5 Inverter Fed Drive Scheme

The torque developed in an induction motor is proportional to both the rotor (or slip) frequency ω_r and square of the flux. Therefore, to obtain the full torque capability of the motor at any speed, the flux must be maintained at the rated value. If speed control is attempted by varying the stator voltage, while keeping the frequency constant, the flux and consequently torque capability of the machine get drastically reduced. The torque speed characteristics under this method of control are shown in *figure* 5.1.

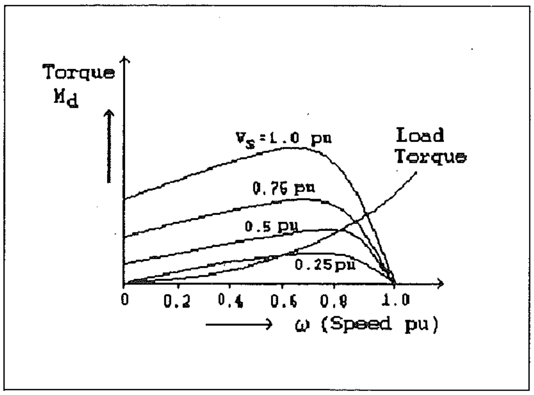

Figure 5.1

Since the stator frequency is constant, the synchronous speed remains the same in all cases. As the voltage is reduced, the peak torque ability of the motor gets reduced. Although speed is controlled, the motor operates at high values of slip and high currents. This type of control is not very efficient. Some applications with related torque and speed requirements use this scheme. *Variable Frequency Control* is the preferred method to maintain the torque capability of the motor at all speeds in the control range.

Variable Frequency Control

Consider the equivalent circuit of the induction motor, reproduced in *figure* 5.2.

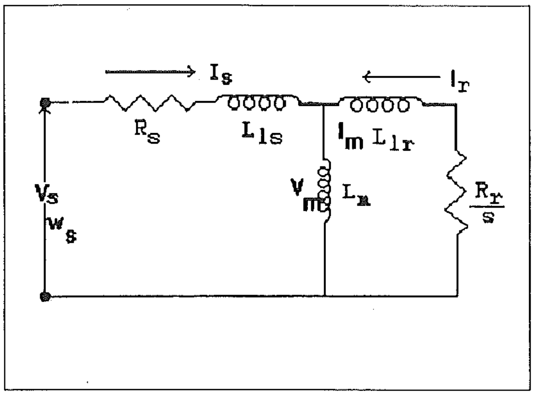

Figure 5.2

The rotor current I_r is given by

$I_r = - (V_m) / (R_r/s) + j\omega_s L_{lr}$

The airgap power $P_{ag} = 3 |I_r|^2 R_r/s$

$= 3 V_m^2 (R_r/s)^2 / ((\omega_s L_{lr})^2) + (R_r / s)^2)$

$= 3 (V_m^2 / (R_r/s)) / (1 + (\omega_r.L_{lr}.s/R_r)^2)$

The output torque $M_d = P_{ag}$/synchronous speed in mech rad/sec.

$M_d = 3(P/2)(1/\omega_s) (V_m^2.s/ R_r^2 + (\omega_r L_{lr})^2) R_r$

$M_d = 3(P/2) (V_m /\omega_s)^2 (\omega_r / R_r^2 + (\omega_r L_{lr})^2) R_r$

The above equation implies that the developed torque of the machine will depend only on ω_r, irrespective of the stator frequency ω_s, provided the ratio V_m/ω_s is kept constant. This ratio is the amplitude of the airgap flux.

Thus by keeping the airgap flux constant, and varying the stator frequency ω_s, a family of torque speed curves can be obtained for the motor as shown in *figure* 5.3. This method of speed control is referred to as constant flux control. It is to be noted that constant flux control is only possible up to rated voltage and frequency. For further increase in frequency beyond rated frequency, the voltage cannot be increased proportionally as this would exceed the rating of the machine. Beyond rated frequency, the peak torque ability of the motor decreases as the ratio V_m/ω_s is less than the rated value. This region of operation is referred to as the *Field Weakening* region.

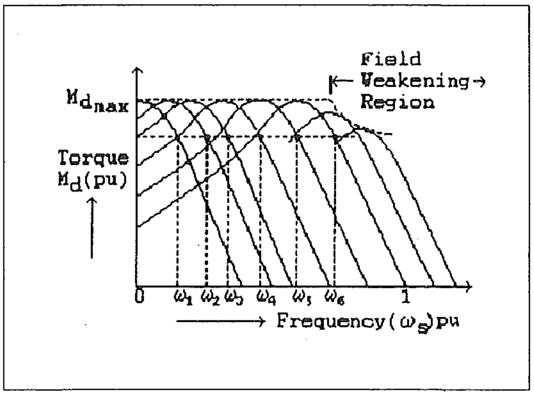

Figure 5.3

It is seen that any load torque demand within the capability of the machine can be met at all speeds up to the rated speed. Further, it is possible to obtain high torques for starting the motor by operating it at a reduced frequency.

However, the above method is difficult to implement as the airgap voltage V_m cannot be measured directly. It can be calculated by measuring the motor terminal voltages and currents, but this results in considerable complexity of the control circuits. As an alternative method, the airgap flux can be measured directly by incorporating flux sensing coils or Hall sensors in the motor and integrating their output voltages.

This requires modification of the motor. Further, it is difficult to carry out the integration at low frequencies. In practice, the above technique is implemented in an approximate manner, by keeping the ratio of the terminal voltage V_s to ω_s constant.

The terminal voltage and the airgap voltage are reasonably close in magnitude at speeds above 10% of rated speed. At very low speeds (and hence stator frequencies) the drop in the stator resistance and leakage reactance becomes appreciable in magnitude compared to the airgap voltage. Therefore, at low speeds, keeping V_s/ω_s constant is not equivalent to keeping the flux constant. The torque capability of the machine therefore comes down. The family of torque speed curves for constant V_s/ω_s control (or constant V/f control as it is referred to) is shown in *figure* 5.4. To some extent, the drop in torque ability at low speeds can be counter balanced by giving a boost to the stator voltage V_s at low frequencies above the constant V/f value. *figure* 5.5 shows two possible V/f relationships that can be employed.

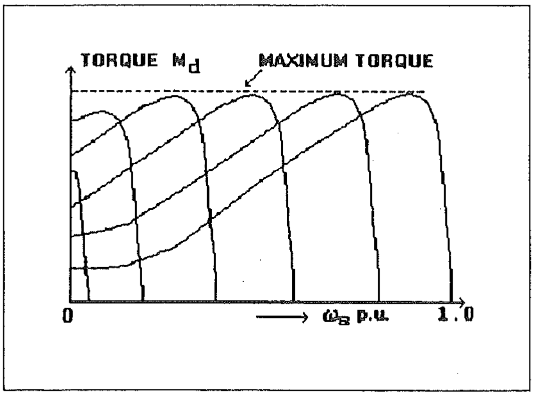

Figure 5.4

In a variety of industrial drive applications, the speed range is limited to 1:2 or 1:3. The drive is not required to operate in the steady state at very low speeds. In such applications, the motor will only traverse through the low frequency range while starting.

Inaccuracies in the V/f ratio in this region, are tolerated (provided the machine is able to develop enough torque to accelerate).

The constant V/f method is suitable for Adjustable Speed Drives - **ASDs**. The control scheme can be used in conjunction with either six-step inverters or **PWM** inverters. In six-step inverter operation at low frequencies, the 5th and 7th harmonics also have low frequencies and the torque pulsations may become objectionable.

In addition, a second power converter is needed in cascade to vary the **DC** link voltage. With currently available power switches, **PWM** inverters are more economical. Hence, only drives using **PWM** inverters are considered. Both voltage and frequency are controlled within the inverter itself.

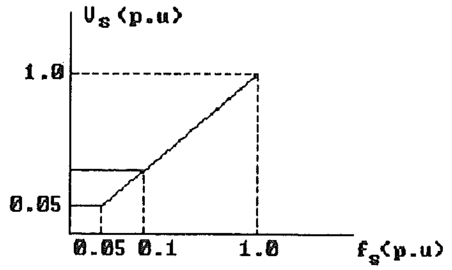

Figure 5.5

5.1. Block Diagram of Inverter Fed Drive

The block diagram of an Adjustable Speed Drive - **ASD** incorporating a **PWM** inverter and an induction motor is shown in *figure* 5.6. Power is normally available as **AC**. A front-end rectifier and filter are needed to create the **DC** voltage for the inverter. The simplest type of rectifier is the uncontrolled diode rectifier, as shown in *figure* 5.6.

Any fluctuations in the mains voltage causes fluctuations in the **DC** bus voltage. A controlled rectifier can be used to regulate the **DC** bus voltage. In either case, power flow cannot be reversed, *i.e.*, regeneration is not possible. This is not a limitation as the majority of industrial drives do not require regeneration.

The drive control system accepts as inputs - the speed command and feedback signals available from the motor. It generates the stator frequency command f* and voltage command v*. The PWM circuit then generates the gating signals required to impress the commanded voltage and frequency on the motor.

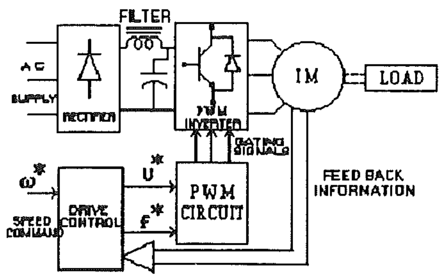

Figure 5.6

5.2. Open Loop Drive With V/f Control

In a speed control system, the actual speed of the motor is measured through a tachogenerator in order to accurately control the speed. In many industrial drives, it is desirable to avoid the installation of a tacho, from the point of view of cost, installation problems, reliability, etc. The resulting regulation in speed is accepted. Such drives are referred to as *Open Loop* drives. No feedback information is available from the motor and the drive control has only the speed command to act upon. As discussed earlier, the voltage and the frequency have to be related to each other through the V/f program.

This program generates the voltage command using the frequency command as the input. As a result of this, the task of the drive control reduces to that of generating the frequency command using the speed command as input.

Since the rated or full load slip of an induction motor is usually small, the simplest approach to generating the frequency command is to directly use the speed command as the frequency command. The resulting drive control block diagram is shown in *figure* 5.7. With such an arrangement, the motor will always run at a speed which is less than the commanded speed. The difference in speeds corresponds to the prevailing load torque. If this speed error is acceptable, then the system will perform satisfactorily in the steady state.

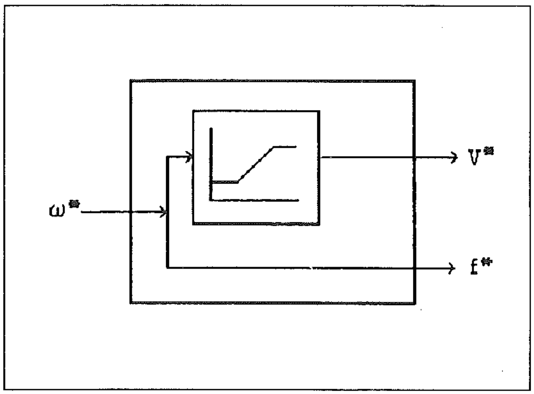

Figure 5.7

However, the simple arrangement above, may result in the motor pulling out when the speed command is changed suddenly. This may be explained as follows : refer to *figure* 5.8a, let the machine operate initially at frequency f_{s1}, at the point A on the torque speed characteristic. If the speed command is changed suddenly resulting in a sudden change of frequency to f_{s2}, the new torque speed curve prevails. Because of the inertia of the mechanical system, the machine speed cannot change suddenly. Therefore, the operating point jumps to B on the new curve.

The slip at B is large and will result in large stator currents. The developed torque is larger than the load torque and the motor will accelerate. The operating point will move along the characteristic and settle at C.

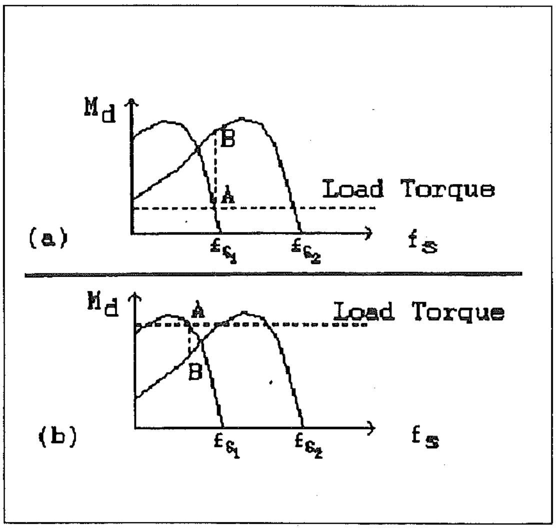

Figure 5.8

The above transient may be acceptable provided the resulting transient overcurrents can be handled by the inverter. Consider, however, the situation depicted in *figure* 5.8b.

In this case, when the operating point jumps to B from A, the resulting developed torque is less than the load torque. The motor decelerates, resulting in further reduction of developed torque and further deceleration. The motor will eventually pull out and come to a stop. In the process, large currents may be drawn from the inverter. Similar arguments can be advanced for sudden reduction of frequency.

Therefore, the simple drive control scheme of *figure* 5.6 has to be modified to prevent sudden changes in the frequency command f*. This can be achieved by making the frequency command f* track the speed command ω* at a finite speed, through what is referred to as a *slow start* circuit.

In the simplest case, this consists of an RC circuit. The rate of change of f* must be limited to such an extent that the motor speed variations are able to keep track of changes in f*. The resulting block diagram is shown in *figure* 5.9.

In the steady state f* will be equal to ω*. However, the speed of response of the drive to changes in the speed command is now very much limited. This is not a serious drawback in many drives, as speed changes are commanded infrequently.

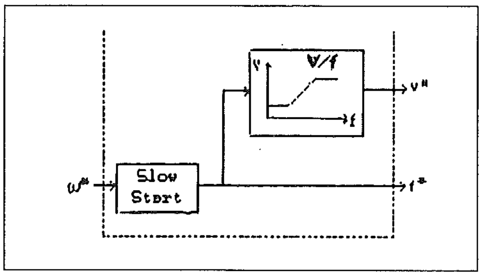

Figure 5.9

5.3. Slip Compensation to Improve Speed Regulation

In the above method of control, the motor speed will always be less than the commanded speed due to the slip speed. For a given speed command, the speed will drop as load is increased. The speed regulation of drive can be improved by a technique known as *slip compensation.*

Slip compensation technique operates without incorporating a tacho and utilises the fact that the amplitude of the stator current I_s and the slip frequency ω_r of the machine are related to one another. This technique therefore requires the value of the stator current in order to correct the frequency command. The measurement of current is accomplished in a relatively easy manner and slip compensation can be used if better speed regulation is required. The principle of slip compensation can be explained as follows.

From the equivalent circuit of *figure* 5.2, the magnetizing current and the stator current can be related by

$$I_m = I_s \{ (R_r/s) + j\omega_s L_{lr} \} / \{ (R_r/s) + j\omega_s(L_{lr} + L_m) \}$$

or

$$I_s = I_m \{ R_r + j\omega_r L_r \} / \{ R_r + j\omega_r L_{lr} \} \quad , L_r = L_{lr} + L_m$$

Thus,

$$|I_s|^2 = |I_m|^2 \{ 1 + (\omega_r T_r)^2 \} / \{ 1 + (\omega_r T_{lr})^2 \} \qquad \text{...5.3-1}$$

where $T_r = L_r/R_r$; $T_{lr} = L_{lr}/R_r$

Using eq. 5.4-1 with I_m assumed to be the rated value of magnetizing current, the magnitude of the stator current I_s can be calculated for different values of rotor frequency ω_r. The resulting relationship between slip frequency and stator current is shown in *figure* 5.10.

If the magnitude of the stator current in the machine can be measured, the corresponding slip frequency signal ω_r can be generated using a function generator incorporating the graph of *figure* 5.10. This signal can then be added to the speed command signal and the sum used as the frequency command. The resulting overall drive control scheme is shown in *figure* 5.11.

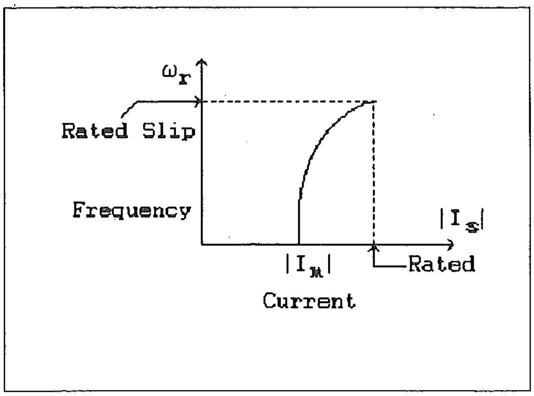

Figure 5.10

The line current of the motor is sensed using a current sensor. The frequency of the current is variable. The current signal is then rectified and filtered to get a **DC** signal proportional to the amplitude of stator current. This signal is then used to generate the slip compensation signal which is then summed with the output of the slow start circuit to obtain the frequency command. Since the slip frequency at rated load is small, good speed regulation of the order of 1% can be achieved. Errors in the motor parameter values and magnetizing currents assumed to generate the slip compensation signal affect speed regulation.

As slip compensation constitutes a positive feedback, excessive compensation may result in the motor pulling out following an increase in the speed command.

5.4. Drive with Speed Feedback

If a tachogenerator can be provided to measure the speed, then the motor speed can be directly controlled. The block diagram of the drive can then be as shown in *figure* 5.11.

The output of the speed controller is directly used as the slip frequency by adding it to the speed feedback signal to generate the stator frequency command. Limiting the controller output as shown, the maximum slip frequency can be limited and the pull out of the machine can be avoided.

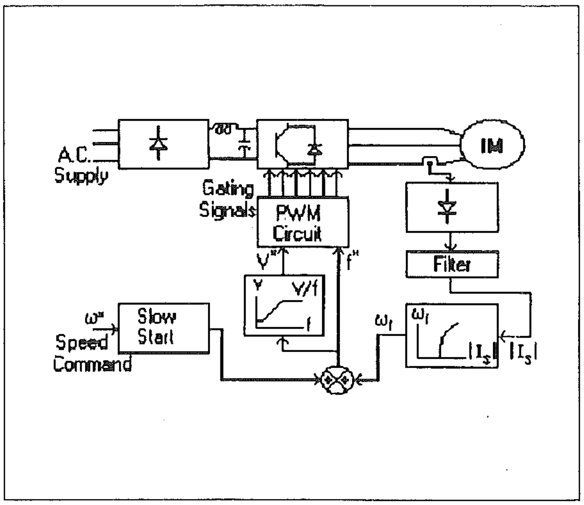

Figure 5.11

5.5. Summary

Simple drive schemes for inverter fed induction motors have been outlined. The control schemes are based on steady state relationships in the machine and are not suitable for applications requiring fast dynamic response. For such applications, more sophisticated algorithms based on the dynamic model of the induction motor become necessary.

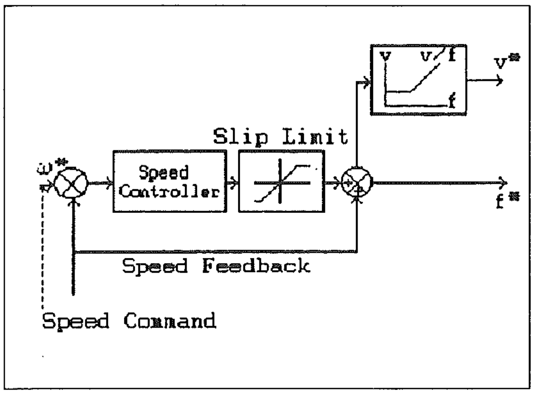

Figure 5.12

NOTES