Section 4.4 - CSI non-slaient pole synchronous motor drive

4.4.1 Performance with current-source inverter (CSI) drive

Current-source driven synchronous motor drives generally give higher dynamic response and better reliability because of the higher dynamics of current control possible with current source inverters and the automatic current limiting feature in a CSI drive. In variable-speed applications, the synchronous motor is normally driven from stiff current sources rather than voltage sources. Two CSI schemes are in general use. In one scheme, sinusoidal currents in the three phases are continuously regulated with SPWM inverters employing MOSFETs. Low power servo drives using permanent magnet synchronous motor fall in this category. Three-phase SPWM IGBT inverter driven synchronous motor drives in low and medium power synchronous motor drives used in the process and mill drive industries also fall in this category. Such SPWM inverter drives require continuous position feedback from a high resolution (>10 bits) from optical encoders or magnetic resolvers. The continuous position signal is used to control the amplitude and phase angle of the three-phase sinusoidal current supply relative to the back emf phasors ($E_f$) of each phase.

In another scheme, which are found in large power applications, quasi-square-wave currents of variable amplitude are delivered to the motor using naturally commutated inverters which employ thyristors. These drives do not require continuous position feedback signals but only use the six commutating signals (from three shaft-mounted Hall position sensors) over one cycle of the supply current. The Hall sensors allow the phase angle of the quasi-square-wave current waveforms to be synchronised with respect to the zero crossings of the line-line voltages of the motor. This control scheme is quite similar to the scheme for the BLDC drive and its position sensor requirement is rather modest and simpler that the sensor for the scheme with continuous control.

The scheme of figure 4.4.1 is preferred for lower power drives where very high dynamic response is required from the drive. The three-phase sinusoidal currents of variable amplitude and frequency are produced and regulated within the inverter. The inverter typically employs gate turn-off switches, such as the IGBT, MOSFETs, and pulse-width modulation techniques within the inverter. Motor phase currents are sensed and used to close independent current controllers for each phase as indicated in the figure 4.4.1. Normally, two current controllers suffice for a balanced star-connected motor. In this scheme, three-phase sinusoidal AC currents are supplied to the motor, the amplitude and phase angle of which can be independently controlled, as desired.

The rotor position sensor E is a position encoder which can be of absolute or incremental types. Absolute encoders produce Gray or BCD coded discrete signals of 8 or more bits using as many optical or magnetic transducers as the number of bits. Incremental encoders produce two square-wave signals which are ±90 degree displaced from each other depending on the direction of motion. The frequency of these two signals (A and B outputs) are proportional to the speed of the shaft. In addition, an index short duration (Z) pulse signal is produced once per revolution. The absolute position of the shaft can be determined from these three signals, to a resolution which is given by the number of pulses/revolution of the encoder.

The digital position of the rotor from E allows, via the Look-Up-Table, the generation of the three current references of the desired amplitude $m$ and angle $\gamma$. The angle $\gamma$ refers to the phase...
angle of the current phasor with respect to the back emf phasor of each phase. The actual phase currents are forced to follow these references by the high-gain closed-loop PWM current controllers.

![Diagram of a synchronous motor drive](image)

Figure 4.4.1 Current regulated PWM (CRPWM) synchronous motor drive

The scheme of figure 4.4.2 is used in high power synchronous motor drives. A variable DC current source is established by closed loop control of a DC power supply. The phase angle controlled AC-DC thyristor bridge converter terminated with a large DC link inductor serves as the regulated but stiff current source. The scheme is suitable for large synchronous motors for which thyristor switches are used in the inverter. The current loop is established by sensing the DC link current and by using a closed loop current controller which continuously regulates the firing angle of the front-end controllable AC-DC rectifier. Switching of the six thyristors are synchronised with the phase back emf waveforms, the zero crossings of which are obtained from three Hall sensors (H) mounted on the shaft. It will be shown later that with this type of control, the motor torque is proportional to level of the DC link current.

Note that the dotted trace of figure 4.4.3 represents the fundamental component of the quasi-square current of phase ‘a’. Switching of the six thyristors in converter driving the motor takes place autonomously, arranged by position sensor \( E \) and the converter switching logic. The angular displacement \( \gamma \) of the phase current waveform (or its fundamental component) with the respect to the back emf waveform of the corresponding phase is indicated in figure 4.4.1. Due to the presence of the large DC-link inductor, phase currents may be considered to remain essentially constant between switching intervals. The quasi-square phase current waveforms contain many harmonics, which may be responsible for some torque pulsations for this drive at low speed.
The above scheme uses a thyristor converter for driving the motor. The motor is usually operated with over excitation, so that the thyristor switches can commutate with the help of the motor back emf for turning the thyristors off at the end of a conduction period. Note that with over-excitation, the motor current leads the back emf so that when a phase current passes through zero, the anode-cathode voltage across the conducting thyristor is favourable i.e., the outgoing thyristor is reverse biased by the back emf of the motor. This type of drive is normally used in very large power applications for which the only suitably rated, naturally commutated thyristor switches are available.

The motor can be reversed easily by reversing the phase sequence of switching of the inverter. The drive can also be braked regeneratively by increasing the firing angle of the input rectifier above 90° while maintaining the DC link current at the desired braking torque level until braking is no longer required. The rectifier now absorbs the energy of the overhauling motor, regeneratively.
4.4.2 Brushless DC operation of CSI driven synchronous motor

In the following analysis, it is assumed that the supply current waveform for each phase is sinusoidal and of controllable amplitude or RMS value. It is also assumed that the phase angle between current and induced back emf in each phase can be arbitrarily chosen. All of these tasks are arranged through continuous rotor position feedback and continuous control of stator currents in closed loops. In other words, phase current references, and hence actual rotor currents, are assumed to be synchronised with the rotor position (angle). [In a more general sense, this type of control is equivalent to controlling the motor currents in the rotor reference frame].

Consider the cylindrical rotor synchronous motor the phasor diagram of which is redrawn in figure 4.4.4(b). The angular relationship between $E_f$ and $\gamma$ is also indicated in this figure. It should be noted from the results that follow that the developed torque at any speed is independent of $R$ since a high gain (stiff) current source drive is used. The developed power and torque in terms of the commutation angle $\gamma$ are given by

$$P = 3E_f I \cos \gamma$$

(4.4.1)

$$T = \frac{3E_f I \cos \gamma}{\omega_m} = \frac{3E_f I \cos \gamma}{\omega_k / p} = \frac{3pE_f I \cos \gamma}{2\pi f_1}$$

(4.4.2)

The ratio $\frac{E_{f1}}{f_1}$ at any operating speed is constant and proportional to the rotor flux amplitude, so that

$$T = K\dot{\phi}_f I \cos \gamma$$

(4.4.3)

Note that angle $\gamma$ can be arbitrary chosen.
Case A: Maximum Torque per Ampere (MTPA) operation ($\gamma = 0^\circ$)

If $\gamma = 0^\circ$, the motor developed torque is maximum per ampere of stator current (MTPA operation).

$$ T = K \dot{\phi}_f I $$  \hspace{1cm} \text{Nm}  \hspace{1cm} (4.4.4)$$

which is very similar to the torque expression of a separately excited brushed DC motor. In other words, the developed torque of a cylindrical-pole synchronous motor can be controlled directly by controlling the amplitude of the stator phase current. The maximum torque per ampere (MTPA) characteristic is achieved when $\gamma = 0^\circ$. Note that operation with $\gamma$ maintained at zero angle (see Figure 4.4.5(b)) at all times is key to this brushless DC motor like operation.

However, the motor input current phasor now invariably lags the voltage phasor at the motor terminals. [see the phasor diagram of figure 4.4.5(b)]. Note that $E_f$, which is determined by the level of excitation. It also determines the angle $\phi$ to some extent. Clearly, when maximum torque per ampere characteristic is required, a power factor less than unity has to be accepted.

Case B: Operation with field weakening

Operation above base speed is normally obtained with field weakening. In this speed range, because of the limited DC link voltage available, the rotor field must be weakened otherwise the amplitude of the phase induced emf will exceed the DC link voltage and current control will not be effective. Field weakening is a means of keeping $V_o$ at the rated level for speeds higher than the base speed. Note that $E_f = K \dot{\phi}_f \omega$ implies that speed $\omega$ can be increased by decreasing $\phi_f$.

For synchronous motors with rotor field winding, weakening of the rotor field is easily arranged by reducing the field current which is supplied via slip rings from a separate but controllable converter. The field current is normally regulated with a fast current control loop, so that it can effectively and quickly change the field current when the motor is accelerated to higher than base speed or decelerated from this speed fast. Otherwise the motor voltage could exceed the rated value during the acceleration to, and deceleration from, above the base speed.
For a permanent magnet motor, rotor flux $\phi_r$ can be reduced by armature reaction. For example, if $I$ is made to lead $E_f$, the $d$-axis component of $I$, i.e., $I_d$, will lead $E_f$ by $90^\circ$. The mmf due to $I_d$ then opposes the rotor $d$-axis mmf, as indicated in figure 4.4.6. Note that $N_s \phi_{ad} = L_d I_d + N_s \phi_f$.

If the airgap is small, the negative $d$-axis component of the armature current may reduce the rotor flux as required. The air gap is large in a surface magnet motor, and field weakening is consequently not very effective for such motors. Permanent magnet motors with magnets buried into the rotor have smaller airgap and allow operation with field weakening (i.e., operation above the base speed).

**Case C: Unity power factor operation**

The power factor with which a motor operates is an important issue, especially for a large drive. The power factor is given by the cosine of the angle $\phi$ between the input voltage and current to the motor. A large $\phi$ results in a poor power factor which means that in order to deliver a load, the motor must draw a larger current than what would be drawn from the inverter if the power factor were high. For a large drive, a poor power factor may not be acceptable from the consideration of the cost associated with supply of high input current from the supply.
Operation of the synchronous motor with a current source inverter allows power factor compensation directly, using the commutation angle (\(\gamma\)) adjustment. This is more direct than via excitation control for voltage source inverter drives. Consider the following two cases.

**I lags \(E_f\)**

![Figure 4.4.7(a)](image1)

In Figure 4.4.7, the overall power factor is lagging, since \(\gamma\) is a lagging angle. The power factor angle \(\phi\) is larger than \(\gamma\). Note that since the motor is under-excited and \(I\) lags \(E_f\) and \(I_d\) magnetizes the rotor.

**I leads \(E_f\)**

If the \(I\) phasor is chosen to lead \(E_f\), the overall power factor can be much better, as indicated in Figure 4.4.8, including unity. Note that the motor now operates with less than maximum torque per Ampere (MTPA) characteristic.

![Figure 4.4.8(a)](image2)

Note also that the d-axis component of \(I\) now tends to demagnetise the rotor (field weakening).

It should be noted that \(\gamma\) angle adjustment as a means for power factor correction is only applicable to machines with suitable \(E_f\) (i.e., level of rotor excitation) and synchronous reactance parameters.