, requires a compromise between the constant torque and constant power capabilities. For example, in [23] it was shown that when the leading dimensions of 6/4 and 8/6 SRMs were fixed, and the rotor pole arc was varied, the constant power range was extended to > 6 times base speed when the rotor pole arc was narrower than the stator pole arc and the depth of the rotor pole was relatively large. However, the machines under consideration had relatively low torque densities. The constant power capability also depends on the number of stator and rotor poles. When the number is increased the constant power capability and the overload capability are reduced, albeit the higher the torque/power density and the higher the power factor and efficiency. By way of example, [23] shows that a 6/4 machine exhibits a much wider constant power range (viz. up to ~7 times base speed) than an 8/6 machine (viz. up to ~4 times base speed), which compares to a constant power operating speed range of ~2 times base speed for a 24/16 SRM [18]. Often, however, the number of stator and rotor poles is dictated by the space envelope constraints. In summary, not only is the ratio of the aligned to unaligned inductance reduced as the number of stator and rotor poles is increased, but the constant power operating speed range is compromised due to the limited scope for phase advancing, and although the constant power performance could be enhanced by reducing the number of turns per phase,
this compromises the torque capability for a given inverter voltage-ampere rating.

Alternatively, the extended high-speed constant power operation can be improved with continuous phase current excitation, by increasing the number of turns per phase. The torque per ampere capability below base-speed is then not significantly compromised, as has been demonstrated for a 24/16 SRM [24] and an 18/12 SRM [25] (Fig. 8), which shows an SRM which was developed for a mild hybrid vehicle application.

The use of conduction overlap between two phases to increase the torque and to reduce torque pulsations is common practice [6]. Fig. 9 illustrates overlapping conduction by advancing [6] or retarding [24] long-dwell commutation [15], both also incorporating phase advance.

Bipolar excitation (Fig. 10) [6], [22], [26] can also be employed to improve the torque density and reduce torque pulsations, as well as to increase the efficiency. The long flux paths that are associated with SRMs supplied from conventional unipolar drives then become short flux paths, and the torque and efficiency are significantly enhanced at both low and high speeds. However, the improvement in performance gradually reduces as the excitation current is increased and the magnetic circuit becomes more highly saturated.

Finally, a control strategy which employs freewheeling diodes in parallel with the power switching devices in a conventional half-H-bridge inverter together with an appropriate zero-voltage period (Fig. 11) can also be used to boost the power capability when an SRM is operated as a generator [22], [27].

![Fig. 8](image1.png)

**Fig. 8.** SRM with integrated flywheel and clutch for mild-hybrid vehicle [25]. Cranking: 45 Nm (0–300 rpm), continuous motoring: 200 Nm (300–1000 rpm), transient motoring: 20 kW (1000–2500 rpm), continuous generating: 15 kW (600–2500 rpm), transient generating: 25 kW (800–2500 rpm). (a) Schematic. (b) Rotor/stator without winding. (c) Assembled unit.

![Fig. 9](image2.png)

**Fig. 9.** Overlap excitation techniques for extending constant power operating range. (a) Conventional excitation at high speed with phase advance. (b) Overlapping excitation with commutation advanced. (c) Overlapping excitation with commutation retarded.

![Fig. 10](image3.png)

**Fig. 10.** (a) Conventional excitation. (b) Bipolar overlapping excitation.
D. Acoustic Noise, Torque Ripple, and Their Reduction

The acoustic noise which is radiated from an SRM is often cited as a major disadvantage. At low rotational speeds the acoustic noise is due predominantly to resonances that are induced by the torque ripples, and may be reduced by appropriate profiling of the phase current waveform. The key to obtaining the optimal current profile is an effective method for estimating the instantaneous torque. At high rotational speeds the acoustic noise is dominated by radial vibration resonances [28]. The acoustic noise becomes significantly higher at high rotational speeds and loads. However, various techniques have been proposed for reducing the vibration and acoustic noise. The most effective method is to employ a relatively thick stator yoke [29], [30] since this increases the mechanical stiffness and, thereby, reduces the vibrational response. However, the outer diameter is then increased, but this, in general, is advantageous in improving the overload capability since the stator yoke becomes less saturated. Reducing the supply voltage is also usually helpful in reducing the acoustic noise at light load. SRMs also generate significantly lower noise when operated under voltage control rather than current control, due to the fact that random switching of the current controller results in a wide-band harmonic spectra, thereby increasing the likelihood of inducing mechanical resonances [31], [32]. In [33], the relationship between the vibration of the stator and the rate of change of the phase currents at turn-off was highlighted, while a current shaping algorithm to limit the rate of change of current at turn-off and, thereby, achieve a smoother radial force waveform was described in [34] and [35]. However, the method proposed in [36] is arguably the most effective, in that it introduced a zero-voltage loop between two step changes in the applied voltage, such that, together with a knowledge of the stator natural frequencies, anti-phase stator vibrations were induced. However, it has limitations [37], since, while it is very effective when SRMs are operated in both single pulse mode and PWM voltage control, it is much less effective with PWM current control, since this results in a varying PWM switching frequency. A fixed frequency current controller can, however, alleviate the problem. Further, the technique is less appropriate for application to SRMs which exhibit multiple resonances. The vibration and acoustic noise can also be reduced [38] by employing two-phase overlapping excitation, which, as stated earlier, is beneficial for extending the constant power operating range. In general, however, the acoustic noise emissions from SRMs remain a significant issue.

IV. PERMANENT-MAGNET BRUSHLESS MACHINES

A. Brushless DC and AC Machines and Drives

Due to the permanent-magnet excitation, PM brushless machines are inherently efficient [39]–[48]. They are generally classified as being either sinusoidal or trapezoidal back-EMF machines [48] (Fig. 12). The corresponding control strategies are usually classified as being either brushless DC (BLDC), or brushless AC (BLAC). In a BLDC drive, the phase current waveforms are essentially rectangular, while in a BLAC drive the phase current waveforms are essentially sinusoidal. Ideally, in order to maximize the torque density and minimize torque pulsations, it is desirable to operate a machine which has a trapezoidal back-EMF waveform in BLDC mode, and a machine which has a sinusoidal back-EMF waveform in BLAC mode. In practice, however, the back-EMF waveforms may depart significantly from the ideal, and, indeed, irrespective of their back-EMF waveform PM brushless machines may be operated in either BLDC or BLAC mode, although the performance, in terms of efficiency and torque ripple, for example, may be compromised. Similar to induction machine drives, when operating at low torque an optimal flux level exists for minimum iron and copper loss, and hence, maximum efficiency.

Fig. 13 shows a schematic of a typical PM brushless drive. In both BLDC and BLAC drives, rotor position information is necessary, although the required position
resolution is different. For BLDC drives, in which the phase currents only have to be commutated on and off, low-cost Hall sensors are often employed, while for BLAC drives, in which the phase current waveforms have to be precisely controlled, a relatively high-cost resolver or encoder would be generally used. In addition, however, numerous sensorless techniques have recently been developed or are under development for both BLDC and BLAC drives.

Although various rotor topologies and stator winding dispositions may be employed, BLDC machines predominantly have surface-mounted magnets on the rotor, and a concentrated nonoverlapping, fractional-slot, stator winding [Fig. 14(a)]. This results in short end-windings and, therefore, a low copper loss, and the potential for a high torque density, while a six-step inverter can be employed with PWM current chopping. Two-phase, 120°/60° conduction is the most common operational mode for a three-phase BLDC machine, while maximum torque per ampere in the constant torque region and extended speed operation can realized by advancing the commutation (Fig. 15). Similar operational characteristics can be obtained in a BLAC drive by controlling the phase currents in such a way that they produce a demagnetizing component of armature reaction, which reduces the effective back-EMF by flux-weakening.

Various design features may be employed to obtain a sinusoidal back-EMF waveform. For example, the stator slots and/or rotor magnets may be skewed, a distributed stator winding might be employed, or the permanent magnets could be appropriately shaped or magnetized, etc. However, a distributed overlapping winding [Fig. 14(b)], results in longer end-windings, which results in a higher copper loss and a lower torque density, while skewing of either the stator or rotor makes manufacture more complicated. Hence, it is often preferable to either shape the magnets or impart a sinusoidal magnetization distribution [49], which results in an essentially sinusoidal air-gap field distribution, which is conducive to a low cogging torque and also a low iron loss. The rotor back-iron in a self-shielding, sinusoidal magnetized PM machine [49] is not essential since negligible flux flows within the inner bore of the magnet. This is, therefore, also conducive to a low rotor inertia, which can be an important consideration. Recently, however, there has been a trend to employ a fractional ratio of slot number to pole number and a concentrated stator winding for BLAC motors so as to achieve a sinusoidal back-EMF waveform and a low cogging torque. However, when the slot number per pole is fractional, the reluctance torque is usually relatively small with a concentrated stator winding. In order to utilize the saliency, an overlapping stator winding is usually required [Fig. 14(b)], as will be discussed in Section IV-D.

Dq-axis theory can be used to analyze the electromagnetic performance of a BLAC machine, and the optimal relationship between the d-axis and q-axis currents in vector control and flux-weakening control strategies being determined analytically [50], BLAC motors are relatively

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**Fig. 13. Schematic of PM brushless drive.**

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**Fig. 14. Stator winding dispositions. (a) Nonoverlapping winding. (b) Overlapping winding.**

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**Fig. 15. Torque-speed characteristics of PM brushless machines.**
easy to control and exhibit excellent performance, in terms of maximum torque per ampere control and optimal extended speed operation [51]–[53]. In contrast, the control strategy to realize constant power operation for a BLDC drive is generally more complex.

As was shown in [54] and [55], above the base-speed the maximum achievable output power and torque when a machine is operated in the BLAC mode are higher than that which can be achieved when the same machine is operated in two-phase, 120° elec. conduction BLDC mode, irrespective of whether it has a trapezoidal or sinusoidal back-EMF waveform (Fig. 16). At high speed, the phase current waveform will approximate to a sinusoid even in a BLDC drive, due to the influence of the winding reactance, while any harmonics in the back-EMF waveform will cause the flux-weakening performance to deteriorate. However, by employing a three-phase, 180° elec. conduction strategy, the high-speed power capability of a BLDC machine can be improved, although below base-speed its torque capability will be reduced [48], [55]–[58], as illustrated in Figs. 17 and 18.

B. Permanent-Magnet Brushless Machine Topologies

In this section, the basic topologies of PM brushless machine, classified according to the location of the permanent magnets, are described.

1) Radial-Field Machines—Permanent Magnets on Rotor: A radial-field PM brushless machine may have either an internal rotor or an external rotor, while the PMs may be located either on the surface or the interior of the rotor.

a) Surface-Mounted Permanent-Magnet (SPM) Machines: This is the most widely used topology for PM brushless machines [Fig. 19(a-1)]. However, since the d-axis and q-axis stator winding inductances of such machines are the same, they exhibit zero reluctance torque. Further, in general, the armature reaction field is relatively small and the stator windings have a low inductance, since the magnet has a relative permeability which approximates to that of air, i.e., $\mu_r \approx 1$, and the effective air gap is the sum of the actual air gap length and the radial thickness of the magnets. However, the magnets are exposed directly to the armature reaction field, and, hence, are susceptible to partial irreversible demagnetization. SPM machines are also generally to have a relatively limited flux-weakening capability. However, the flux-weakening capability, as well as the merits of PM machines having a fractional number of slots per pole and a concentrated stator winding, will be discussed later.

Fig. 19(a-2) shows a schematic of a motor in which the magnets are inset into the rotor surface. The magnet pole-arc is, therefore, less than a full pole-pitch. However, since the q-axis inductance is now greater than the d-axis inductance, a reluctance torque can be developed.

b) Interior Permanent-Magnet (IPM) Machines: Fig. 19(b) shows examples of brushless machines in
which the magnets are accommodated within the rotor. In Fig. 19(b-1) the magnets are radially magnetized, while in Fig. 19(b-2) they are circumferentially magnetized. Generally speaking, however, leakage flux from the magnets is significantly greater than that in SPM machines. However, since the magnets are buried inside the rotor iron, the magnets are effectively shielded from the demagnetizing armature reaction field during flux-weakening operation. Further, since the \( d \)-axis inductance is smaller than the \( q \)-axis inductance, a reluctance torque exists, while the \( d \)-axis inductance is high compared with that of an equivalent surface-mounted magnet motor topology. Therefore, generally, such machine topologies are eminently appropriate for extended speed, constant power operation in the flux-weakening mode [48], [51]. Indeed, a variant of the topology illustrated in Fig. 19(b-1) is employed in the Toyota hybrid vehicle [4], Fig. 20. The V-shaped disposition of the permanent magnets serves to increase the air gap flux and the distributed stator winding enables the reluctance torque to be utilized.

Multiple layers of magnets may also be employed to further increase the saliency ratio, although, in practice, the number of layers is usually limited to \( \leq 3 \). An extreme case, however, is to employ an axially laminated PM rotor in which permanent-magnet sheets are sandwiched between the laminations [60]. In this way, a small volume of permanent-magnet material, which is generally a bonded ferrite or rare-earth, such a machine can exhibit an extremely wide flux-weakening capability and a high torque density, without the risk of generating an excessive back-EMF should an inverter fault occur at high rotational speeds. However, such a rotor structure is relatively complex and expensive to manufacture [61], [62].

A virtue of the rotor topology shown in Fig. 19(b-2) is that, when the pole number is relatively high, flux focusing can be exploited and the air-gap flux density can be significantly higher than the magnet remanence. Hence, low-cost, low-energy product magnets, such as sintered ferrite, may be employed. By way of example, Fig. 21 shows a generator, which was developed for an electric vehicle auxiliary power unit [63]. Flux-focusing enables an air-gap flux density of 0.6 T to be achieved when sintered ferrite magnets, having a remanence of 0.38 T are employed. Such a machine topology also exhibits a higher \( d \)-axis inductance since the armature reaction flux only passes through a single magnet, rather than two magnets as in the other machine topologies, making it very suitable for extended constant power operation.

2) Radial-Field Machines—Permanent Magnets on Stator: When the permanent magnets are located on the stator, the rotor must have a salient pole geometry, similar to that of an SR machine, which is simple and robust, and suitable for high-speed operation. The stator carries a nonoverlapping winding, with each tooth having a concentrated coil. The permanent magnets can be placed on the inner surface of the stator teeth, sandwiched in the stator teeth, or mounted in the stator back-iron. Irrespective of their location, however, the torque results predominantly from the permanent-magnet excitation torque, i.e., the reluctance torque is negligible, although the torque production mechanism relies on the rotor saliency. Compared with conventional permanent-magnet brushless machine topologies, generally, it is easier to limit the temperature rise of the magnets as heat is dissipated more effectively from the stator.

a) Permanent Magnets in Stator Back-Iron—Doubly Salient PM Machine: The machine topology which is shown in Fig. 22(a) is referred to as a doubly salient...
permanent-magnet machine. For a three-phase machine a magnet is required in the stator back-iron for every three teeth, while for a four-phase machine a magnet is required for every four teeth. The variation of the flux-linkage with each coil as the rotor rotates is unipolar, while the back-EMF waveform tends to be trapezoidal [64]. Thus, this topology is more suitable for BLDC operation. However, the rotor may be skewed in order to obtain a more sinusoidal back-EMF waveform to make it more appropriate for BLAC operation. Further, it will be noted that the air-gap reluctance as seen by the permanent magnets is essentially invariant with the rotor position. Therefore, the cogging torque is not significant. However, a major disadvantage is that, due to the unipolar flux-linkage, the torque density is relatively poor compared to that of other PM brushless machines [65], although, as was reported in [66], it can still be higher than that of an induction machine.

b) Permanent Magnets on Surface of Stator Teeth—Flux-Reversal Permanent Magnet Machine: This machine topology is also commonly referred to as a flux-reversal PM machine [Fig. 22(a)] [67], [68]. Each stator tooth has a pair of magnets of different polarity mounted at its surface. When a coil is excited, the field under one magnet is reduced while that under the other is increased, and the salient rotor pole rotates towards the stronger magnetic field. The flux-linkage with each coil reverses polarity as the rotor rotates. Thus, the phase flux-linkage variation is

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**Fig. 21.** Generator for EV auxiliary power unit [63]. 9 kW at 4200 rpm, sintered ferrite magnets (remanent = 0.38 T), max. air-gap flux density: 0.6 T. (a) Stator. (b) Rotor. (c) Flux distribution.

**Fig. 22.** Alternative radial-field PM machine topologies with magnets on stator. (a) Magnets in stator back-iron—doubly salient PM machine. (b) Magnets on surface of stator teeth—flux-reversal PM machine. (c) Magnets in stator teeth—flux-switching PM machine.
bipolar, while the phase back-EMF waveform is, again, essentially trapezoidal. Such a machine topology exhibits a low winding inductance, while the magnets are more vulnerable to partial irreversible demagnetization. In addition, significant induced eddy-current loss may be induced in the magnets, which also experience a significant radial magnetic force. Further, since the air-gap flux density is limited by the magnet remanence, the torque density may be compromised.

c) Permanent Magnets in Stator Teeth—Flux-Switching PM Machine: This machine topology is also referred to as a flux-switching permanent-magnet machine [Fig. 22(c)] [69]–[71]. The stator consists of “U”-shaped laminated segments between which circumferentially magnetized permanent magnets are sandwiched, the direction of magnetization being reversed from one magnet to the next. Each stator tooth comprises two adjacent laminated segments and a permanent magnet. Thus, flux-focusing may be readily incorporated, so that low-cost ferrite magnets can be employed [70]. In addition, in contrast to conventional PM brushless machines, the influence of the armature reaction field on the working point of the magnets is minimal. As a consequence, the electric loading of flux-switching PM machines can be very high. Therefore, since the phase flux-linkage waveform is bipolar, the torque capability is significantly higher than that of a doubly salient PM machine [65]. The back-EMF waveform of flux-switching PM machines is essentially sinusoidal, which makes them more appropriate for BLAC operation. In addition, since a high per-unit winding inductance can readily be achieved, such machines are eminently suitable for constant power operation over a wide speed range.

3) Other PM Brushless Machine Topologies

a) Axial-Field Machines: Axial-field PM machines have an axially directed air-gap flux [72], [73] and can comprise a single-sided stator and a single rotor, a double-sided stator and a single rotor, or a single stator and a double-sided rotor. In each case, a large axial force exists between the stator and the rotor. As with conventional radial-field PM brushless machines, the stator can be slotted or slotless, although it is more difficult to manufacture a slotted stator for axial-field machines. Thus, slotless designs are more common. However, while this eliminates cogging, it exposes the winding air-gap flux. Hence, a multistranded conductor or Litz wire may be required to minimize the eddy-current loss. Further, since the effective air gap is large, the winding inductance is generally relatively small, which may limit the constant power speed range.

b) Transverse-Flux Machine: Generally, transverse flux machines have a relatively large number of poles, all of which interact with the total ampere-conductors of each phase. This enables very high electric loadings and, hence, high torque densities to be achieved [74]–[78]. However, they have a significant leakage flux and a relatively high winding inductance, as well as a poor power factor [79], [80]. This impacts significantly on the associated VA rating of the power electronics converter, which has inhibited its application.

C. Design and Control Issues for PM Brushless Traction Machines

As stated earlier, traction machines are required to have a high torque density, a high overload capability, a wide operating speed range, and a high efficiency, while it is desirable that they have a degree of a high fault tolerance and are low cost. In this section, design considerations related to the above issues are discussed. However, they often contradict each other. For example, reduction of the cross-coupling magnetic saturation may also reduce the saliency ratio and consequently the reluctance torque; the selection of the base-speed is usually a compromise between the constant torque performance at low speed and the constant power performance at high speed.

1) Torque Density and Overload Capability: The general torque equation for a PM brushless machine, which has both excitation torque and reluctance torque components, is given by

\[ T = \frac{3}{2} p [\psi_m I_q - (I_q - L_d) I_d I_q] \]  

(5)

where \( p \) is the number of pole-pairs, \( \psi_m \) is the stator winding flux-linkage due to the permanent magnets, and \( L_d, I_q \) and \( I_d, I_q \) are the \( d \)- and \( q \)-axis inductances and currents, respectively. In order to maximize the torque density, it is desirable to increase \( \psi_m \) by reducing the leakage flux. This can be achieved by introducing airspace flux barriers or interpole magnets, as illustrated in Fig. 23. \( \psi_m \) can also be increased by utilizing flux focusing [4], [63], as illustrated in Fig. 24. The torque density can also be enhanced by increasing the saliency ratio [3], [81], as illustrated in Fig. 25. Further, since the short-duration torque capability is determined primarily by the demagnetization withstand capability of the magnets and the level of magnetic saturation, reducing the \( d \)- and \( q \)-axis cross-coupling magnetic saturation by incorporating air flux barriers, as illustrated in Fig. 26, can enhance the overload capability.

2) Flux-Weakening Capability: It is well known [62], [82] that the maximum flux-weakening capability, defined as the ratio of the maximum speed to the base-speed, under supply inverter voltage and current limitations, can be achieved when a PM brushless machine is designed to have 1.0 per-unit \( d \)-axis inductance such that

\[ L_d = \frac{\psi_m}{I_r} \quad \text{or} \quad \frac{L_d I_d}{\psi_m} = 1 \]  

(6)
where $\psi_m$ is the stator flux-linkage due to the magnets, $L_d$ is the $d$-axis inductance, and $I_r$ is the rated current.

Although it is possible to design a PM brushless machine which satisfies the foregoing requirement, generally, for most PM machines $L_d I_r / \psi_m < 1$, since the $d$-axis inductance is relatively low as a consequence of the recoil permeability of the magnets being approximately equal to 1.0. Nevertheless, the higher the ratio of $L_d I_r / \psi_m$ the higher will be the flux-weakening capability [Fig. 27(a)], which, theoretically, is “infinite” when the ratio is 1.0. However, the higher the flux-linkage $\psi_m$ to achieve a high low-speed torque capability, the more difficult it is to realize wide-speed operation (Fig. 27) [83].

In [62], it was shown that it was possible to design any PM brushless machine to achieve “infinite” flux-weakening capability. Clearly, however, if the rated current is high (e.g., the machine is liquid cooled), it is...
much easier to satisfy (6), even for surface-mounted magnet machines, which have a high \( \psi_m \) and a relatively low \( L_d \). For example, in [84] “infinite” flux-weakening capability was achieved with an SPM machine equipped with a self-shielding, sinusoidal magnetized rotor having no back-iron, and in [85] with an SPM machine in which only alternate stator teeth carried a coil. However, in general, it is much easier to achieve a wide operating speed range with machines equipped with an interior permanent magnet rotor, since generally \( m \) is lower, while \( L_d \) is higher.

3) Demagnetization Withstand Capability: Operation in the flux-weakening mode is a necessary requirement for traction applications, while NdFeB is the most commonly employed permanent-magnet material for PM brushless machines. However, the magnets are required to have an adequate demagnetization withstand capability at the maximum operating temperature, when they are most vulnerable to partial irreversible demagnetization. In addition to effective thermal management, one means of enhancing the demagnetization withstand capability is to provide a low reluctance path for the demagnetizing d-axis armature reaction flux such that it does not pass through the magnets. One example of achieving this is to employ narrower stator slot openings and thick tooth-tips, as illustrated in Fig. 28(a), or thick rotor slot bridges in an IPM machine, as illustrated in Fig. 28(b). However, such features will also have an influence on \( \psi_m \) and \( L_d \). In general, however, it is easier to realize a high demagnetization withstand capability for IPM machines. Nevertheless, it has been shown [86] that, by careful design, the magnet working point in an SPM machine can remain reasonably high up the magnet demagnetization characteristic, even when the machine has “infinite” flux-weakening capability, due to the fact that 1.0 per-unit \( d \)-axis inductance results primarily from stator slot leakage and end leakage fluxes.

4) Rotor Eddy-Current Loss: PM BLAC and BLDC machines are usually considered to have negligible rotor loss. However, the rotor loss may be important in machines equipped with surface-mounted magnets, in terms of the resulting temperature rise. Eddy currents may be induced in the permanent magnets, the rotor back-iron, and any conducting sleeve which may be employed to retain the magnets, by time and space harmonics in the air-gap field. More specifically, they result from [87]: a) stator slotting; b) stator MMF harmonics which do not rotate in synchronism with the rotor; and c) nonsinusoidal phase...
current waveforms, which result from six-step commutation and PWM.

In general, however, the rotor eddy-current loss is relatively small compared with the stator copper and iron losses. Nevertheless, it may cause significant heating of the magnets, due to the relatively poor heat dissipation from the rotor. In turn, this may result in partial irreversible demagnetization, particularly of sintered NdFeB magnets, which have relatively high temperature coefficients of remanence and coercivity and a moderately high electrical conductivity. It is particularly important to consider the rotor eddy-current loss in a) machines with a high fundamental frequency, e.g., high-speed and/or high-pole number; b) machines with large stator slot openings, e.g., transverse flux machines; c) high power density brushless dc machines, e.g., force-cooled traction machines with a high electric loading; and d) machines whose windings span a fractional pole-pitch and which have nearly equal pole and slot numbers [88]. If the eddy-current loss is unacceptable, the magnets may be segmented, axially and/or circumferentially [89].

5) Stator Iron Loss: Due to the fixed PM excitation, the no-load iron loss increases with the rotational speed, while the full-load iron loss in the constant torque operating range is generally around 20%–50% higher. However, the iron loss which results on load in the flux-weakening mode depends on the machine topology, as illustrated in Fig. 29. In general, SPM machines have the lowest full-load iron loss, and despite the increase in fundamental frequency it usually becomes much lower than the no-load iron loss as the degree of flux-weakening

![Fig. 28. Improvement of demagnetization withstand capability by introducing d-axis armature reaction demagnetization flux path. (a) SPM stator design. (b) IPM rotor design.](image)

![Fig. 29. Variation of iron loss in SPM and IPM machines when their open-circuit stator iron loss are designed to be the same.](image)
is increased [90]. IPM machines generally have a significantly higher full-load iron loss, which may be comparable to or higher than the no-load iron loss, since the armature reaction field has a higher harmonic content due to the small effective air gap [90], [91]. However, when the magnets are simply inset into the rotor surface the harmonic content in the armature reaction field increases further, and generally results in the highest full-load iron loss [86].

6) Fault-Tolerance: An important consideration when operating in the extended speed, flux-weakening mode is the consequence of an inverter fault which results in the loss of the demagnetizing armature reaction field and an excessively high back-EMF [92], [93]. In this regard, IPM machines may be advantageous, since, for a given output torque, the PM excitation torque, and, hence, the volume of magnet material and the maximum back-EMF are lesser. However, the consequences of an inverter fault occurring when a PM brushless machine is operating in the flux-weakening region remains a challenging issue.

D. Recent Developments

1) Fractional Slot Machines: SPM brushless machines which have a fractional number of slots per pole and a concentrated winding have been the subject of recent research. They have an inherently low cogging torque, short end-windings and, hence, a low copper loss, a high efficiency, and a high power density, as well as excellent flux-weakening performance [85], [94]–[100]. The stator coils may be wound either on all the teeth or only on alternate teeth (Fig. 30) [95], [97]. In the latter case, the phase windings are effectively isolated, both magnetically and physically, and a high per-unit self-inductance can readily be achieved to limit the prospective short-circuit current, by utilizing the relatively high air-gap inductance and the leakage flux at the slot openings. Due to the physical separation of the coils and the negligible mutual inductance between phases, the possibility of a phase-to-phase fault is minimized. Therefore, the fault tolerance and flux-weakening capability of such machines can be significantly higher than for more conventional machine designs. Fig. 31 shows a three-phase, 24-slot, 22-pole, PM BLAC machine which was developed for a supercapacitor-based electrical torque boost system for vehicles equipped with down-sized IC engines [99]. However, since the torque is developed by the interaction of a stator space-harmonic MMF with the permanent magnets, a relatively high rotor eddy-current loss can result from both the fundamental and low-order space-harmonic MMFs which rotate relative to the rotor [88], [89]. As stated earlier, however, the magnets can be segmented to reduce the eddy-current loss. A further advantage of such machines is that, due to the fractional number of slots per pole, the cogging torque is very small without employing design features such as skew. However, the reluctance torque component is negligible even when an IPM rotor is employed.

2) Hybrid PM and Current Excitation: Since the PM excitation is fixed in a PM brushless machine, the current phase angle has to be progressively advanced as the speed is increased above base-speed so that a demagnetizing d-axis current component is produced which reduces the flux-linkage $\psi_m$ with the stator winding. Ultimately, however, this may cause partial irreversible demagnetization of the magnets. At the same time, due to the inverter voltage and current limits, the torque-producing q-axis current component has to be reduced correspondingly. Consequently, the torque and power capability are limited. Thus, a compromise has to be made between the low-speed torque capability and high-speed power capability.

Hybrid permanent magnet and field current excitation has been shown to be beneficial in improving the power capability in the extended speed range, enhancing the low-speed torque capability, and improving the overall operational efficiency. There are several ways of realizing such hybrid excitation. For example, dc winding may be located on the rotor [101] or the stator [102]–[107], which is preferable since it does not require slip-rings. The magnetic circuit associated with the dc excitation may be either in series or in parallel with the magnetic circuit associated with the PM excitation. However, although series excitation is simple it requires a higher excitation...
MMF due to the low recoil permeability of the magnets. On the other hand, parallel excitation is more effective electromagnetically but leads to a more complex machine structure. Fig. 32 shows three examples of PM brushless machines equipped with hybrid excitation, based on doubly salient pole [102], consequent-pole [103]–[105], and claw-pole [106], [107] machine topologies. The dc excitation winding enables the air-gap flux, and, hence, the torque capability, to be enhanced at low speed, to be reduced at high speed to facilitate extended speed operation, and to be optimized over the entire speed range to improve the efficiency. It also reduces the likelihood of an excessively high back-EMF being induced at high speed in the event of an inverter fault.

**Fig. 31.** Three-phase, 24-slot, 22-pole, PM BLAC machine with modular stator winding and IPM rotor [99]. Rated output power = 18.5 kW, rated speed = 1700 rpm, rated torque = 105 Nm. (a) Cross section of three-phase, 24-slat, 22-pole IPM BLAC machine. (b) Machine test rig.

**Fig. 32.** Hybrid excited PM machines. (a) Hybrid excitation based on doubly salient pole structure [102]. (b) Hybrid excitation based on consequent pole structure [105]. (c) Hybrid excitation based on claw-pole structure [106].
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V. CONCLUSION

The operational characteristics, design features, and control requirements for induction machines, switched reluctance machines, and permanent-magnet brushless machines for vehicle propulsion systems have been reviewed, with emphasis on their low-speed torque and high-speed power capability. Given that they offer a higher efficiency and torque density, particular emphasis has been given to permanent-magnet brushless machines. Various PM brushless machine topologies have been highlighted, and their relative merits have been briefly described. In general, however, all three machine technologies can meet the performance requirements of traction drives, and each machine technology has merits.

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