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Modern Motor Control Applications and Trends

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ABSTRACT

This paper reviews the state of the art of electric drives technology in three specific areas (a) technical requirements of high−performance ac machines control, (b) most popular electrical machines and (c) control techniques. Key development trends including the dominance of ac adjustable speed drives in new applications, with basically three technical approaches (a) induction machine (IM), (b) permanent magnet synchronous machine (PMSM) and (c) switched reluctance machine (SRM). The aim of this paper is to provide complete overview with a strong practical aspect.

INTRODUCTION

Electrical machines/machineries are used in a wide power range from 10^{-6} W in electronic watches to more than 10^{8} W in power plants. They cover a wide range of torque of more than 10^{7} Nm in mills and speed > 10^{5} RPMs in centrifuge applications and flywheels.

Their applications make our live easier wherever physical activities take place, including transportation of goods and people or industrial production processes. It is estimated that for industrialized countries, about half of the consumed electricity is converted to mechanical energy.

There are some reasons why electric drives are so promising [2]: (a) electrical drives are very adaptable and versatile to almost any operating conditions or environments such as completely enclosed, submerged in liquids, exposed to explosive or radioactive surroundings. They do not need fuels and do not emit exhaust fumes so they do not have detrimental effect on their environment. Today's wire isolations withstand temperatures around 200°C which makes them possible to work in an extremely harsh environment. The acoustic noise is low compared to combustion engines. (b) Electric machines can work immediately with full load, without the need of heating up and usually have several times of overload capability. There is no need to refuel and service period is long compared with other propulsions. (c) EMs have low power loss 11at no−load conditions and can achieve high efficiency. (d) The controllability is easy and essential for the electric drives. Todays advanced control methods allow a wide range of speed and torque regulation in steady state as well as in dynamic conditions, where typically high performance is achieved by an electronic control. (e) Modern electric drives can operate in all four quadrants of torque vs speed plane as depicted in Figure 1. During braking (quadrants 2 and 4) the drive regenerates energy back to the source (machine is transforming mechanical to electrical energy) and vice versa for driving (quadrants 1 and 3).

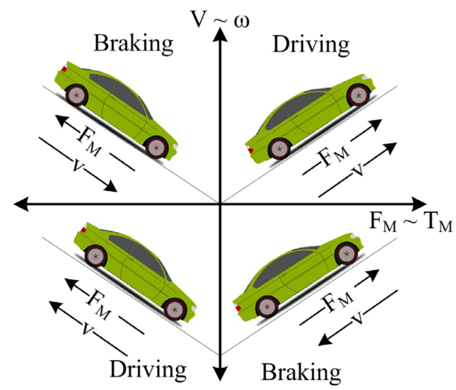

Figure 1. Operating Regimes of an Electric Drive

To complete the introduction, some characteristic which can be seen as a disadvantage of the electric drives, have to be mentioned [2]: (a) first of all, dependency on a continuous power source could bring problem mainly with vehicle propulsions. When there is no power rail available, an electric source has to be part of the vehicle which is usually bulky, heavy and expensive. In Figure 2, you can see that except power grid, the potential power sources could be: storage battery, rotating generator with combustion engine and then solar or fuel cells. The lack of storage battery advanced technologies hampers the spread of this energy−storage means. (b) Mainly due to the saturation of and complexity of cooling of electric machines the power density is lower compared with high−pressure hydraulic drives.

INTRODUCTION OF ELECTRIC DRIVE STRUCTURE

An electric drive is nothing than electromechanical energy conversion to control a mechanical load or process. The electrical power part means pe = v·i and mechanical power part implies $p_m = T_e \times \omega$, where p_e is electrical power (W), p_m is mechanical power [W], v is voltage (V), i is current (A), Te is mechanical torque (N.m) and ω is angular frequency (rad/s). As shown in Figure 1, an electric machine can naturally cross all four torque−to−speed planes so mechanical power could have a positive or negative sign based on the operating point. This fact is pointed by arrows inside the blocks in Figure 3. In this case the boost stage and/or powers source cannot handle negative power in the dc link rail has to be so called dynamic brake (DB block). Electric machines represent electrical load shown in Figure 2. At that moment, in a steady−state condition, when the converter changes supply frequency or phase voltage the electromotive force ($e_a = f(\omega, i_{ph})$) is suddenly higher than the supply voltage v_a and a current starts flowing back to the power source. The current is charging the dc link capacitor and brings the dc link voltage up. To avoid a dangerous high voltage, the dynamic break dissipates the energy in the power resistor as heat.

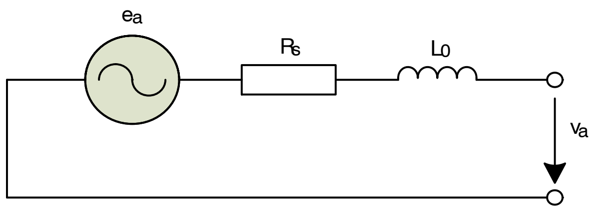

Figure 2. Equivalent Circuit of a Machine for One of Three phases

Today, modern drives make use of power electronic converters to (digitally) control this electro−mechanical energy conversion process. In addition, as drives are being integrated more and more in systems, communication buses to higher−level computer networks are essential to support commissioning, initialization, diagnostics and higher−level process control. Consequently, the main drive components consist of an electro−mechanical energy converter (typically an electric machine or actuator), a power ac−dc converter and an embedded digital control unit. The digital control unit directly controls the power semiconductor switches of the power electronic converter through the gate drivers to ensure correct power device switching, galvanic isolation, monitoring and the fastest protective features. Finally not only appropriate control hardware, sensors, high−speed digital logic devices and processors are needed but also suitable control algorithms. From this perspective, drive technology is a fairly modern development.

In terms of quantities to be measured for high performance drive there are couple feedbacks for accurate control. Basically it depends on what is the target application. For example, easy open−loop speed control of an induction machine such as shown in Figure 10 doesn't need any feedback quantities measurement. On the other hand, for a high−performance electric drive shown for example in Figure 3, it is recommended to measure the dc link rail voltage for protective and control reasons. The protective feature observes the dc link voltage increasing while an electric machine operates in dynamics and regenerative modes. The control purpose comes from fact that machine's voltage (line and phase) is generated by a pulse width modulation (PWM) (see Figure 4) as depicted in Figure 5. Carrier signal *c(t)* dictates the switching and sampling frequency and while *m(t)* represents the required (fundamental component).

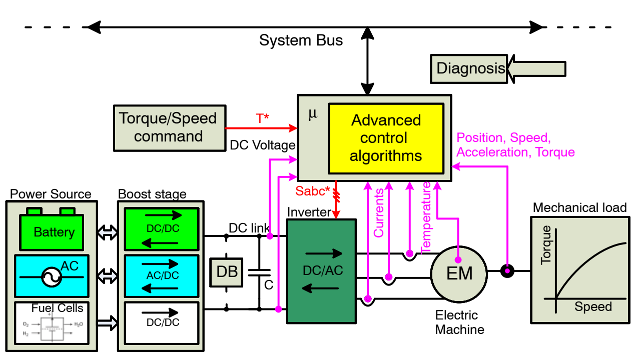

Figure 3. Electric Drive System Structure

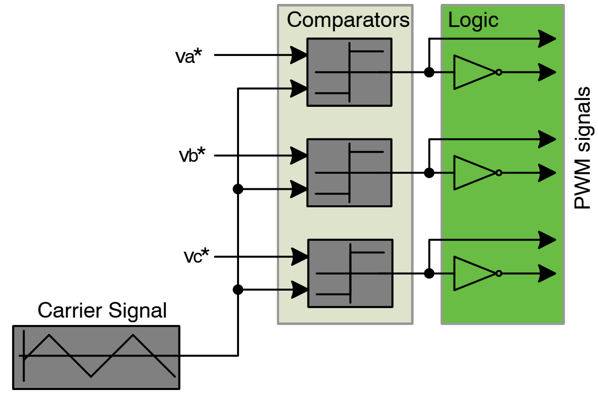

Figure 4. PWM Modulator for Three−phase HB Inverter

The instantaneous phase voltage is known cycle by cycle. Current measurement is also performed for protective and control reasons. In case of a symmetrical three phase neutral isolated electric machine, at least two of three current measurements are needed because $i_a + i_b + i_c = 0$, so the third one could be easily calculated. ($i_{a,\ b,\ c}$ are phase currents).

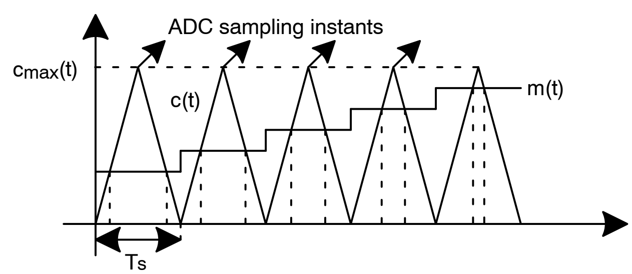

Figure 5. Pulse Width Modulation Pattern

The high−performance drives often contain a current loop (see Figure 18) to keep the required current at the desired value. It also allows electrical torque calculation and easier speed and position loop design. Because the current loop is always much faster than the speed or position control loop, for the design of these loops (speed and/or position) we can often neglect the electrical part of the structure. In addition, there is a possibility for precise electrical torque control.

Practically, the most common electric drives are fans or pumps. The traditional method of flow control consists of operating at a constant speed. For adjustable speed drives with a power grid frequency and voltage controller, you can adjust the flow by throttle opening. This is typical for induction machines where $T_e \approx V_s^2$, V_s being the stator voltage. The efficiency of this method of flow control is poor, as shown in Figure 6 [1], where the power consumption is plotted with the loading factor. Variable−frequency speed control of the drive with a fully open throttle reduces the power consumption, which is indicated in the figure. For example, with 60 % loading, the efficiency improvement can be up to 35%. Since drives operate most of the time in light–load conditions, the energy savings for a prolonged time period can be substantial. The payback period for investment cost of power electronics is small, compared to the energy cost which is high. In addition to the economic factor, efficient utilization of energy reduces the energy demand and correspondingly helps solve the environmental pollution problem, because most of the electrical energy is generated by fossil fuels.

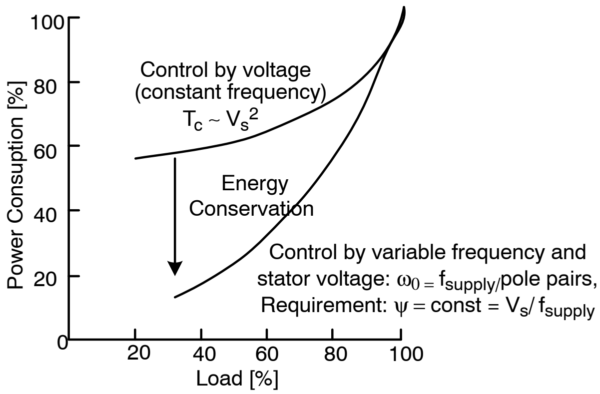

Figure 6. Energy–saving Characteristics with Variable–frequency Speed Control

MOTOR THEORY

Induction Machine

The most widespread motor is the induction machine (IM). Induction machine gained its leading position because of its simplicity, easy maintenance and low price. Disadvantage of IM is consumption of reactive power needed by the motor when operating. Induction machines are manufactured in a range starting from several watts up to several tens of MW.

Induction machines have two main parts – stator and rotor. Stator features windings embedded in slots and connected to grid. The three–phase stator winding is sinusoidally distributed and connected in either wye or delta configuration. According to the rotor type, we can distinguish two induction motor types – with wounded rotor and with cage rotor. Cage rotor is composed of metal bars casted in slots and shorted with end rings. A wounded rotor uses a similar winding as that found in the stator. Magnetic circuit of stator and rotor are made of laminated steel sheets. The air gap is uniform and scales with the motor power.

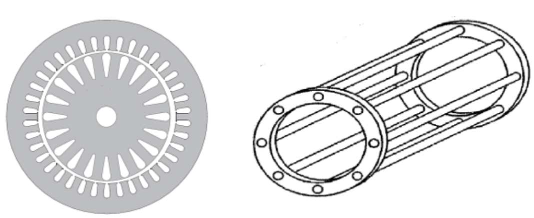

Figure 7. Cross–section and Rotor Cage of the Induction Machine

When three sinusoidal currents displaced in time by 120° from each other flow through the stator winding, an air gap flux density wave with radial direction is produced. Flux density is also sinusoidally distributed around the air gap and rotates at an angular velocity equal to the angular frequency of the stator currents. As the flux wave revolves around the rotor conductors, it generates voltage in them. As the rotor bars are shorted, a set of sinusoidally distributed currents is produced. Motor torque is a result of interaction between the air gap flux and induced rotor currents. In order to generate the necessary rotor current, the rotor mechanical velocity ω_r relative to the flux wave velocity ω_0 must exist and it is called the slip S, in per–unit system is defined as

$$S = \frac{\omega_0 - \omega_r}{\omega_0} \qquad \text{(eq. 1)}$$

Induction machine can work either as a motor, a generator or a brake. Transition between the regimes is smooth and is best described by torque–slip characteristic in Figure 8.

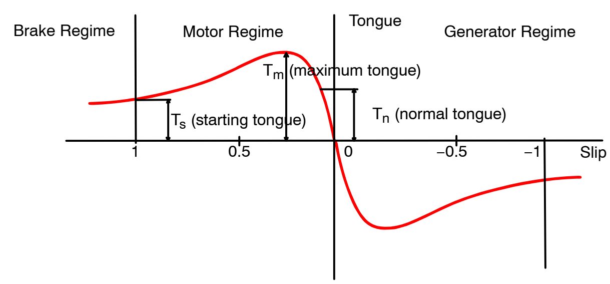

Figure 8. Torque–slip Characteristic of the Induction Machine

The torque characteristic is described by Kloss's eq. (2):

$$T = \frac{2T_m}{\frac{s}{s_m} + \frac{s_m}{s}} \qquad \text{(eq. 2)}$$

Where T_m is a maximum torque of the machine and Sm is a slip corresponding to T_m.

PM Synchronous Machine

Unlike in induction machine, the synchronous machine rotates always at the synchronous speed ω_0, which depends on the grid frequency and the number of machine poles. As in eq. (3) where f is the frequency of the ac supply and P is the number of pole pairs in the motor.

$$\omega_0 = \frac{2\pi f}{P} \qquad \text{(eq. 3)}$$

A conventional synchronous machine has the same stator winding as an induction machine. Stator generates a rotating magnetic field. Rotor has a winding connected to a dc source through slip rings. Magnetic circuit of the rotor can be solid or made of laminated steel sheets. During the operation, the rotor locks its position with the rotating field of the stator: the motor is said to be in synchronization. From the principle of operation the motor can't operate at different speed than synchronous, thus change of the motor load doesn't influence the rotor speed, but load angle (β) between stator and rotor field is changed. Figure 9 shows the load angle between the stator and rotor and torque characteristics of the synchronous motor.

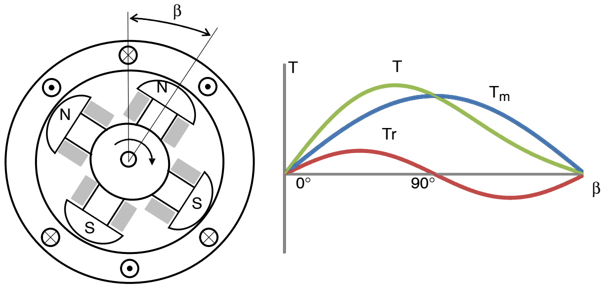

Figure 9. Load angle and Torque Characteristic of the Synchronous Machine

The main part of the torque characteristic is Tm. It is a sinusoidal function and it scales approximately according to eq. (4).

$$T_m = F_{m1} F_{m2} \sin(\text{beta}) \qquad \text{(eq. 4)}$$

Where F_{m1} is magneto−motive force (MMF) of stator and F_{m2} is MMF of the rotor.

The second part of the torque is reluctance torque Tr which depends only on the shape of the rotor due to a different magnetic reluctance in the d and q axes. Torque of the motor is sum of T_m and T_r. In permanent magnet synchronous machine (PMSM), the rotor winding is replaced by permanent magnets (PM). This solution offers several advantages such as better reliability due to the absence of slip rings and brushes, better efficiency and cooling, because no dc losses are present in the rotor. Disadvantages of PMSM are higher price, risk of demagnetization of the permanent magnets and impossibility of changing the rotor magnetic field. In the market, several types of PMSM exist and differ in the way magnets are embedded into the rotor. Three types are mostly used in industry and appear in Figure 10.

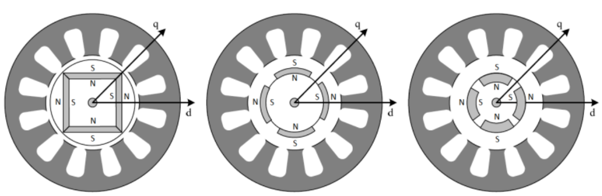

Figure 10. Three Main Types of PMSM from Left: Interior Mounted PM, Surface Mounted PM, Embedded PM

The position of the rotor magnets has a great impact on the longitudinal and transverse inductance (L_d and Lq) of the machine. A motor with surface−mounted magnets offers the best utilization of the magnets. On the other hand, this construction is not mechanically robust, magnets are liable to demagnetization, and eddy current losses are present in them. The ratio between L_d and Lq (saliency ratio) is around 1.1. Above mentioned disadvantages are solved by motor with interior mounted magnets. As the magnets are mounted inside the rotor, they are mechanically and electrically protected. Disadvantage is high leakage flux (typically 1/4 of the total flux) of the PM. Because of the geometry of the rotor (saliency ratio of around 2.5) a significant reluctance torque is present. The reluctance torque is used mainly under excitation regime for reaching higher speeds. A motor with surface interior mounted magnets combines the previously mentioned types. Saliency ratio is around 2.

Switched Reluctance Motor

The switched reluctance motor (SRM) presents a simple arrangement. Rotor and stator have both salient poles. The rotor does not feature winding and magnets and it is made of laminated steel sheets to minimize eddy−current losses. Torque is created only by the reluctance effect. Every stator tooth has its own winding creating a stator pole. Two opposite stator poles are connected either in series or in parallel. The motor has to be excited by a sequence of consequent pulses forcing the motor to rotate. When the rotor pole moves in line with the stator pole it is said to be in an aligned position. This is a position of the maximal stator inductance.

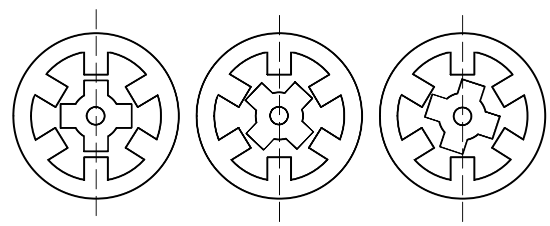

Figure 11. Rotor Position of the SRM a) Aligned Position, b) Unaligned Position, c) Partially Aligned Position

The minimal stator inductance occurs when the axis between two rotor poles align with the stator poles. This is called an unaligned position. Figure 12 Shows triangular shaped inductance profile along the stator of the SRM.

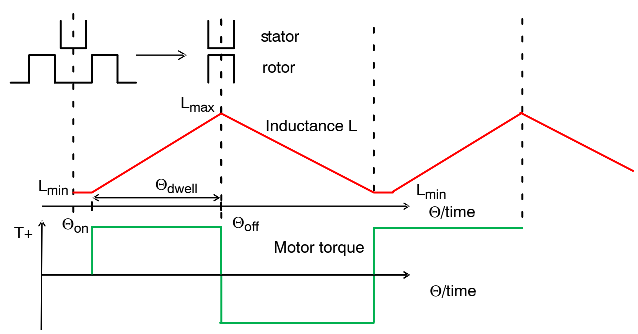

Figure 12. Rotor Position of the SRM a) Aligned Position, b) Unaligned Position, c) Partially Aligned Position

When current flows through the stator phase, torque is created in the direction of the increasing inductance. The torque direction depends only on the sign of $dL/d\theta$, where dL represents a change on the phase inductance and $d\theta$ is a change of the rotor position. When poles are coming to the aligned position, the term $dL/d\theta$ is positive, thus the torque is positive too, no matter the stator coil current direction. When rotor poles are leaving the aligned position and approach the unaligned position, the torque is negative. The motor torque in all rotor positions is controlled by the applied voltage and by the switching turn−on and turn−off angle θ_{on} and θ_{off}. The interval between θ_{on} and θ_{off} is called the θ_{dwell}. It is evident from what is mentioned above, that for a proper operation the SRM needs a rotor position feedback for the motor phase commutation. As feedback, rotary encoders or hall sensors can be used. Nowadays algorithms for sensorless control exist, most of them are based on evaluating the magnetic circuit parameters that depend on the rotor position.

A SRM is a simple construction machine suitable for high−speed applications mainly in the white−goods industry. Most of the losses are present in the stator which has good cooling. Because no magnets are present in the rotor, the maximum operating temperature can be higher compared to a PMSM. The motor torque is not dependent on the phase current polarity. It can, for certain applications, reduce the amount of semiconductor switches required for driving. Disadvantages of the SRM are significant torque ripple and noisy operation. The reduction of these problems leads to multiphase engines which are difficult to manufacture and to drive.

CONTROL OD AC ELECTRIC DRIVES

V/f Control Strategy

The open−loop volts/frequency (V/f) control of an induction motor is the most popular speed control method because of its simplicity. These types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 60 Hz or 50 Hz power supplies for constant−speed applications. For adjustable−speed applications, frequency control is straightforward as could be seen from eq. (3). However, voltage is required to be proportional to frequency so that the flux ($\psi = V_s/\omega_e$) remains constant, neglecting the stator resistance Rs drop. Figure 13 shows the block diagram of the easiest open loop V/f speed control method [1].

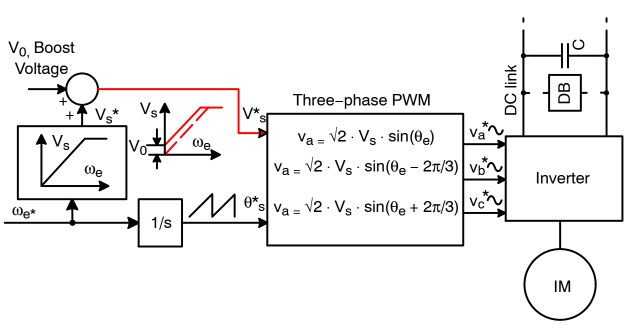

Figure 13. Open Loop Vs/f Speed Control of an Induction Machine

The open−loop operation implies the absence of feedback signals normally needed for the control. The frequency ω_r* is the required variable (electrical rotor angular speed where mechanical speed is $\omega_m = \omega_r/Pole\ pairs$) because it is approximately equal to speed ω_e (see equation (1)), neglecting the small slip frequency ω_{sl}, of the machine. The phase voltage Vs* command is directly generated from the frequency command by the function generator, so that the flux ψs remains constant. If the stator resistance and leakage inductance of the machine are neglected, the flux will also correspond (only in steady state) to the air gap flux ψ_m or rotor flux ψ_r. As the frequency becomes low, the stator resistance voltage drop starts to be a major part of the stator voltage, thus weakening the flux. The boost voltage Vo is added so that the rated flux and corresponding full torque become available down to zero speed. Note that the effect of boost voltage becomes negligible at higher frequencies. The ω_e* signal is integrated to generate the angle signal because $\theta = \iota\omega_{dt}$ where θ is a position. The corresponding sinusoidal phase voltages (v_a, v_b, v_c signals) are generated by the expressions shown in the figure.

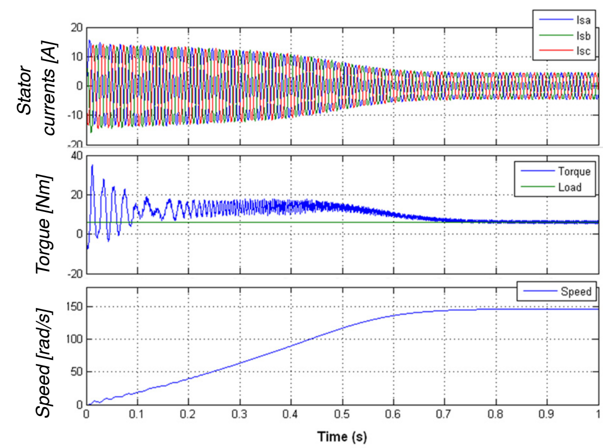

Figure 14. Startup of an IM with Open Loop V/f Speed Control (Simulation)

As illustrated, the V/f open loop control has the disadvantage that the torque scales with slip. Mainly during dynamics when the slip varies due to the load. In addition, line voltage variation, incorrect V/f function generator, stator resistive drop variation by current, and machine's parameter variation causing incorrect flux value represent some annoyances brought by this configuration. Figure 14 shows the typical open loop induction machine startup at load condition [7]. For instance, the torque is increased by incrementing the slip and the flux tends to decrease. Note that the flux variation is always sluggish. If the flux weakens, the developed torque will decrease the machine's acceleration or deceleration capability will decrease. This temporary flux drop reduces the torque sensitivity to slip and sluggish response time. It also reduces potential instabilities during dynamic changes. An improvement of open−loop V/f control is closed−loop speed control with slip regulation as shown in Figure 15 [1]. Here, the speed loop error generates the slip command $\omega_{sl}{}^{*}$ through a proportional−integral (PI) controller and limiter. The slip is added to the feedback speed signal to generate the stator frequency command as shown. The required frequency ω_r* also produces the voltage command through a V/f function generator, which incorporates the low−frequency stator drop compensation. Since the slip is proportional to the developed torque at constant flux, the method can be considered as an open−loop torque control within a speed control loop. With a step in speed command, the machine accelerates freely with a slip limit that corresponds to the stator current or torque limit, and then settles down to the slip value at steady state as dictated by the load torque. If the command speed ω_r* is reduced by a step, the drive goes into regenerative dynamic braking mode and decelerates with constant negative slip $-\omega_{sl}$ as indicated.

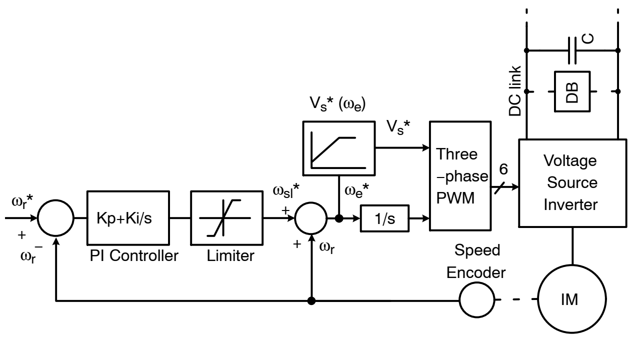

Figure 15. Close Loop Speed Control with V/f Control

Vector or Field−Oriented Control Strategy

So far, we have discussed scalar control techniques of voltage−fed inverter drives. Scalar control is somewhat simple to implement, but the inherent coupling effect (i.e., both torque and flux are functions of voltage or current and frequency) gives sluggish response and the system is easily prone to instability because of a high−order (5th−order) system effect. The foregoing problems can be solved by vector or field−oriented control. The invention of vector control originates in the beginning of 1970s. At that time, the demonstrations that an induction motor could be controlled like a separately−excited dc motor, brought a renaissance in the high−performance control of ac drives. Vector control is applicable to both induction and synchronous motor drives. Undoubtedly, vector control and the corresponding feedback signal processing, particularly for modern sensorless vector control, are complex and the use of powerful microcomputer or DSP is mandatory. It appears that it will eventually be accepted as the industry−standard control for ac drives. Space vector theory combines the individual phase quantities in to a single vector (see left side of Fig. 16) in the complex plane allowing simple handling and transformation to any rotating frame (right side in Figure 16) [6, 16]. In the space vector transformation, the direction of the magnetic axis of each phase is assigned to its electrical quantities as could be seen in Figure 16 (left side). If the real axis a is aligned with the magnetic axis of phase a, as shown in Figure 16, the transformation for the phase currents is given by [7]:

$$i_{-\alpha\beta} = K\frac{2}{3}\left(i_a(t) + i_b(t)e^{j2\frac{\pi}{3}} + i_c(t)e^{j4\frac{\pi}{3}}\right) \qquad \text{(eq. 5)}$$

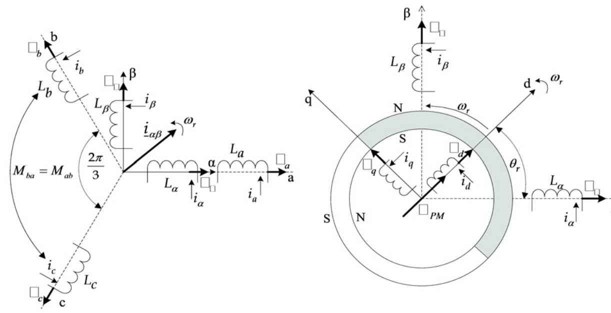

Figure 16. Left: Definition of Stationary Coordinates [abc] and [αβ]. Right: Transformation [αβ] to the Rotating [dq] Coordinates (for PMSM)

A major advantage of this transformation is that the space vectors may be expressed in any arbitrary rotating [dq] frame by means of a coordinate rotation eq. (6). Of particular interest for the control of synchronous machines is the rotating frame oriented with the rotor field i.e. $\varphi = \theta_r$:

$$i_{-dq} = i_{-ab\alpha\beta}e^{-j\varphi} \qquad \text{(eq. 6)}$$

Equation (5) represents the dynamic model of the PM machines (non−salient and salient respectively) in a rotating reference frame (which is a convenient frame to implement field−oriented control) and we call that [dq] frame fixed on the rotor developed by R. H. Park [15, 16]. Furthermore, synchronous rotation with the rotor saliency effectively eliminates any variations of the inductance matrix with rotor position. Obtaining the synchronous [dq] frame model requires the application of eq. (6) to the standard mathematical model of PMSM in [abc] coordinates. The result of this operation is [4]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \frac{d}{dt}\left\{\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}\right\} + \begin{bmatrix} R_s & -L_q\omega_r \\ L_d\omega_r & R_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \underbrace{\omega_r\begin{bmatrix} 0 \\ \Psi_{PM} \end{bmatrix}}_{BEMF} \qquad \text{(eq. 7)}$$

The vector control structure is easier to be explained for a PMSM. The regulation structure is derived by expressing the instantaneous torque of a PMSM. The torque instantaneously developed by the PMSM can be found, in the [dq] frame fixed on the rotor, in the form [3]:

$$T_e = \frac{3 \cdot p_p}{2} \cdot \left(\underbrace{\psi_{PM} \cdot i_q}_{\text{magnet torque}} + \underbrace{i_d \cdot i_q \cdot \{L_d - L_q\}}_{\text{reluctance torque}} \right) \qquad \text{(eq. 8)}$$

Where p_p is a number of pole pairs, i_d, i_q, L_d, L_q are stator currents and inductances in the [dq] frame fixed on the rotor, respectively. In equation (8), two components of the torque can be identified: the first term, usually noted as magnet torque, is directly proportional to i_q and independent of i_d. The second term is the reluctance torque, which is only present in a salient machines where $L_d - L_q \neq 0$ and is proportional to the current product $i_d i_q$. In the PMSM with surface mount magnets, the reluctance torque is equal to zero and therefore the torque is regulated only by i_q. The d−axis flux on the other hand is fixed by the rotor magnets, except during flux weakening, and i_d is normally controlled to zero to achieve maximum torque per ampere operation. This makes the control structure for this type of machines very simple. For IPMSM, it is possible to optimize control with to minimize electrical losses and/or optimize the drive efficiency. This leads to a minimum converter rating but it is sacrificing fast transients. The reluctance torque is significant with IPMSM. In these motors, more torque per each ampere of stator current can be achieved by advancing the stator current vector angle and forcing some negative id current. The torque in pu (per unit) units could be derived from eq. (8) as $T_{e\_pu} = i_{q\_pu} (1 - i_{d\_pu})$ where stator current amplitude is $|Is| = \sqrt{(i^2_q + i^2_d)}$. Figure 17 shows the constant $(T_{e\_pu} = 1 \text{ or } T_{e\_pu} = 2)$ torque as function of i_{d_pu} and i_{q_pu} stator current components.

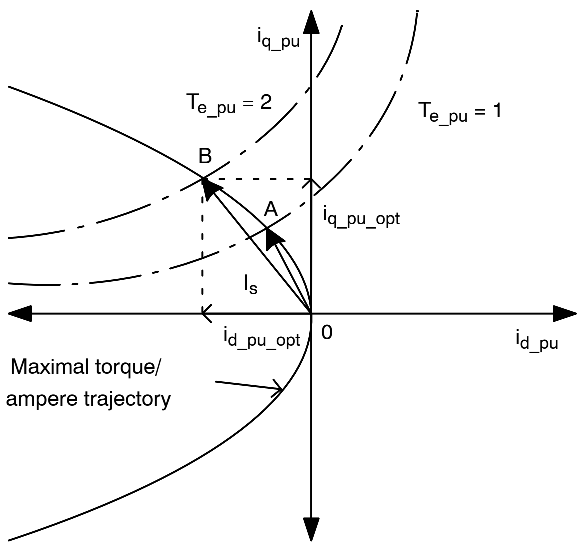

Figure 17. Maximum Torque/Ampere Trajectory on Constant Torque

Consider, for example, $T_{e\_pu} = 1$ locus. It is evident that the distance on the locus from the origin represents the amplitude of stator current |Is|. Point A on the locus represents minimum stator current which means maximum torque/ampere criteria will be satisfied for T = 1 with stator current |0A|. The particular mapping (function gen. 1, 2 in Figure 18) of torque reference T_e* into i_d* and i_q* is not unique but is given by an optimization criteria such as maximum torque per ampere. The control of the currents is performed in the rotor coordinates [dq] by PI regulators, also used in the speed loop circuitry. By expressing complex mathematical equations in [abc] stationary coordinates by one space vector in any rotating coordinates [dq] eq. (7) gives us advantage to “see” all values as dc terms and it eliminates the dependency on the quantities on rotor position. These two facts make the independent control of excitation and torque easy. They also simplify the design of PI regulators and control structures. Figure 19 shows the key quantities in a vector−controlled PMSM machine during startup and reversing. Typically high dynamics of the 2.5−kW drive is reached during startup from 0 RPM to 1000 RPM in less than 70 ms and the transition from 1000 RPM to −1000 RPM is obtained in less than 150 ms. The two components of space vector id and iq are decoupled in dc but not during the dynamic phase. Figure 19 contains both components of stator voltage vector $i_{\alpha\beta}$ which are ac because the [αβ] frame does not rotate with the rotor but remains stationary.

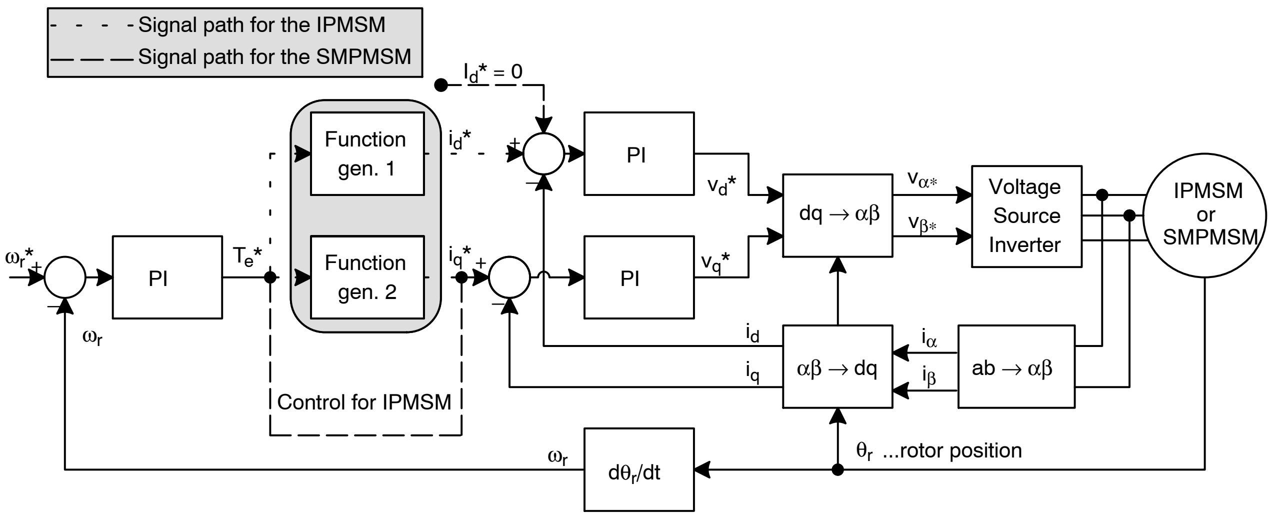

Figure 18. Vector Control Structure of the SMPMSM

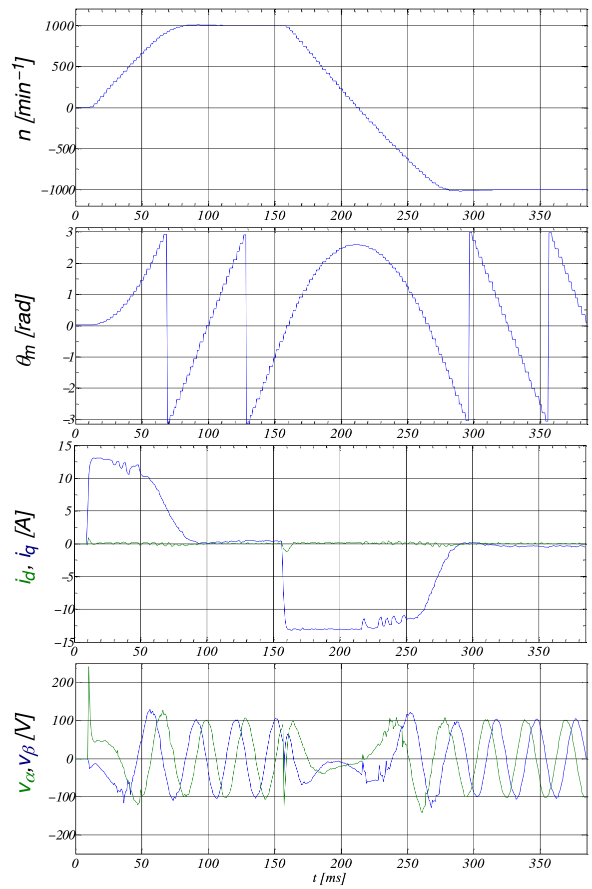

Figure 19. Basic Quantities of a Vector Controlled PMSM (Experiment)

Control of Switched–Reluctance Machines

Switched–reluctance motors (SRMs) and their performance characteristics were discussed briefly in the second section. Figure 21 describes a voltage inverter for a SRM as a device featuring eight stator poles and six rotor poles. A pair of opposite stator poles is supplied by a converter phase winding which carries a bipolar current. The current pulses in the phases are synchronized with the rotor position. Figure 22 shows an SRM drive structure where a four–phase, voltage–fed inverter excites the respective machine phases. The machine is shown with a position sensor that also generates the speed signal. Phase *a*, for example, is excited by IGBTs Q_a and Q_a'. When the devices are turned off, the energy stored in the inductance flows to the source through the freewheel diodes.

All four machine phases are excited sequentially in synchronism with the rotor position to set a bipolar torque. In the speed control system shown in the figure, the speed loop generates the absolute current command |I*|, which is linked with the torque through $T_e = 0.5 \times m \times i^2$, where *m* is the inductance slope [1, 5]. In the constant–torque region, the phase current magnitude is controlled by HB (hysteresis–band) PWM technique or standard PWM modulation [5]. A particular phase is enabled by the commutation angles θ_{on} and θ_{off} (see Figure 20). At high speeds, as explained before, the current control is lost due to high BEMF (back electromotive force $BEMF = \omega_r\, d\psi/dt$, where ψ is flux linkage). In other words we don't have enough voltage in the dc link to push the current, which leaves only the single pulse angle control mode. For the six–pole rotor, the period of the inductance profile is $2\pi/6$. The drive can be controlled in all four quadrants.

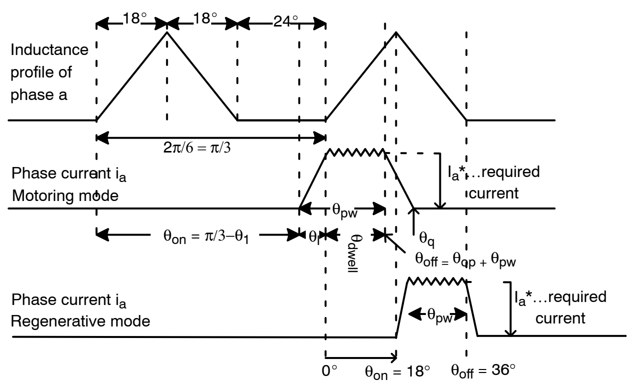

Figure 20. Waveforms for 6 Poles SRM Explaining Commutation Angles

Based on Figure 20, in the motoring mode, current *ia* is turned on at an advance angle θ_1, and it rises linearly to the magnitude *I* at the reference point (0°), which is given by the relation $\theta_1 = I \times (Lm\ \omega_r/V_{dc})$, where Lm = minimum inductance, ω_r = motor speed [1, 5]. Based on this observation, we can calculate $\theta_{on} = \pi/3 - \theta_1$. The current amplitude is maintained at a desired value by the Hysteresis Band (HB) PWM or by the standard current–loop control–based PWM modulator. Then θ_{off} is given by $\theta_{off} = \theta_1 + \theta_{on} + \theta_{dwell} = \theta_{on} + \theta_{pw}$, where θ_{dwell} = dwell angle (fixed value) and θ_{pw} = pulse width angle. The current reaches zero at an angle θ_q. The dwell angle is restricted so that θ_q does not extend much in the negative inductance slope [1]. The decoder block in Figure 22 decodes and evaluates the actual rotor position. Based on the actual position and the required regime of a SRM, the decoder generates the appropriate phase sequence. A torque control loop can be added within the speed loop to enhance the response, but the feedback torque computation becomes somewhat more complex. A position control loop can also be added over the speed loop, if desired. Figure 23 shows startup dynamics and steady–state operation of an unloaded four–phase SRM. There are all phase currents with their typical non–linear shape at steady state, individual current torque production and total torque "seen" on the shaft. The main disadvantage lies in a relatively high torque ripple as it can be seen in the figure. This ripple could bring serious noise or vibration problems.

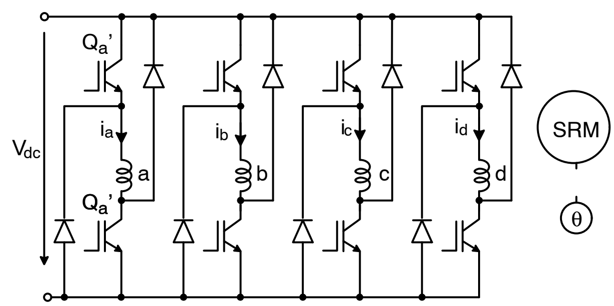

Figure 21. Four–phase Power Inverter for SRM Control

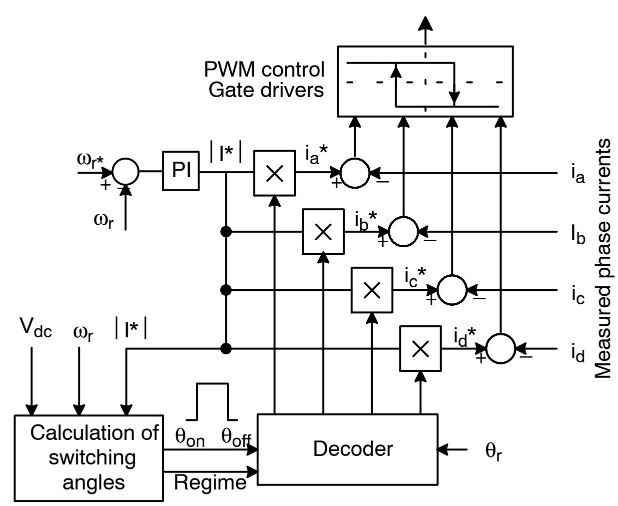

Figure 22. Four–phase Switched Reluctance Motor Control Structure

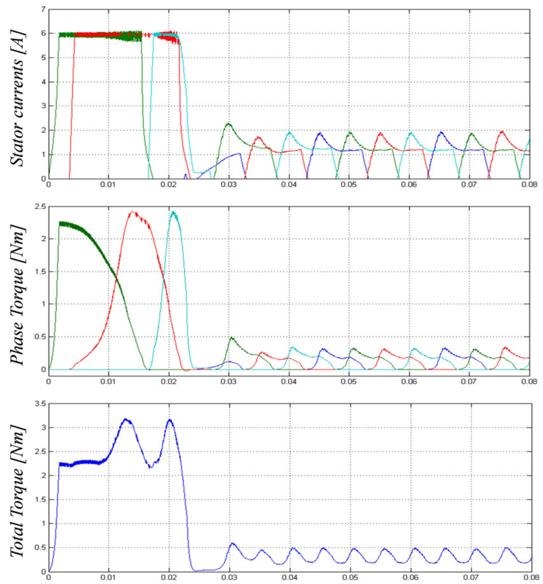

Figure 23. Basic Quantities for Four − Phase SRM (Startup, Experiment)

TRENDS

Based on Figure 3, we can identify couple of trends improving the general structure of modern ac drive. It was mentioned that the required voltage and current sensors are mandatory for control and safety reasons. These voltage sensors are not bulky and do not impact the overall system BOM. However, for the control of ac drives such as the vector−control and direct−torque control, the rotor position is required to perform vector rotations and to control speed/position and torque too. In a typical application, the rotor position can be obtained by using mechanical speed (position) sensors like encoders or resolvers. Unfortunately, the use of these sensors will increase the overall cost and weight of the systems. Reliability and noise immunity of the systems will also be affected

Trends in Control Techniques

Research in the area of sensorless control of the PMSM is beneficial because of the elimination of the feedback wiring. It makes the systems more reliable and cheaper. It is well known that two different methods exist to estimate the speed and rotor position in a vector−controlled ac machine. In the first category (model−based method), information is obtained from the back electromotive force (BEMF see eq. (7)). Figure 24 shows the simplified structure of such architecture. These estimation techniques show good performance in the medium− and high−speed range. Since the back EMF vanishes at low speed, low−and zero−speed operation is challenging. The situation is depicted in Figure 25. The figure shows the measured RPM and estimated speed (^) during start−up and reversing transients of a 2.5−kW PMSM. There is a strong instability in the zero− or low−speed range causing dangerous speed overshoot. In the second category (non−model based method), a high−frequency (HF) carried signal is added (see Figure 27), and information about the rotor position or speed is obtained from the current response (by modulator). The basis for the injection methods (self−sensing method) relies on a certain amount of saliency present in the machine. There are several sources of saliencies in ac machines. For example: rotor inherent saliency, saturation−based saliency (yoke, teeth), rotor stator teeth harmonics, lamination direction−based saliency, eddy current−based saliency, rotor eccentricity saliency etc. Figure 26 shows some experiment done with a high−frequency signal injectio technique. These are measured and estimated speeds(RPM) during start−up and regulation to zero speed! We can see that this technique makes the control at zero speed possible and offers position control without position sensor!

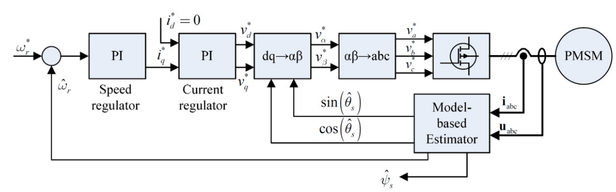

Figure 24. Structure of a Model Based Sensorless Vector Control of PMSM

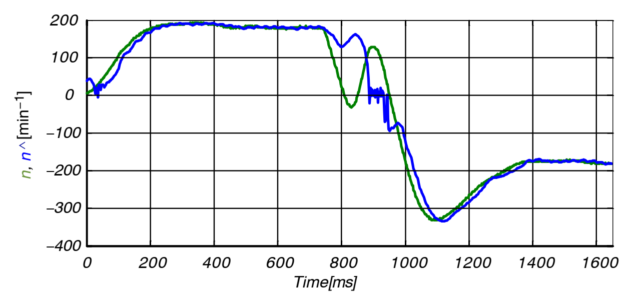

Figure 25. Model Based Sensorless Vector Control of PMSM (Experiment)

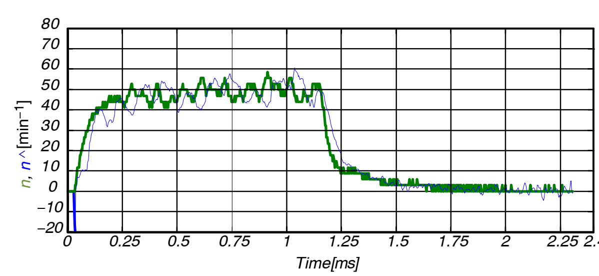

Figure 26. Non−model−based Sensorless Vector Control of PMSM (Experiment)

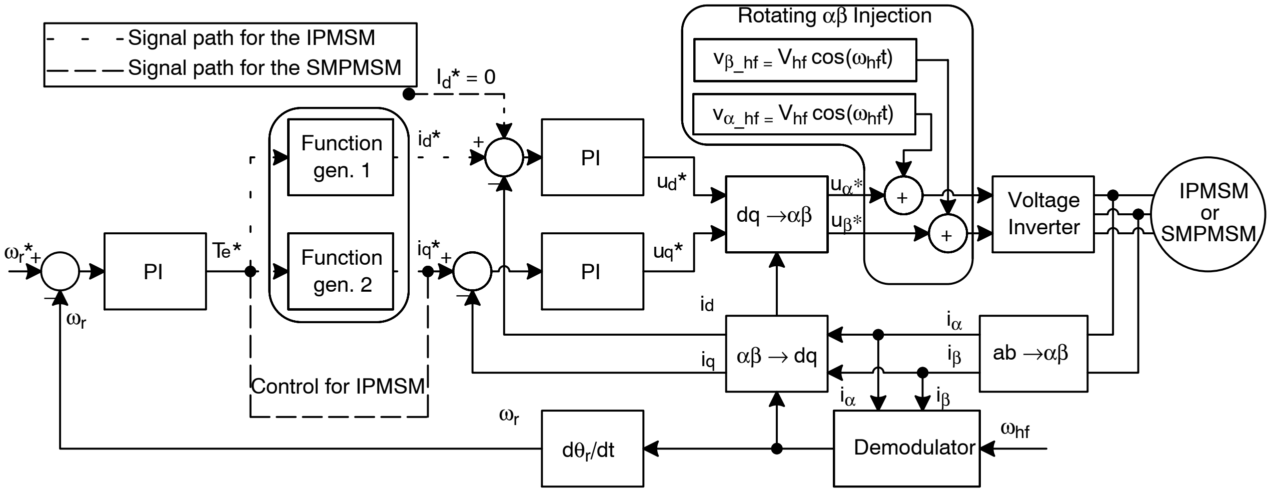

Figure 27. Model Based Sensorless Vector control of PMSM (Experiment)

Trends in Voltage Source Inverters

Power conversion in low and middle power ranges is getting much more demanding in terms of efficiency and power quality requirements. This is especially true in applications where renewable sources, such as wind, solar or battery (EV or HEV), have taken a primary role as energy suppliers. The market also demands integration of the power converter into the overall system. This leads to enhanced efforts in designing new power topologies or utilization of existing but complex structures such as multilevel topologies, precisely optimized active and/or passive components or accurate customer designs optimization. In Figure 28, you can see a three−phase neutral point clamp inverter (NPC) for electric drives where traditionally three−phase half−bridge is industry standard. For high dc link voltages, these devices can be connected in series, but the problem of matching arises. This may be solved by means of multilevel (more than two levels) inverters too. In Figure 28, the dc−link capacitor has been split to create the neutral point 0. The experimental result is depicted in Figure 29 where we compare output voltage and current for half−bridge and three−level NPC. Figure 29 shows immediately, online and at the same time, that a standard half−bridge produces only two levels of output voltage which means: (a) high *dv*/*dt* stresses passive and active components, (b) high *dv*/*dt* produces high switching loss, (c) high *dv*/*dt* makes gate drive more difficult, (d) voltage pattern produces higher ripple current and high *dv*/*dt* produces higher EMI in comparison with three−level topology. The impacts of high *dv*/*dt* to the ac machines follows: they cause *dv*/*dt*−induced problems, such as machine winding insulation deterioration, bearing current, and machine terminal overvoltage. One of the ways to solve the problem is to reduce the *dv*/*dt* by soft switching, installing low−pass *LC* filter at the machine terminal or increase the number of levels in the output phase voltage. Multilevel inverters offer the advantages of easy voltage sharing of devices, lower *dv*/*dt*, and improved PWM quality. The disadvantages are the difficulty of neutral−point voltage balancing, more numbers of devices and more gate drivers.

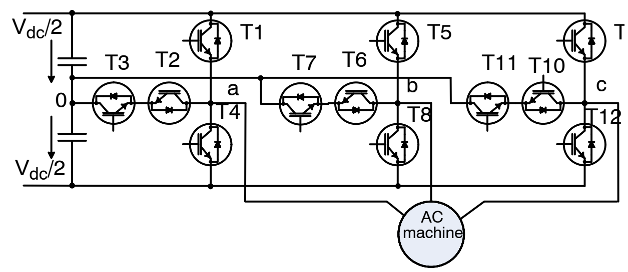

Figure 28. Three−phase Voltage Source Neutral Point Clamp Inverter as Advanced Topology for AC Machine Supply

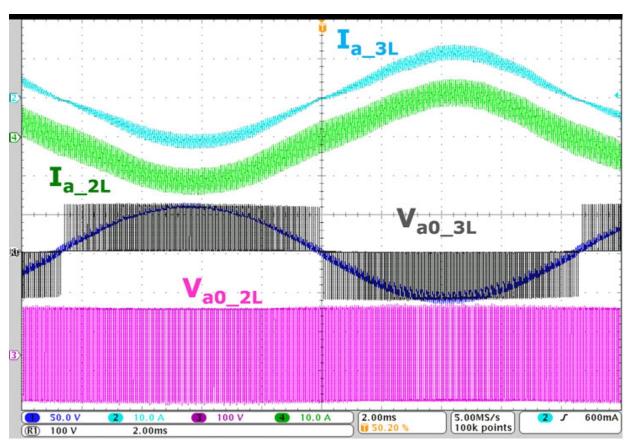

Figure 29. Comparison between Two Level Power Topology such as Conventional Half−bridge and Three−level Advanced Topology

Trends in AC Machines

European commission issued a regulation No. 640/2009 with amendment No. 4/2014. This regulation established minimum efficiency requirements for low−voltage motors. From January 2017 motors from 0.75 kW to 375 kW have to meet the efficiency requirements IE3 of IEC 60034−30−1 as shown in Figure 30. Obtaining such an efficiency level requires precise finite−element analysis method (FEM) simulations of the machine. From simulations, precise distribution of the magnetic field in the machine and in the air gap can be identified. Another market trend is improving overall motor reliability and fault prevention. This can be achieved by placing a smart sensor inside the motor. This sensor can monitor various motor parameters such as bearing vibrations, surface temperature, motor speed, supply frequency etc., these values can be wirelessly sent to a smartphone or other device. By monitoring the motor parameters, faults can be preceded and maintenance can be planned in order to reduce motors downtime.

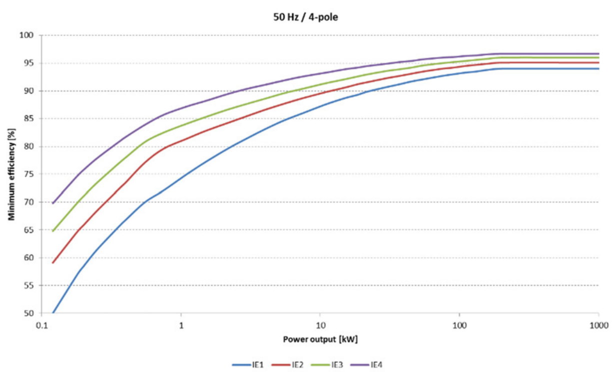

Figure 30. IE Class for 50 Hz 4−pole IM According to IEC 60034−30−1:2014

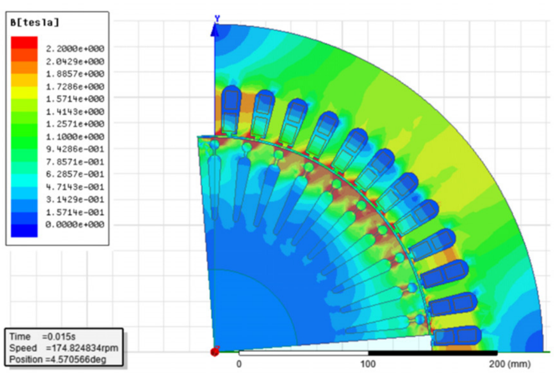

Figure 31. FEM Analysis of Startup of an Induction Machine

CONCLUSION

In the first part of the paper, we gave a general description of electric drives. This section described mainly pros and cons of electric drives versus combustion and pressure hydraulic actuators. As part of mandatory knowledge in the electric drive “world”, the torque−to−speed plane and electric machine regimes were introduced too. The generic electric drive structure was introduce to show how mechanical, power electronics and control functions, hardware and software, are interleaved in modern electric drive. In the second part, the constructions of three types of motors were described together with the principles of their operation. The induction motor for its robustness and easy construction is the legitimate industry market leader. New material development in permanent magnets and pursuit for high efficiency make the PMSM a good selection for compact and effective drives. SRM has strong representation especially in low−power and high−speed applications where it can benefit from easy construction and wide speed variability. Its disadvantages like a pulsating torque can be accepted or used. The third section describes two approaches how to control ac machines with the sinusoidally−distributed stator windings: (a) scalar (V/f) control and (b) vector control. The formerly−mentioned arguments are traditional methods for loads such as fans or pumps with poor electrical and mechanical dynamics. Vector control offers a high−performance ac machine control method but it is more complex, requires more sensors and more detailed parameters of the controlled machine must be known. A simple electric drive with SRM is defined including waveforms proving the evidence of high torque ripple of the SRM and a simple control technique. Electric drives with SRM tend to be extremely popular owing to their simplicity, low cost and robustness. In the last section we tried to indicate three major trends existing in electric drives.

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