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Chapter 2

ELECTRIC MOTORS FOR DRIVES

In this chapter we will introduce typical electric drive configurations and various electric motors for electric drives.

2.1. ELECTRIC DRIVES - A TYPICAL CONFIGURATION

A modern electric drive [1-8] capable of controlled variable speed is made of some important parts (Figure 2.1) such as:

- the electric motor;
- the power electronic converter (PEC);
- the electric and motion sensors;
- the drive controller;
- the command interface.

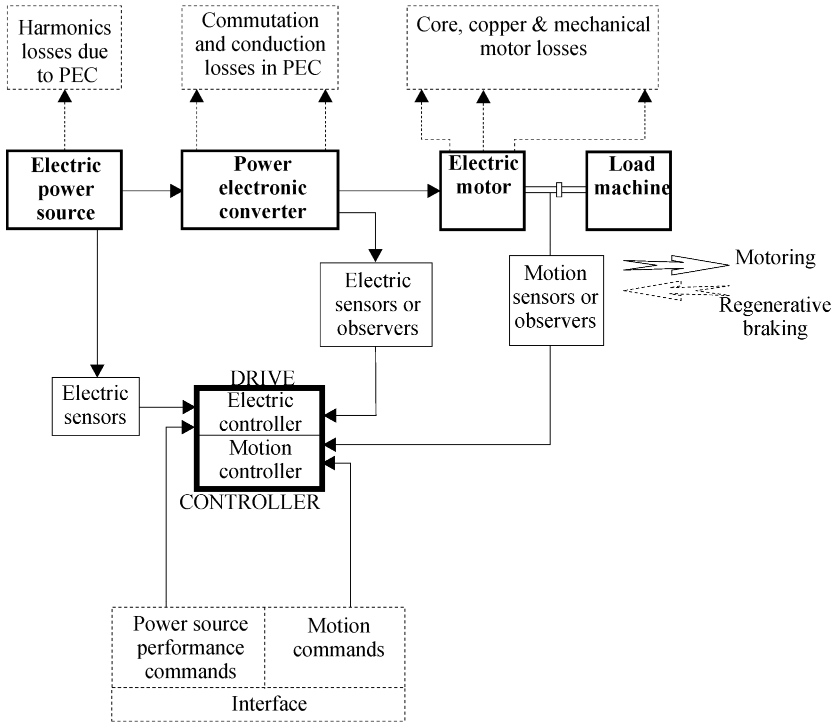


Figure 2.1. Electric drive basic topology

The drive controller may be considered to be made of motion-speed and/or position-controller, more or less the same for all types of electric drives, and the electric controller which refers to current and voltage (or flux linkage and torque) control within the PEC.

Electric sensors (observers) refer to voltage, current, flux as measured (or calculated) state variables while motion sensors (observers) mean position and/or speed and torque as measured (or calculated) state variables.

The electric controller has, in general, electric sensor (observer) inputs from both the power source and the PEC output. The motion controller handles, in general, only motion sensor (observer) outputs.

On the other hand, the electric controller commands are related to power source side energy conversion performance commands (unity power factor, harmonics elimination) while the motion controller commands relate to motion (speed, position, torque) control commands handled through an interface from a local digital controller or from a remote process control host computer. As expected, both electric and motion controllers are blended together in the drive controller hard and soft.

By now both the drive controller and the interface are carried out by high performance digital signal processors (DSPs) which can handle several MFLOP/s, not an excessive feature with modern electric drives.

In what follows in this chapter, we will briefly characterize the candidate electric motors used for drives. The various losses occurring in an electric drive (Figure 2.1) will be dealt with in relation to specific motors and PECs in subsequent chapters. The sensors will be described in some detail when applied to various electric drives. The motion controllers, more or less common to all electric drives, will have a separate chapter devoted to them in relation to DC brush motor drives.

Finally, electric controllers tend to be more specific and will be treated during discussions of applications for various electric drives.

And now a short classification of electric motors for electric drives follows.

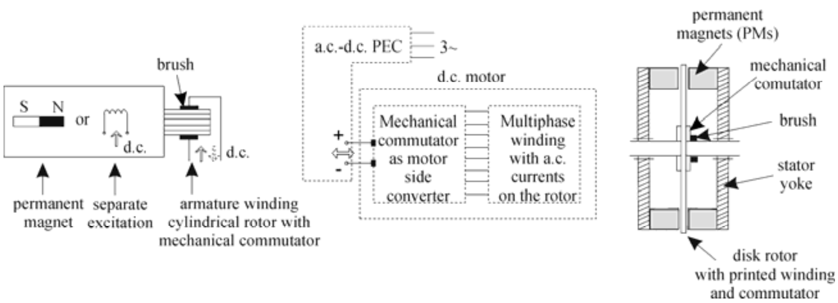
2.2. ELECTRIC MOTORS FOR DRIVES

In essence, all existing types of electric motors may be accompanied by PECs with digital motion controllers to produce high performance electric drives. The ideal speed-torque curve for motion control is a straight descending line. This fact and the ease to produce a variable DC voltage source for a wide range of speed control, had made the DC brush motor the favorite variable speed drive up to 1960. Since then the development of reliable price-competitive PECs with variable AC voltage and frequency capability and the linearization of the speed-torque curve through the so-called VECTOR CONTROL have contributed to the take over of the variable speed drive applications by AC motors. Let us start with the DC brush motor.

2.3. DC BRUSH MOTORS

A typical topology of a DC brush motor with stator PM (or electromagnetic) excitation and a rotor comprising the armature winding and the mechanical commutator with brushes is shown in Figure 2.2a. The mechanical commutator is, in fact, an electromechanical DC-AC bidirectional power flow power converter as the currents in the rotor armature coils are AC while the brush-current is DC

Figure 2.2c shows an axial airgap PM DC brush motor with a printed, winding, ironless-disk rotor and mechanical commutator with brushes. PM excitation, especially with the nonmagnetic disk rotor, yields extremely low electric time constants L/R (around or less than 1 ms in the sub kW power range). Thus quick response in current (torque) is expected, though the current (torque) harmonics are large unless the switching frequency in the PEC is not high enough.



a) b) c)

Figure 2.2. DC brush motor: a.) with cylindrical rotor;

b.) equivalence of DC motor to AC motor plus motor side power converter;

c.) with PMs and disk rotor.

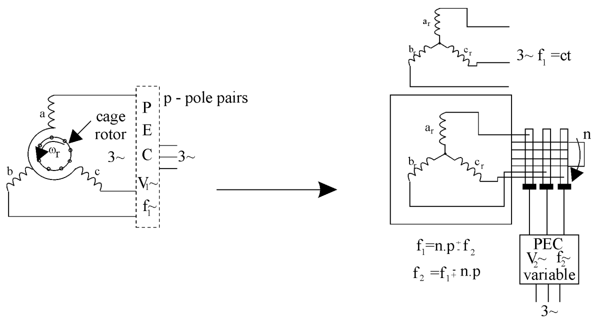
Unfortunately the mechanical commutator, though not bad in terms of losses and power density, has serious commutation current and speed limits and thus limits the power per unit to 1-2 MW at 1000 rpm and may not be at all acceptable in chemically aggressive or explosion-prone environments.

The PEC, as a DC variable voltage source (Figure 2.2b), when capable of four quadrant operation (positive and negative DC voltage and DC current output), is as complicated and as expensive as the PEC for AC motors. Moreover, fast speed reversal is quite a problem.

Still, the DC brush motors, especially with PM excitation, are and will be used for a good period of time, in numerous applications, where 1-2 quadrant operation suffices at low powers and moderate speeds.

2.4. CONVENTIONAL AC MOTORS

By conventional AC motors we mean traveling field motors — induction, synchronous with electromagnetic excitation and reluctance synchronous — that may be used either at on-line start (constant speed) or variable speed (with PEC) applications. Consequently, the rotors of all conventional AC motors have squirrel cages for asynchronous starting. Among them the induction motor (Figure 2.3a) is mostly used for variable speed drives.



a.) b.)

Figure 2.3. Three phase induction motor: a.) with a cage rotor and PEC in the stator; b.) with slip-rings wound rotor and PEC on the rotor.

A PEC system controls the voltage V_1 and frequency f_1 in the stator. This is a full power PEC and is adequate for wide speed control (below 1/2). For high power applications with limited speed control, a limited power PEC supplies the wound rotor through the slip rings (Figure 2.3b) with adequate (low) voltage V_2 and frequency f_2 while the stator is line-fed at constant V_1 and f_1.

Thus the sizing and costs of PEC drives are drastically reduced though, for full torque starting, a special arrangement is required as the PEC cannot handle directly the rather large starting rotor currents and voltages. Still the slip ring-brush mechanical system poses notable problems of maintenance and may not be used in hostile environments.

The cage-rotor induction motors cover wide power ranges from 0.5kW to 10MW while even higher powers may be handled through wound-rotor configurations.

Electromagnetically excited conventional synchronous motors have three-phase AC windings on the stator and a DC excited cage rotor with salient or nonsalient poles (Figure 2.4).

A conventional synchronous motor when used in variable speed drives requires two PECs - one full power AC-AC PEC in the stator and a low power (1-5%) AC-DC PEC that supplies, in general through slip rings and brushes, the excitation windings on the rotor. A coordinated control of the two PECs provides for speed (active power) and reactive power control and for efficient wide speed range control in high power applications (MW and tens of MW range).

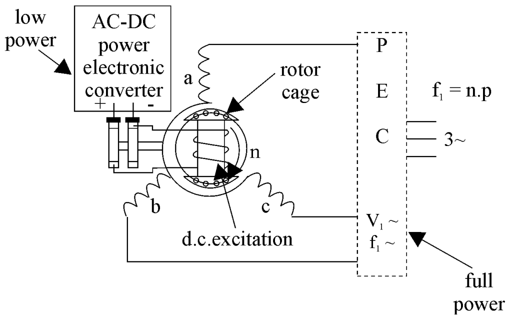


Figure 2.4. Conventional salient pole rotor synchronous motor fed through a full power PEC in the stator

Why do, above 2 MW, synchronous motors predominate over induction motors? Because the reactive power control through excitation is possibly easier with synchronous motors, and thus the requirements in this regard from the full power PECs are lower. Consequently, the PECs are simpler and less expensive and the overall costs of the drive are lower, though the synchronous motor, for comparable power and speed, is more expensive than the induction motor. The efficiency of the synchronous motor above 2 MW is also, in general, higher than that of the cage-rotor induction motor.

Conventional reluctance synchronous motors (RSMs) have a cylindrical stator with three AC windings and a windingless rotor with a moderate orthogonal axis magnetic saliency up to 4 (6) to 1. High magnetic saliency is obtained with multiple flux barriers (Figure 2.5)

A cage on the rotor is sometimes maintained for stability purposes when the motor is fed through a full power AC-AC PEC with a rigid relationship between frequency f_1 and motor speed n ($n = f_1/p$).

The conventional RSMs are to some extent (up to 100kW) used in low dynamics variable speed drives with open loop speed control as the speed does not decrease with load. Consequently, control is simpler than with induction motors.

The main drawback of the conventional RSM is the low power factor and not high enough torque density (Nm/kg), which leads to higher kVA ratings of the PEC (by 15-20%).

Besides the conventional AC motors (which may also be used for line-start constant speed applications due to the action of the rotor cage), in the last decades, new motor configurations totally PEC-dependent, have been introduced. The main types of PEC dependent motors are described below.

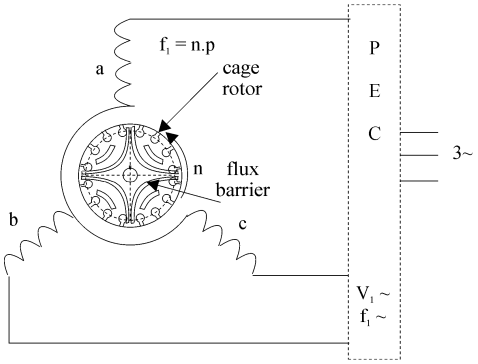


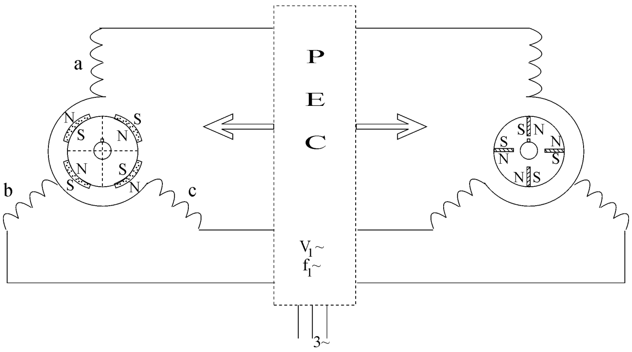
Figure 2.5. Conventional reluctance synchronous motor

fed through a full power PEC in the stator

2.5. POWER ELECTRONIC CONVERTER DEPENDENT MOTORS

Evidently PEC dependent motors can not operate without PECs. They are, in general, multiphase motors (to limit torque pulsations) and provide for self-starting from any initial position. In essence this new breed of motors may be fed through unipolar or bipolar multiphase currents in tact with the rotor position. Also they have singly salient or doubly salient magnetic structures with or without permanent magnets (PMs) on the rotor.

PEC-dependent motors with PM-rotors [13] have evolved from synchronous motors by replacing the electromagnetic excitation with high energy PMs (Figure 2.6).



a.) b.)

Figure 2.6. PM synchronous motor (PM-SM) - singly salient

a.) pole magnet rotors, b.) interpole magnet rotors

The absence of the rotor cage renders the PM-SM fully dependent on PECs as the stator frequency and rotor speed should be in synchronism at all moments.

The stator three-phase windings are concentrated (one coil/pole/phase) when rectangular bipolar current control (based on inexpensive rotor position sensors) is performed. For more refined performance (wider speed range (1/1000 range)) sinusoidal current control is performed. A more expensive precise position sensor (or observer) is needed.

For both rectangular and sinusoidal current control, nonoverlap windings have also been introduced recently (from 1 W to tens of kW power levels) to reduce copper losses and frame length and to reduce PM torque at zero current (cogging torque).

The pole magnet and interpole magnet rotors have both advantages and disadvantages as shown in the chapter on PM-SM motor drives.

The other category of PEC-dependent motors is the so-called stepper motors. In fact they are doubly salient multiphase motors with windingless rotor and unipolar position-dependent or position-independent current control through AC-DC (unipolar current) PECs (Figure 2.7).

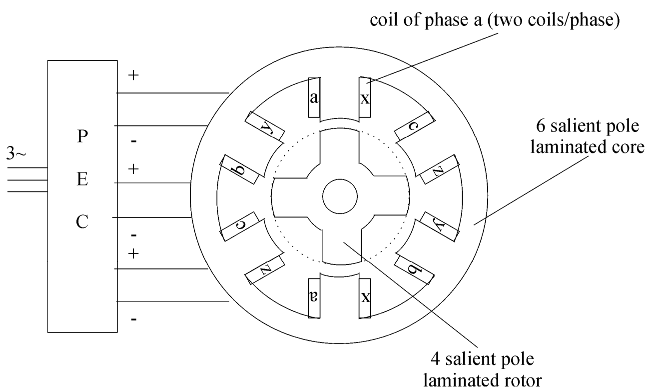


Figure 2.7. Three-phase switched reluctance 6/4 motor (SRM) - PEC dependent.

It is evident that the switched reluctance motor, SRM [14] — a commercial name for the power step motor with rotor position controlled slewing (continuous motion) — works on the principle that by sequentially supplying each phase with a current pulse when the inductance of that phase increases will produce positive torque (motoring). Regenerative braking is obtained if the phase is supplied when the inductance slope is negative. The phases are switched on and off based on position feedback (provided by a position sensor or observer) and thus torque and motion control “without loosing steps” is obtained.

The SRM has undergone more than two decades of development and seems ready now for marketing for powers from a few watts to megawatt levels, both for low and high dynamics applications. The SRM is, together with PM-SM, a competitive motor for high performance variable speed drives.

The reluctance or hybrid (PM-reluctance) stepper motors resemble the SRM and PM-SMs with rectangular current, but they rely on open-loop feed-forward (position independent) control with moderate dynamics and acceptable position precisioning by a notable increase in the number of stator and rotor poles and the number of phases (4-5 in general).

Stepper motors refer to low power positioning applications only. For more details on stepper motors, please see [15].

PM-SM and SRM drives will be devoted separate chapters in this book.

Other cageless rotor converter-dependent motors are spin-offs from electromagnetically-excited synchronous motors (SM), induction motors (IM), reluctance synchronous motors or doubly salient motors RSM (by adding PMs on the rotor or on the stator).

Despite of their severe torque pulsations, single phase PM synchronous (brushless) motors, as well as single phase SRM drives, configurations are being gradually introduced in low power (for home appliances or small electric actuators on cars) applications to cut costs by reducing the number of controlled power electronic switches in the static converter.

They will be discussed later, (briefly), in pertinent chapters.

2.6. ENERGY CONVERSION IN ELECTRIC MOTOR/GENERATORS

In all systems where mass is not destroyed or produced, the principle of energy conservation holds. So energy is not created nor destroyed, it is only converted from one form into another. This principle, together with the Faraday, Ampere, Gauss, Ohm and Newtonian mechanical laws and theory of electric circuits govern the electro-mechanical energy conversion in electric motor-generators.

The electromechanical energy conversion in electric motor – generators, implies a few forms of energy:

$$\left\langle \begin{matrix} \text{Energy form} \\ \text{electrical source}(\pm) \end{matrix} \right\rangle = \left\langle \begin{matrix} \text{mechanical} \\ \text{energy}(\pm) \end{matrix} \right\rangle + \left\langle \begin{matrix} \text{stored} \\ \text{magnetic} \\ \text{energy} \\ \text{increase} \end{matrix} \right\rangle + \left\langle \begin{matrix} \text{energy} \\ \text{converted} \\ \text{to heat} \\ (\text{losses}):(+) \end{matrix} \right\rangle \tag{2.1}$$

The electric energy from the electric source and mechanical energy are considered positive for motoring and negative for generating.

The energy converted into heat has three main causes:

- Electric machine coils (copper) losses: p_{Co};
- Mechanical losses (gear friction and windage losses): p_{mec};
- Magnetic (hysteresis and eddy current) losses in the magnetic cores of the machine: p_{iron}.

Including the losses at their location we obtain:

$$\left\langle \begin{matrix} \text{electric} \\ \text{energy} \\ -p_{Co} \end{matrix} \right\rangle = \left\langle \begin{matrix} \text{magnetic energy} \\ \text{storage increase} \\ +p_{iron} \end{matrix} \right\rangle + \left\langle \begin{matrix} \text{mechanical} \\ \text{energy} \\ +p_{mec} \end{matrix} \right\rangle \tag{2.2}$$

So, in fact, the electrical to mechanical energy conversion in an electric motor implies an intermediate energy form for storage: the magnetic energy, mostly present in the magnetic field of the airgap between the rotor (mover) and the stator (fixed part) of the electric motor (Figure 2.8.).

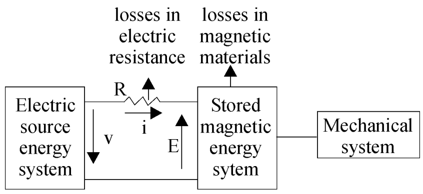


Figure 2.8. Energy conversion in electric motor / generators

The net electrical energy increment dW_e may be described in terms of voltage v, current i, electromotive voltage e.m.f. e:

$$dW_e = (v - Ri)i \cdot dt \tag{2.3}$$

To realize electrical to mechanical energy conversion the coupling electromagnetic field in the machine has to produce a reaction to the electric circuit (to electric source voltage v), e:

$$-e = v - Ri; dW_e = -(e)i \cdot dt \tag{2.4}$$

If the electric energy is transmitted to the coupling magnetic field in the machine through more than one electric circuit (phase) eqn. (2.4) contains more terms.

According to Faraday's law the e.m.f. e is:

$$e = -\frac{d_s\lambda}{dt} \tag{2.5}$$

d_s/dt is the total time derivative of the flux linkage λ, which may contain two terms: a transformer (pulsational) term and a motion-caused term.

According to (2.4):

$$dW_e = i \cdot d_s\lambda\ ,\ dW_{mec} = T_e d\theta_r \tag{2.6}$$

dW_{mec} is the mechanical energy increment.

Where T_e is the instantaneous electromagnetic torque developed by the electric machine and $d\theta_r$ the rotational motion angle increment.

From (2.4) – (2.5) and the energy conservation condition:

$$dW_e = id_s\lambda = dW_m + T_e d\theta_r \tag{2.7}$$

dWm is the stored magnetic energy increment.

If the magnetic flux linkage is constant ($d_s\lambda = 0$) the energy increment from the electrical energy source is zero and thus the electromagnetic torque T_e is:

$$T_e = -\left(\frac{\partial W_m}{\partial \theta_r}\right) \tag{2.8}$$

This situation occurs only when the rotor-stored mechanical energy of the motor is converted into losses in the shortcircuited (v = 0) electric generator mode.

The electromagnetic torque is negative and the machine is braked gradually close to standstill.

In most applications the case when there is electric energy transfer from (to) the electric source is more relevant as it defines the electric motor and electric generator operation modes.

In such cases (2.7) writes:

$$dW_m = id_s\lambda - T_e d\theta_r ; i = -\frac{\partial W_m}{\partial \lambda} \tag{2.9}$$

with λ and θ_r as independent variables.

We may choose the current i instead of flux linkage λ as independent variable. But in that case a new function – magnetic coenergy W'_m – may be defined as:

$$W_m^{'} = i\lambda - W_m \tag{2.10}$$

Differentiating this equation we obtain:

$$dW_m^{'} = id\lambda + \lambda di - dW_m \tag{2.11}$$

Or, with (2.9):

$$dW_m^{'} = id\lambda + \lambda di - id\lambda + T_e d\theta_r \tag{2.12}$$

And finally:

$$T_e = \left(\frac{\partial W_m^{'}}{\partial \theta_r}\right)_{i=const} ; \lambda = \frac{\partial W_m^{'}}{\partial i} \tag{2.13}$$

$$W_m = \int_0^{\lambda_0} id\lambda ; W_m^{'} = \int_0^{i_0} \lambda di \tag{2.14}$$

Eqn (2.9) presupposes that the magnetic flux linkage λ varies in time and thus the electric energy exchange with the electric machine dW_e is now nonzero.

In accord with eqns. (2.8) and (2.13) the electromagnetic torque T_e is nonzero only when the magnetic field coenergy varies with respect to rotor position θ_r.

Let us consider a primitive switched reluctance motor (SRM) with two stator and two rotor poles (Figure 2.9).

We have, in fact, an inductance L (made of two coils in series or in parallel) with an airgap and a magnetic core. It is evident that when the rotor moves around, the magnetic permeance varies with θ_r.

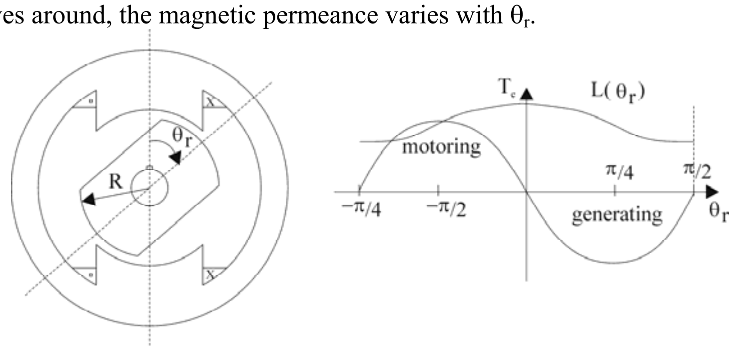


Figure 2.9. The 2 / 2 stator / rotor pole primitive SRM:
a) cross section, b) inductance L and torque T_e versus angle θ_r.

Approximately:

$$L(\theta_r) \approx L_0 + L_2 \cos 2\theta_r \tag{2.15}$$

If the magnetic saturation is neglected, L_0 and L_2 are constant, the magnetic coenergy W'_m of this coil is:

$$W'_m = \int_0^{i_0} L(\theta_r) i di = \frac{i_0^2}{2} L(\theta_r) \tag{2.16}$$

The electromagnetic torque T_e is:

$$T_e = \left(\frac{\partial W'_m}{\partial \theta_r}\right)_{i_0 = const} = \frac{i_0^2}{2}\frac{\partial L(\theta_r)}{\partial \theta_r} = -i_0^2 L_2 \sin 2\theta_r = -T_{em} \sin 2\theta_r \tag{2.17}$$

The polarity of the current does not influence the torque polarity. Positive torque means motoring and negative torque implies generating. As the torque has positive and negative values with θ_r it follows that the 2/2 SRM may not start from any initial rotor position and thus special measures (a parking permanent magnet, for example) are needed to provide self starting from same (parking) position. Multiphase SRMs may start from any position.

2.7. SUMMARY

We summarize the motor candidates for variable speed electric drives in Table 2.1.

Table 2.1. Electric motors for drives

Motor type	Singly salient	Non salient	Doubly salient	Unipolar current	Bipolar current	Conventional (caged rotor)	Converter dependent (cageless rotor)
DC brush	X			X			X[1]
Induction		X			X	X	
Excited synchronous	X	X			X	X	X
Reluctance synchronous	X				X	X	X
PM synchronous	X	X			X		X
Switched reluctance			X	X			X
Stepper motor			X	X	X		X

There are applications that require linear motion and, provided competitive costs/performance rates are reasonable, linear motors become practical solutions. There is a linear counterpart for every type of rotary motor. Also their control is similar to that of their rotary counterparts.

Linear motor drives have their separate literature [16, 17].

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[1] DC brush motors may be supplied through a series resistor and in this sense they are conventional (converter independent for variable speed) but this method is energy consuming and thus it is hardly used anymore.