Controlled AC Electrical Drives

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***Abstract*— Use of AC electrical machines in controlled electrical drive applications is reviewed. The major types of electrical machine are briefly summarized to set context and to establish the physical basis for the control techniques used. Machine properties are the key to successful control and can be obscured by the necessary mathematics required for machine analysis and control scheme derivations. The main focus of the paper is on control techniques which are being applied to make AC drives a rapidly growing area. Development of the control is discussed concentrating on recent trends suitable for practical applications in industry with good dynamic behavior. A particular feature is the increasing importance of speed or position sensorless techniques.**

Index Terms— **AC machines, sensorless control, variable speed, electrical drives, controlled drives, vector control.**

List of Acronyms

AC	Alternating Current
DC	Direct Current
DSP	Digital Signal Processing
DTC	Direct Torque Control
ECM	Electronically Commutated Machine
EKF	Extended Kalman filter
EMF	Electro-Motive Force
FE	Finite Element
FFT	Fast Fourier Transform
IM	asynchronous or Induction Machine
KF	Kalman Filter
LPF	Low Pass Filter
MRAS	Model Reference Adaptive System
NN	Neural Network
PM	Permanent Magnet
PMM	Permanent Magnet Machine including brushless DC machine
PWM	Pulse Width Modulation
SI	Signal Injection
SM	Synchronous Machine
SMC	Sliding Mode Control
SRM	Switched Reluctance Machine
SynR	Synchronous Reluctance
TPM	Trapezoidal Permanent (Magnet) Machine
VC	Vector Control
VFI	Voltage Fed Inverter

I. INTRODUCTION

THE paper begins by reviewing briefly electrical machines for electric drive applications, focusing on AC driven machines. The survey then moves on to discuss control techniques for drives. It covers the important historical developments before concentrating on recent research advances, particularly contrasting traditional sensor based schemes with sensorless methods, complementing and updating two extensive reviews by Holtz [1], [2], and recently by Acarnley and Watson [3]. Such sensorless techniques are the subject of much active research; just for the 2 year period 2005-2006 over 130 papers featuring this topic were published in IEEE Transactions and IET Proceedings alone.

AC electrical machines can be divided into two broad classes, synchronous and asynchronous or induction. Their basic characteristics are described, since this reflects on the methods for control which can best be used. It is a particular contention of this review that good control methods are based on physical insight into the machine characteristics. Mathematical treatments, although required for sound development, can obscure this physical insight at times.

Control methods used in AC machines are next highlighted, concentrating first on the basics of vector control (VC). This control method and its variants, combined with the advances in both power electronics and electronic processing power, is mainly responsible for the increased modern use of AC machines in higher performance dynamic applications.

Sensorless techniques are discussed next with the methods broadly divided into two classes, those using the fundamental properties or model of the machine, and those exploiting subsidiary features, often by using signal injection (SI). Fundamental model methods are widely applicable to the main classes of AC machine used in drives but are inherently incapable of prolonged working at zero speed. SI methods are capable of zero speed operation, but the properties used are usually machine specific, limiting the generality of their industrial application. This particularly applies to the induction machine (IM), still preferred for the majority of cases.

II. AC ELECTRICAL MACHINES

A. Classes of AC electrical machine

There are two recognized broad classes of AC electrical machine, synchronous (SM) and asynchronous or induction (IM) [4], [5]. A third class is introduced here for clarity, the Electronically Commutated Machine (ECM).

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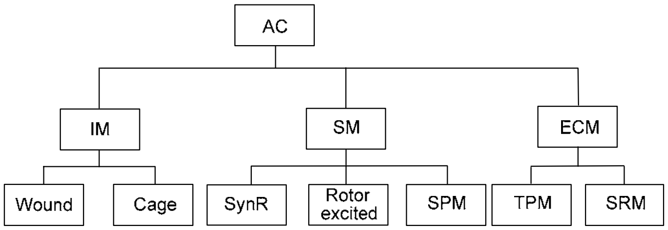

Fig. 1. Broad classes of AC electrical machine

Such ECM machines have electronic commutation or switching as an inherent part of the operation. This is different to electronically producing a variable frequency sine wave supply, say by pulse-width modulation (PWM), and using this instead of mains excitation. Also their modeling cannot rely on classical d-q axis theory. Figure 1 summarizes these classes of AC electrical machine. Most typically the outer or stator part of the machine is excited with polyphase windings fed by AC excitation. The other major component - the rotor, turns within the stator, pulled by the rotating magnetic field synchronous to the stator excitation. SMs, with mains or electronically generated sinusoidal voltage excitation, produce torque when rotating in the steady state at a rotor speed equal to the synchronous speed directly governed only by the excitation fundamental frequency, *f,* and *p*, the pole-pair number: $\omega_r = \omega_s = 2\pi f / p$.

SMs can have rotor DC fed winding or permanent magnet (PM) excitation. Field excited SMs are only economic in the very largest of drives (steel mills, ocean liners, etc.). They are heavily used for large scale electricity generation, with PM being used at more modest ratings. PM field SMs with electronic switching of their AC excitation are usually termed brushless PM machines or brushless DC machines (termed PMM here), although they can also be thought of as variable frequency inverter fed SMs [5]. Since the speed of an AC drive is determined by the frequency, exactly for the SM, closely for the IM, a wide range variable speed requires an electronically varied machine supply frequency. All electrical machines are capable of being operated inverted, i.e. stator/rotor interchanged but one configuration is usually the most practical. This is usually that which avoids external electrical connections to the moving rotor. Motor or generator operation is also inherently possible from the machine, although not necessarily from the drive depending on the power electronic configuration. Also each machine type can be unrolled, along one or two axes of symmetry, to form a linear or tubular version of the machine. Much ingenuity has been, and still is, devoted to these special machines, which can be extremely useful in some special applications [6]-[8].

Despite the principles of these machine types being known for over 100 years and exploited with great ingenuity in AC drives, as Jahns and Owen describe in their historical survey [9], considerable progress is still being achieved. This is fueled by advances in materials, electronics, and of course by the inventiveness of engineers. Brushless PM machines, favored for many high performance servo drives, rely on power electronic switching of the (usually) stator currents for their operation, and better PM material for their economy, with position sensing and electronic processing to drive the switching. Electrical motors are estimated to use over half of the total electrical power produced in a typical industrialized economy. In the industrial sector the proportion is believed to be about 2/3. The majority of these drives are IMs.

This IM dominance is being challenged by advances in PM machines, particularly for very high performance applications. Zhu and Howe, in an extensive, well illustrated review of machines and drives particularly for electric vehicles, discuss configurations of machines [10]. Previously PM drives were mainly applied to high precision applications because of higher cost. PMM features, including high power density and reduced rotor losses resulting from material improvements, are now making such drives competitive with IMs for positioning and less demanding applications. Elimination of the mechanical rotor sensor is especially useful in such general drive applications [1]. The major types of electrical machines adopted for industrial and traction drives are DC commutator, IM, SM (mainly PM), and the switched reluctance machine (SRM), see Jahns and Blasko, and Ehsani *et al* [11], [12].

B. Induction Machines

In an IM, rotor excitation is induced from the stator field requiring an asynchronous rotor speed to give torque production. The relative velocity between field and rotor speed needed for induction and torque is defined by the p.u. slip, $s = (\omega_s - \omega_r)/\omega_s$. Slip must be small for high power efficiency. The cylindrical rotor usually has cast rotor cage conductors in slots uniformly distributed around the rotor surface; more rarely in larger sizes it can have a wound rotor with accessible connections via slip rings. At a fundamental level seen from the stator the IM has no axis of symmetry and the stator winding inductance does not depend on rotor position. Slotting, and differential or cross magnetic saturation, changes this simplified view and produces effects which can be exploited for position and velocity sensing.

C. Brushless PM Machines

In the usual brushless configuration motion of the PMM rotor relative to the stator induces a motional EMF. This EMF is a function of rotor position and speed, which makes estimation of either possible. Such PMM drives divide into two sub-categories, *sine wave* (SPM) and *trapezoidal* (TPM) [3]. Both obey the SM speed relationship, and are operated as a variable speed drive by electronic commutation. The sine type can also be operated with mains excitation open loop without position feedback as a conventional SM. It has ideally sinusoidal motional EMF producing torque with low ripple. The trapezoidal ideally requires rectangular current blocks for best torque production, and mains supply is not an option. Only coarse feedback is needed, sensing requirements are less demanding as position is needed only at the commutation points, (every 60º electrical for a 3-phase machine).

The magnetic structure of the PMM governs the position variation of inductance and motional EMF. Four such rotor structures have been described for a PMM [3]. In a *surface-mounted* magnet arrangement the phase winding inductance is small with often negligible variation with rotor position. *Inset* magnets, often used for trapezoidal machines, usually have substantial winding positional inductance variation. Other configurations with *interior* or *flux concentrating* magnets lead to higher inductances or significant saliency effects, causing a substantial variation of winding inductance with position.

D. Other Machine Types including Reluctance

Other machine types are used in drives including synchronous reluctance (SynR), where a salient or flux guided rotor is designed to have markedly different or variable reluctance (VR) on the electrically orthogonal axes. They operate as conventional SMs, and can be regarded as a form of brushless machine without PMs. Robustness, economy, and reliability are features, but performance is typically reduced, at least compared to PM machines.

Switched reluctance machines (SRMs) have received a lot of research attention over recent time. SRMs also require simple switched electronic commutation. They are doubly-salient VR machines (with stator and rotor pole slotting) with pronounced deep slots on both sides of the air-gap, and can use single or multiple teeth per stator pole. These salient poles or teeth on stator and rotor are of critical importance to its operation; their number usually being quoted to specify the device, e.g. a 6/4 SRM is 3-phase with 1 tooth per stator pole, as is an 8/6 but has 4-phases, a 12/10 is 3-phase with 2 teeth per stator pole. They are in one sense SMs, as their speed is governed directly by the stator switching but exploit the difference in pitch between teeth in a vernier action, giving a lower rotor speed than the classical SM equation. One complete electrical cycle of switched stator excitation gives a movement of one rotor slot pitch. Since VR action is exploited without sine wave excitation only unidirectional currents are required, simplifying the converter. Pulsating torque tends to be developed, with simplicity and cheapness being the major features. Understanding and designs have gradually improved over the last two decades, with power density being improved including by use of segmental rotors, first used to considerably enhance SynR machines, as Mecrow *et al* have described [13].

III. AC MACHINE CONTROL PRINCIPLES

A. Background

High performance drive applications usually require a fast torque response, with DC drives preferred in the past. The advantages of AC drives include robustness, compactness, economy, and low maintenance. Previously torque response control was a problem. Advances in power switching devices, electronic processing, and control have led to great improvements. Such controllers build upon good steady state performance and can give excellent transient behavior.

Variable-frequency AC machine control can be divided into *scalar* and field oriented or *VC*. Scalar control uses magnitude and frequency control. VC uses orientation in addition. Variants include *direct torque control* (DTC) which also exploits spatial orientation but aims to control current and hence torque by more directly switching the voltage rather than using PWM [4], [5].

B. Scalar Control

Scalar control is based on steady state relationships, usually only magnitude and frequency are controlled, not space vector orientation. Making terminal voltage magnitude proportional to frequency results in approximately constant stator flux, desirable to maximise the capability of the motor. The classical variable frequency V/f scheme is a scalar control based on this principle, with voltage boost at low frequency usually introduced to counteract the larger effect of stator resistance at low speeds. Scalar control, often open-loop apart from stator current monitoring for fault detection, gives an economical drive with good behaviour, but transients may not be well controlled. More sophisticated variants can improve behaviour, perhaps with better handling of parameter variations, particularly of stator resistance. Buja and Kazmierkowski describe the evolution of the still widely used scalar control methods and their progression to VC [14].

C. Vector Control

In VC the instantaneous position of voltage, current, and flux space vectors are controlled, ideally giving correct orientation both in steady state and during transients. Coordinate transformations (3 phase to 2 or d-q axes) to new *field coordinates* are a key component of standard VC, giving a *linear* relationship between control variables and torque. It is ideally suited to current control via PWM voltage switching. VC can be introduced by considering a DC machine.

In a DC drive the rotating commutator acts as both current switch and rotor position sensor. A DC drive is shown in a schematic diagram in Fig. 2, where i_a is often chopper controlled. The commutator maintains the main flux and the armature mmf directions to be approximately perpendicular under all operational conditions, illustrated by the vector diagram in Fig. 2. This basic arrangement defines the aim of a VC for a high performance AC drive, as summarized in (1), where electrical torque is shown as the product of magnetic flux linkage and current.

$$T_e \propto \psi \, i \tag{1}$$

Usually the VC separates current into field and torque producing components. The perpendicular field system makes the relationships between the machine variables simple, in principle. The flux is a function of the field (producing component) or d-axis current, the torque is proportional to the product of this flux and the torque (producing component) or q-axis current. If the flux is established and can be held constant, the torque response is governed by the current and can be fast and well-controlled.

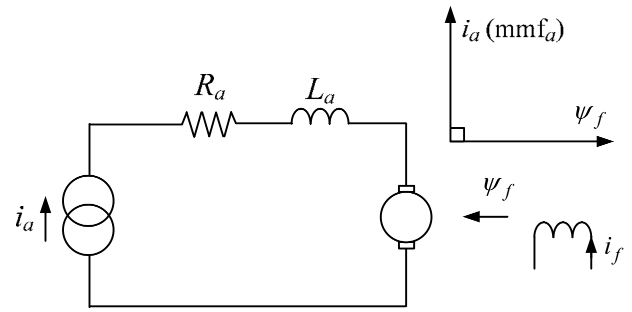

Fig. 2. Flux and mmf in a DC drive

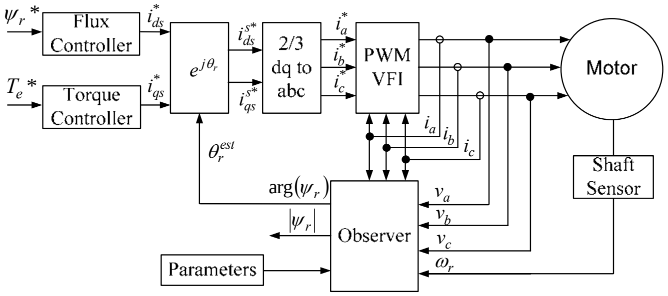

Fig. 3. Basic direct VC scheme with an observer used for rotor flux estimation

Full advantages of VC are given only if the instantaneous position of the rotor flux vector can be established. The usual IM cast cage rotor aids in robustness and economy, but rotor quantities are not accessible. Two variants of VC are used, direct and indirect. In the direct method the instantaneous rotor position for this flux is found either by sensors, or more usually by estimators, or a combination; Blaschke was a pioneer of the approach [15]. Figure 3 shows a basic scheme. Indirect VC for an IM combines a slip calculation with use of rotor position or speed [5]. Slip calculation involves the rotor time constant which can vary considerably mainly due to changes in rotor resistance with temperature.

This need for rotor position or velocity is most obviously required in a SM such as a brushless PM machine since stator excitation must be synchronous to the rotor. It also applies to an IM drive, although the basic symmetry of the rotor implies only relative velocity is originally needed. A straightforward method is to attach a rotor sensor, e.g. an encoder to measure rotor position or speed, and this is still preferred in many cases, but *sensorless* schemes are gaining ground.

D. *Direct Torque Control*

DTC also exploits vector relationships, but replaces the coordinate transformation concept of standard VC with a form of bang-bang action, dispensing with PWM current control [14]. In standard VC the q axis current component is used as the torque control quantity. With constant rotor flux it directly controls the torque. In a standard 3-phase converter simple action of the 6 switches can produce a voltage vector with 8 states, 6 active and 2 zero. The voltage vector and stator flux then move around a hexagonal trajectory; with sinusoidal PWM this becomes a circle. With either the motor acts as a filter so rotor flux rotates continuously at synchronous speed along a near-circular track.

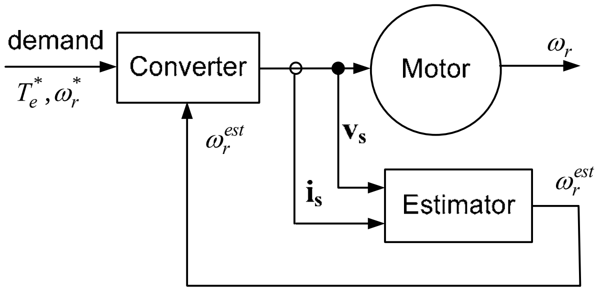

Fig. 4. Schematic of a speed sensorless scheme, *=demand, est=estimated.

In DTC the bang-bang or hysteresis controllers impose the time duration of the active voltage vectors, moving stator flux along the reference trajectory, and determining duration of the zero voltage vectors to control motor torque. At every sampling time the voltage vector selection block chooses the inverter switching state to reduce the flux and torque error. Depending on the DTC switching sectors, circular or hexagonal stator flux vector path schemes are possible. Types of DTC include: switching table based, direct self control, space vector modulation, and constant switching frequency [14].

DTC has these features compared to standard VC:

- No current control loops so current is not directly regulated.
- Coordinate transformation not required.
- No separate voltage PWM.
- Stator flux vector and torque estimation required.

IV. SENSORLESS CONTROL METHODS

A. *General overview*

There is intensive research world wide devoted to sensorless methods. Motor drives without a speed or position sensor have received much research attention in recent years, both for IMs [1], [2], and PM brushless types [3]. Such techniques typically measure stator quantities, usually current, directly via existing transducers normally present in the inverter, and voltage, although not often with a direct measurement. SI methods are also used. Figure 4 shows a typical schematic of a sensorless scheme.

Advantages of such “sensorless” schemes include [1], [2]:

a) more compact drive with less maintenance;
b) no cable to machine transducers, easier application particularly to existing machines, reduces electrical noise;
c) transducer cost avoided;
d) suitable for hostile environments, including temperature.

Despite much effort and progress operation at very low speed is still problematic particularly for an IM sensorless drive. Table I [1] gives a schematic overview of the methodologies applied to sensorless control.

TABLE I:
SENSORLESS METHODS

basis	fundamental model	Asymmetries/motor specific detail effects		
`		saturation	saliencies	slotting
type	IM, PM(inc. emf)	IM	PM	IM, PM
speed error	1-3%	<1%	towards zero	towards zero
applies?	all	some	some	some

Proper comparative analysis of the many variants in the extensive literature on this topic is difficult. This is mainly because a standard set of tests or benchmarks has not been agreed. Even quite simple schemes can give results which are adequate for undemanding applications. Such simple schemes can usually demonstrate operation through zero speed provided the transition is fairly rapid. Hence a reversal over say ±1000 r/min in a short time may be useful to give an overview, but it is not a suitable test unless it is all the application requires. This benchmark issue has been commendably addressed by Ohyama *et al* in a most valuable contribution to standardizing tests [16]. Benchmark tests are proposed in four categories including a staircase speed transient over ±150 r/min in 10 steps, i.e. of 30 r/min, with drive data to be fully specified, including moment of inertia since large values can make results look impressive. Sensitivity to parameter change is also critically important.

B. Model based estimation methods

1) Fundamental Basis – Flux Linkage

Sensorless control of both IM and PM machines can use fundamental model based estimation methods, which in their simpler forms typically work well above about 2% of base speed. These fundamental model based methods usually describe the machine by d-q axis equations, where sinusoidal distribution around the air gap is assumed. As this neglects space harmonics, slotting effects, etc, it is often termed a fundamental model. Fundamental models have an inherent limit. As the stator frequency approaches zero the rotor-induced voltage goes to zero, and the IM becomes unobservable [1]. Methods are either implemented in open-loop form, or as closed-loop observers (estimators), making use of the error between measured and estimated quantities to improve their behavior.

Operation at very low speed and continuously at zero may need SI techniques for position estimation, as particularly in PMMs, inductance may vary with position. These methods utilize asymmetric properties, either the saliency of the rotor, arising naturally in at least some PM types or magnetic saturation.

Some important general points particularly concerning model based sensorless methods can be brought out very straightforwardly. The simplest form for the stator voltage equation using the usual symbols would be:

$$v_s = R_s i_s + \frac{d\psi_s}{dt} \tag{2}$$

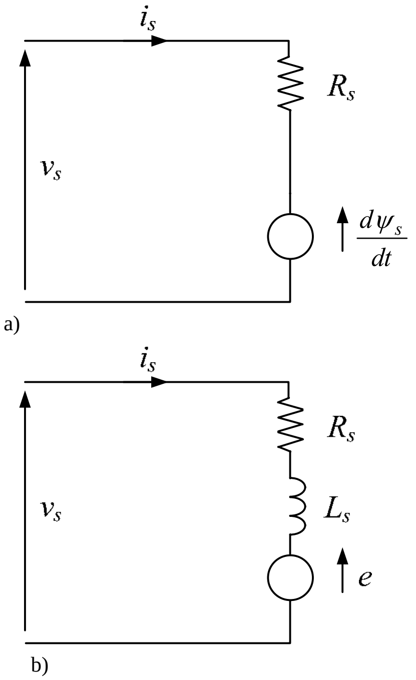

Fig. 5. a) Phase equivalent circuit, for general machines; b) variant , useful for PMMs.

This is illustrated diagrammatically in Fig. 5a. The stator flux linkage ψ_s is a function of speed and frequency, but its rate of change drops to zero at zero frequency. An IM appears to be purely resistive at the stator terminals at sufficiently low frequency/speed. Since flux is a key element in accurate sensorless control, (2) shows the requirement from terminal quantities when recast into integral form:

$$\psi_s = \int_0^t \left(v_s - R_s i_s\right) dt \tag{3}$$

Thus prediction of flux from stator voltage and current requires an integration. The signals used in (3) will have noise and disturbances on the measured values so degrading the accuracy. Digital measurement implies noise and quantization while drift and offset arise from analogue transducers. These effects, and the lack of a perfect integrator, limit the performance obtained. How well this integration can be implemented is a main factor in the low speed applicability of model based methods. The integrator can be replaced by a low-pass filter (LPF) but this modification inhibits the flux estimator's low-speed operating range. This important feature is illustrated in Fig. 6 showing a standard Bode frequency response G_F of the ideal integrator and the approximation using a first order LPF [1]. It behaves as an integrator for frequencies higher than the corner frequency, $1/\tau$. This approximate integrator cutoff or corner frequency, typically 1−3 Hz, defines where speed estimation must become inaccurate, and is an important frequency limit on the estimation. An alternative integrator structure can help. Hu and Wu [17] showed superior performance from a version with adaptive compensation.

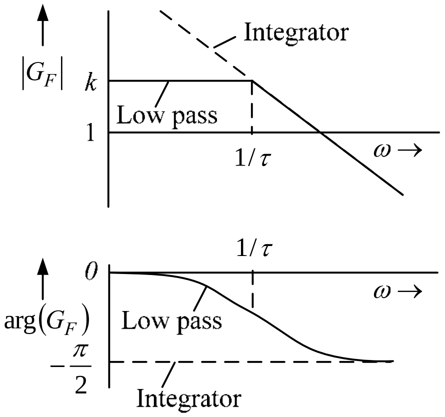

Fig. 6. Ideal integrator approximated by a low-pass filter. Bode diagram.

Fundamental model based schemes will have difficulty maintaining or properly controlling speed in this very low speed region, but cope quite well with fairly rapid transient reversals of speed through zero. The time constant τ of the low pass filter based integrator determines how rapid the transition has to be for good behavior. Inaccurate reference model parameters, mainly stator resistance, also limit low speed results.

For PMMs it is convenient to re-draw the general equivalent circuit, Fig. 5a, (2), by splitting the flux-linkage voltage source into inductive and back EMF sources, see Fig. 5b, to bring out these effects. Sensing using flux-linkage variation for PM machines is inherent in model based methods, and has the same limitations.

Although needed for use of (3) direct voltage measurement is usually avoided, as it is technically difficult and involves isolation problems, so methods for achieving estimates and also techniques for compensating dead-time errors have received attention [18], [19]. Methods focus on using the modulation index of the inverter switching. This, and accurate parameters, is an important area for achieving very good low speed performance in all classes of machine.

Since parameter sensitivity is an issue, identification or parameter tracking schemes are a natural extension. At speeds (stator frequencies) above a few Hertz, the resistive voltage is small as compared with the stator voltage and the induced voltage estimation should be accurate. Perversely this small resistive voltage makes it difficult to identify stator resistance at such higher speeds. Resistance changes with temperature may need to be tracked to maintain system performance at low speed.

The next sections place model based schemes into broad categories depending on the main technique adopted, there is of course considerable overlap with combinations of methods being used. Methods range in complexity from the simpler model reference adaptive system (MRAS), through Kalman Filter (KF) and Extended Kalman filter (EKF) forms, as well as other observer or estimator schemes. Conventional sensor based feed-back control is still being actively developed of course, sometimes augmented by estimation.

2) PM Sensing Using Motional EMF

Practical difficulties in the use of motional EMF sensing occur since the windings carry rapidly changing currents giving substantial inductive effects. The EMF is zero at zero speed so a finite speed threshold must operate. A particular problem in a SM such as the PM machine is that starting is also position dependant, so rotor position and the magnetic field polarity is ideally required to avoid a starting transient which may be in reverse. Special arrangements, perhaps an open-loop ramp, may be made for starting [3], with parameters chosen to suit drive and load.

Simple motional EMF sensing schemes have limitations:

a) sensing is not possible at low speeds;
b) filtering and phase shift needs limit dynamic range;
c) upper limit on the useful speed range when assumed rapid decay of switched off current no longer happens;
d) Phase EMF measured, for a star connection an extra lead is needed.

The third-harmonic component of the EMF waveform of a trapezoidal PM machine can be used reducing the phase-shifting problem with the basic scheme, making operation possible at higher speeds [3]. Nahid-Mobarakeh *et al* use EMF estimation for a PMM, with robustness to measurement and inverter irregularities, to help on-line stator resistance estimation [20]. Nasiri applies new digital deadbeat controller to a vehicle, aiming for a deadbeat dynamic response in speed [21]. A simple robust sensorless method estimates position and velocity, using measured line voltages and currents, but with no low speed test results. Liu *et al* use a sliding mode observer for EMF instantaneous torque estimation with DTC, and a simplified EKF (see later section) for speed. Responses with a ±400 rad/s reversal are shown. At lower speed interpolated back EMF is used [22].

3) PM Sensing Using Inductance Variation

Where inductance is a function of rotor position then position can be deduced from winding current and its rate of change. This applies even at stand-still where motional EMF is zero. There are problems: with surface-mounted magnets, inductance variation with position is only from magnetic saturation; at higher speed motional EMF dominates; inductance variation has two cycles per electrical cycle of the PMM, giving a sensed position ambiguity [3]. J-L. Shi *et al* use an adaptive controller for a sensorless PMM drive using maximum torque control [23]. The current slope change and the rotor saliency gives position estimation with back EMF compensation. This gives good robustness to inertia and friction with an estimation error near ±1°, a 0-5 r/min step is shown at inertia 4.5×rotor [23].

4) Model Reference Adaptive System

The usual MRAS estimates speed using two different machine models, one being speed dependant [1], [5]. Differences between the models can be used to reduce the error in the speed estimate, often with an internal PI controller. The basic MRAS block diagram is drawn as Fig. 7.

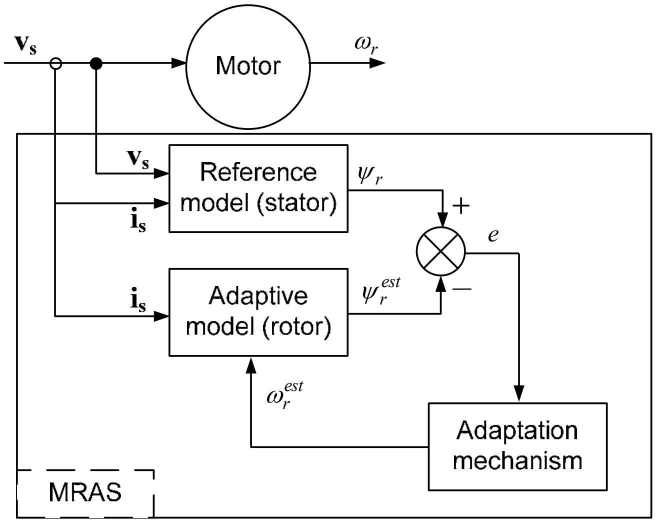

Fig.7. MRAS speed sensorless scheme, *=demand, est=estimated

How well the ideal integrator in the reference model is approximated is one defining factor for performance, as discussed earlier. Good behavior with an IM above 2 Hz stator frequency was reported by Schauder in pioneering industrial based developments [24]. Ohtani *et al* [25] in early work described a *torque MRAS* with better behavior. Better independence to motor parameters, particularly stator resistance is claimed, by matching a lag circuit to rotor time constant. Application to a printed press is described, needing 0.1% rated speed stability. Tests at about 18 r/min or 1/100 of rated speed were shown.

Such schemes are popular as they are not as complex as some other model based approaches, and can be implemented more economically [2]. In an early comparison Armstrong *et al* compared a basic rotor flux MRAS and EKF estimator behavior [26]. The EKF was more resilient to parameter changes, but MRAS is simpler (with a computing complexity ratio of almost 20:1) and can even be better at low speed. Performance was said to already rival an encodered indirect VC drive. A step of 96 to 19 r/min was used in tests.

Later developments include parameter adaptation which is important for low speed behavior. Recently Rashed *et al* report an indirect VC MRAS for rotor flux and stator resistance estimation in a PMM [27]. Operation at 2 rad/s is shown. Cirrincione *et al* use a neural network (NN) predictive adaptive model in a MRAS based IM drive, comparing with an older MRAS scheme. A ±50 rad/s reversal is used in the tests, then ±10 rad/s [28]. Low speed behavior is limited by the LP integrator, with 5 rad/s used in their test. Some zero speed tests are also shown, being viable because of the adaptive model used, and are better than before.

5) Kalman Filter

The KF is a well known more advanced technique in signal processing which has been widely applied to drives. This includes IMs for rotor current (and hence rotor flux vector) estimation in direct VC, and in EKF form including rotor resistance estimation. Variations in motor parameters, particularly rotor resistance, should ideally be tracked, see Atkinson *et al* who use a KF for IM rotor current estimation, EKF for rotor resistance, also a reduced order model was introduced for computational savings [29]. Use of a model, necessary in an indirect VC, makes sensitivity an important issue. Reduced order schemes aid real-time implementation, but the continued development of digital signal processing (DSP) means such compromises are less needed.

Rotor resistance varies for two main reasons. The major effect of temperature on rotor resistance will be relatively slow, so compensation will help avoid a drift in the steady state flux and torque operating point. This effect is of major concern to industrial users of VC, and estimation schemes can offer help. Skin effect changes to rotor resistance can occur more rapidly, being induced frequency dependant. Under steady state conditions skin effects are small as the VC would normally maintain a low slip frequency in a high efficiency motor. Also purpose built variable speed IM drives can use motors with little designed-in skin effect, since a direct mains on-line start is unnecessary. Rotor time constant can also be affected by the influence of magnetic saturation on inductance.

The other decisive parameter is the stator resistance R_s whose effect in (3) gradually dominates as frequency (speed) is reduced. Also its value can vary with temperature by 50%, making use of a simple fixed value difficult. Operation down to perhaps 1 Hz may be possible before stability and errors cause limits.

KF and EKFs have been widely advocated for drives despite the considerable added complexity over MRAS [26], and exhibit lower sensitivity to parameters. Their performance depends on choices for the filter matrices, so this has attracted continuing research attention, see for example Bolognani *et al* [30], although trial and error methods are widely used. Barut *et al* describe use for VC and DTC IMs with voltage and current sensing, but with measured resistance and rated inertia values. Low speed tests show estimation speed errors of 2-4 r/min and extended zero speed holding, to 64 s [31].

Akin *et al* [32] summarizes the drawbacks to a conventional EKF:

a) Costly:	costly calculation of Jacobian matrices;
b) Bias:	biased estimates;
c) Dynamics:	instability due to linearization and erroneous parameters;
d) Assume:	white Gaussian noise;
e) Tuning:	lack of analytical methods for model covariance selection.

They advocate the *“unscented”* KF, overcoming some drawbacks; low speed tests were not reported, since it can be more susceptible to measurement noise.

6) Observers and Other Schemes

As described closed-loop observers can improve robustness against parameter errors and noise. Combinations of MRAS or EKF with adaptation are common, as are other observer based schemes. Forms used include full order nonlinear and sliding mode observers [1]. *Sliding mode control* (SMC) has been widely touted for use in drives as Utkin has described in a widely cited paper [33]. Barambones *et al* apply an integral SMC to an IM based on VC theory, with parameter robustness tested with 20% variations, but with undemanding speed stepping tests from about 800 to 1200 r/min, centered on 1000 r/min [34]. Various parameter tracking methods have been deployed in the past, as reviewed by Toliyat *et al* [35]. These methods included resistance identification using an observer, directly by MRAS, or using reactive power which was claimed to give good sensitivity and dynamic response [1].

Fundamental model observer based methods are widely applied to PMMs with recent research said to concentrate on closed-loop methods [3]. Such estimators may include a simple mechanical system model which requires details of mechanical parameters. Variants without a mechanical model may be more suitable for variable or unknown loads. Earlier attempts with a mechanical model for a PMM include Terzic and Jadric using an EKF with stator resistance estimation, where ±1% speed error above 5% rated was given [19].

Xu and Rahman [36] use an adaptive sliding observer with a KF for stator flux based on a motor current model, for DTC in a PMM. Reported tests include ±24 r/min reversal, also at 10 r/min (0.33 Hz, 0.79% of rated speed). Mohamed shows a novel instantaneous torque control for a direct-drive PMM, achieving low torque ripple [37].

Advances continue for IM sensorless control; Lascu *et al* use a variable structure control, a DTC variant [38]. They note three evolved categories of flux and speed observers:

a) simple models with explicit compensation of inverter nonlinearities and disturbances;
b) adaptive and/or robust observers based on fundamental excitation and advanced models;
c) speed estimation based on high-frequency signal injection and/or saliency induced effects.

Using a speed adaptive sliding mode observer zero and very-low-speed (3 r/min, 0.1 Hz, 0.002 p.u.) performance is demonstrated, claimed to be the lowest without SI; sensitivity to parameter changes were simulated, showing insensitivity to rotor resistance. Zero speed full load operation is said to be stable and accurate. Inverter nonlinearity compensation and stator resistance adaptation improved behavior. A rather large total inertia was used, about 10× that of the IM rotor [38].

Mitronikas and Safacas describe an improved VC method for an IM drive, using a closed-loop stator flux estimator, rotor speed estimation uses a MRAS; the work is supported by simulations and lightly loaded experimental results [39]. Cirrincione *et al* propose an adaptive speed observer for rotor speed based on a new total least-squares neuron for IM drives, using the Luenberger observer equation. Results of ±100 rad/s reversal are given [40]. Very low speed tests <2 rad/s are also shown; even zero speed operation is claimed with stator and rotor resistance adaptation. Edelbaher *et al* [41] used a closed-loop rotor-flux observer based on "extended electromotive force", inverter nonlinearity compensation, and stator resistance adaptation. A ±5 rad/s reversal is shown, zero speed holding is claimed to be satisfactory with results showing perhaps 20 rad/s excursions on a step torque change of 1/3 full load. Bhattacharya and Umanand [42] propose a flux estimation and stator resistance adaptation method that gives the effect of open integration but with an error-decaying mechanism to resolve the DC drift problem. They show the response of the drive during a ±90 r/min reversal.

Not all schemes are focused on achieving good dynamic behavior at very low speed. Salo outlines a new stator current control method for VC PWM current-source-inverter IM drives, suitable for single-chip micro-controller implementation, avoiding stator current transducers [43]. Sonnaillon *et al* also address reducing the sensor count, only DC-link measurements and an IM model are used [44]. Adequate performance in closed loop from 0.05 p.u. speed is claimed, using scalar V/f at lower speeds. Kadowaki *et al* apply secondary flux-based estimation to an actual electric commuter train with an IM rating of 120 kW, to give desired adhesion and comfort [45]. Other high power applications include Bonnet *et al* with a novel doubly fed IM control strategy using DTC, suitable for high ratings with inverter economy [46]. Higher speed range operation is addressed by Casadei *et al* in a DTC IM, where the flux reference is adjusted by torque error, giving spontaneous flux weakening [47]. Kaboli *et al* concentrate on power efficiency improvement by use of flux control methods for loss minimizing [48]. Dynamic results for flux alone are shown, with parameter independence claimed. The high frequencies necessarily injected by rapid response control can cause motor problems such as high bearing currents and rotor shaft heating; this is addressed by Mukherjee and Poddar with controlled filtering proposed to minimise the difficulties [49].

In any SM rotor position affects behavior. Krishnamurthy *et al* address prediction of rotor position for startup at standstill and rotating conditions for SRMs [50]. SRMs are suited to automotive products as Krishnamurthy *et al* discuss, [51] using position estimation via inductance profiles, which can be auto-calibrating. Khalil *et al* cover one approach using the dead-time periods in torque production with SRMs [52]. The scheme allows a wide speed range including zero, low speeds use pulse injection, higher speeds use a sliding-mode observer.

7) Fundamental Model Scheme Problems

Low speed operation is the main area where difficulties arise [1]. The problems include:

a) Signal Acquisition Errors: These are a basic limitation for very low speed operation, minor DC components in the signals used in (3) can produce substantial offsets in the estimated flux linkage even if a pure integrator could be used.

b) Inverter: The inverter introduces nonlinear dead-time effects; very good performance at low speed will require compensation. Further nonlinearites come from power device forward voltage drops and may also require modeling. Additional effects include the sensitivity of voltage drop and dead time compensation to the exact point of current reversal. Estimating the stator voltage vector from the PWM index then becomes inaccurate.

c) Model Parameters: Parameters can be determined in a commissioning phase, either offline or using the inverter to self test aiding accuracy of estimation.. This might include finding a good initial value of the stator resistance using a DC test.

V. SENSORLESS CONTROL THROUGH SIGNAL INJECTION AND PARASITIC EFFECTS

In SI methods the machine is injected with extra, low level signals usually at high frequency. The much higher frequency and low magnitude of the injected signals result in the fundamental behavior of the machine being little changed. The injected signals may be periodic or alternating in a particular spatial direction. These signals are modulated by the orientations of the machine asymmetries, and are then processed and demodulated to yield the required measurement. Such asymmetries occur more naturally in SMs. Signal processing can be difficult owing to required frequency tracking, low spectral separation and poor signal to noise ratio. Modern signal processing techniques can help; according to Giaouris and Finch *wavelet transforms* are best deployed in precisely such challenging situations, where useful components exist at widely spread and varying frequencies and the bandwidths are uncertain [53]. Results of a PMM based study are presented confirming this view. At times exploiting the PWM switching can form the SI, as Holtz has reviewed [1].

In Morimoto *et al* [54] PMM system parameters including the inverter are identified at standstill and under operating conditions. SI is used at first before switching over to EMF based estimation. Persson *et al* propose a magnetic anisotropy method for standstill position esimation in nonsalient PMMs [55]. Signals of 100’s kHz were best for rare earth magnets. As discussed earlier PMM vary in their suitability for SI. Bianchi and Bolognani develop design criteria to aid SI for interior PMM using FE analysis [56]. Guglielmi *et al* discuss cross-saturation effects in SynR machines assisted by PM. Tracking at 100 r/min is shown [57].

In an IM the fundamental model for the rotor is cylindrical, and cannot provide information on the field angle or the position of the rotor at zero speed. Hence non-model based methods have to rely on machine specific effects, such as slotting or magnetic saturation. Voltages induced in the stator windings by spatial rotor slot harmonics can give accurate speed signals. Higher frequency excitation by injected signals, or directly via by inverter switching, serve to detect the spatial orientations of existing asymmetries. Such effects occur naturally in many PMM designs. In the IM magnetic saturation can produce saliency, and slotting effects occur particularly in open rotor slot designs, but these effects are machine specific and significantly reduce the general applicability of these asymmetric based methods. Fundamental model methods will always struggle at very low speed, but can be applied to any machine.

So for IMs SI methods have to exploit machine properties not present in the fundamental machine model. Asymmetries are caused by fundamental field magnetic saturation, or the discrete rotor bars. Rotors have even been designed to aid this effect [1], but this radically hinders general application. Staines *et al* show rotor-position estimation for near standard IMs at zero and low frequency using rotor slotting and zero-sequence current, achieving good results with a 0-10 r/min test, and a mean position error of under 1° mechanical [58]. Caruana *et al* use HF SI techniques for zero-low frequency VC of a standard closed slot IM, with compensating and filtering methods in addition to a KF with ±30 r/min reversal test results [59]. Also using rotor slotting or eccentricity are Shi *et al* but with Hilbert and FFT [60]. Rotor rotation is required for the harmonic effects required, but good percentage accuracies are quoted. Magnetic saturation takes the role of the estimator disturbance as Holtz and Pan [61] describe, using the inverter terminal to star-point voltages. Sustained operation at zero stator frequency, combined with high dynamic performance, is claimed with dynamic test results shown at 50 r/min.

More novel approaches include that of Wang *et al* [62] who present a speed-estimation technique using SI and the standard smooth air gap IM model, combined with a MRAS. This is claimed to work over a wide speed range, including zero speed and fundamental frequency, provided the moment of inertia is sufficiently high, although this is not quantified. Tests show behavior through zero speed with 50 r/min steps. Garcia *et al* do saliency-tracking using SI based on the zero sequence and neural networks, allowing saturation compensation, tested on an IM [63]. Gao *et al* also use SI methods to track an IM anisotropy; either saturation or rotor slotting for flux or rotor-position estimation [64]. The normal commissioning process to reduce disturbances due to unwanted anisotropies is avoided provided loading conditions can apply, resulting in a 0.5 Hz threshold frequency.

VI. CONCLUSION

Controlled electric drive applications using AC electrical machines have been reviewed. The types and properties of the major types of AC electrical machine were first summarized since machine characteristics considerably influence the control methods needed. Control techniques which are being applied to make AC drives a rapidly growing area were then discussed, starting with VC using an analogy with the control achieved in a DC drive by the commutator. Modern trends were then reviewed judging progress by the quantitative performance achieved in comparable tests, where possible.

Speed or position sensorless techniques are of increasing importance. Their features were discussed, splitting techniques into fundamental model based and SI and parasitic techniques. Model based methods have been long available, offering behavior said 20 years ago to rival schemes with sensors. This behavior has been extended at very low speed, and is now truly impressive. Speed control at 3 r/min or 0.3 rad/s, or even zero, has been demonstrated, which even at high inertia is excellent. Operation at nominally zero speed for over a minute has been shown, at steady load. Exact comparison between schemes is difficult, because of a lack of standardization in tests, but this is being rectified. Very low speed behavior is best demonstrated by a series of steps, 30 r/min was suggested. In view of the excellent results claimed in some recent schemes, even smaller steps would be useful. The best performance requires parameter adaptation and correction of inverter nonlinearities. Drive parameters need to be quoted in tests, including moment of inertia. SI can offer extended zero speed, but is machine property dependant. The performances achievable from both classes of method are now such that increasingly they will be applied to more demanding practical applications in industry with very good static and dynamic behavior.

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