Control circuit

The control circuit, or control card, is the fourth main component of the frequency converter and has four essential tasks:

- control of the frequency converter semi-conductors.
- data exchange between the frequency converter and peripherals.
- gathering and reporting fault messages.
- carrying out of protective functions for the frequency converter and motor.

Micro-processors have increased the speed of the control circuit, significantly increasing the number of applications suitable for drives and reducing the number of necessary calculations.

With microprocessors the processor is integrated into the frequency converter and is always able to determine the optimum pulse pattern for each operating state.

Control circuit for PAM frequency converter

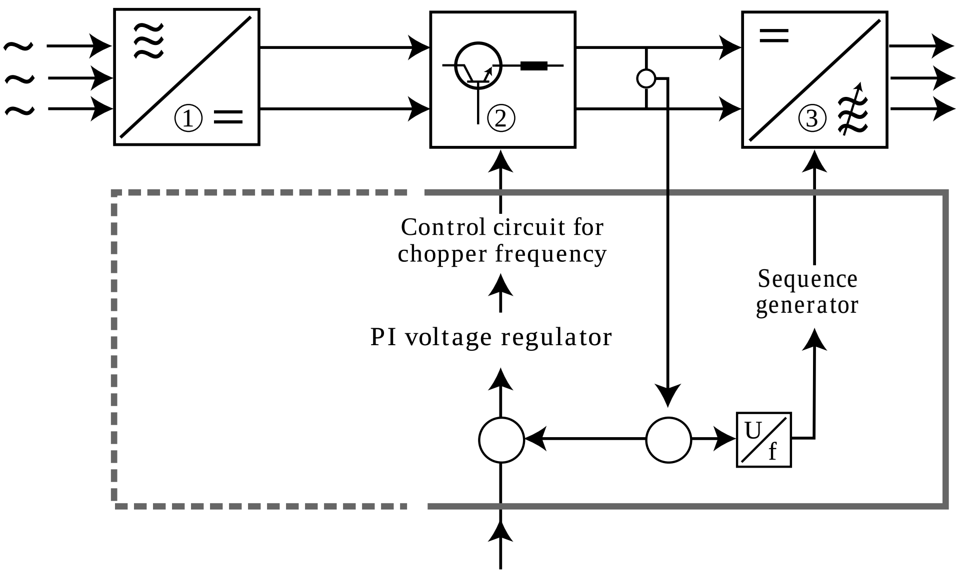

Fig. 2.29 The principle of a control circuit used for a chopper-controlled intermediate circuit

Fig. 2.29 shows a PAM-controlled frequency converter with intermediate circuit chopper. The control circuit controls the chopper (2) and the inverter (3).

This is done in accordance with the momentary value of the intermediate circuit voltage.

The intermediate circuit voltage controls a circuit that functions as an address counter in the data storage. The storage has the output sequences for the pulse pattern of the inverter. When the intermediate circuit voltage increases, the counting goes faster, the sequence is completed faster and the output frequency increases.

With respect to the chopper control, the intermediate circuit voltage is first compared with the rated value of the reference signal – a voltage signal. This voltage signal is expected to give a correct output voltage and frequency. If the reference and intermediate circuit signals vary, a PI-regulator informs a circuit that the cycle time must be changed. This leads to an adjustment of the intermediate circuit voltage to the reference signal.

PAM is the traditional technology for frequency inverter control. PWM is the more modern technique and the following pages detail how Danfoss has adapted PWM to provide particular and specific benefits.

Danfoss control principle

Fig. 2.30 gives the control procedure for Danfoss inverters.

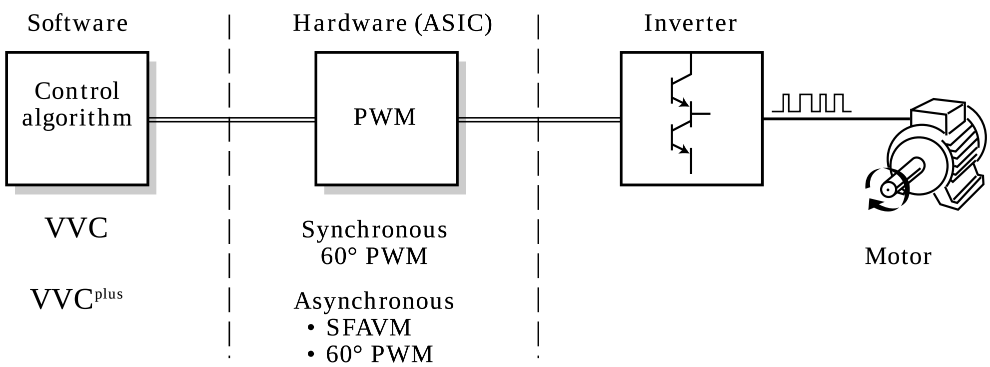

Fig. 2.30 Control principles used by Danfoss

The control algorithm is used to calculate the inverter PWM switching and takes the form of a **V**oltage **V**ector **C**ontrol (**VVC**) for voltage-source frequency converters.

VVC controls the amplitude and frequency of the voltage vector using load and slip compensation. The angle of the voltage vector is determined in relation to the preset motor frequency (reference) as well as the switching frequency. This provides:

- full rated motor voltage at rated motor frequency (so there is no need for power reduction)
- speed regulation range: 1:25 without feedback
- speed accuracy: ±1% of rated speed without feedback
- robust against load changes

A recent development of VVC is VVC^{plus} under which. The amplitude and angle of the voltage vector, as well as the frequency, is directly controlled.

In addition to the properties of VVC , VVC^{plus} provides:
- improved dynamic properties in the low speed range (0 Hz-10 Hz).
- improved motor magnetisation
- speed control range: 1:100 without feedback
- speed accuracy: ±0.5% of the rated speed without feedback
- active resonance dampening
- torque control (open loop)
- operation at the current limit

VVC control principle

Under VVC the control circuit applies a mathematical model, which calculates the optimum motor magnetisation at varying motor loads using compensation parameters.

In addition the synchronous 60° PWM procedure, which is integrated into an ASIC circuit, determines the optimum switching times for the semi-conductors (IGBTs) of the inverter.

The switching times are determined when:

- The numerically largest phase is kept at its positive or negative potential for 1/6 of the period time (60°).
- The two other phases are varied proportionally so that the resulting output voltage (phase-phase) is again sinusoidal and reaches the desired amplitude (Fig. 2.32).

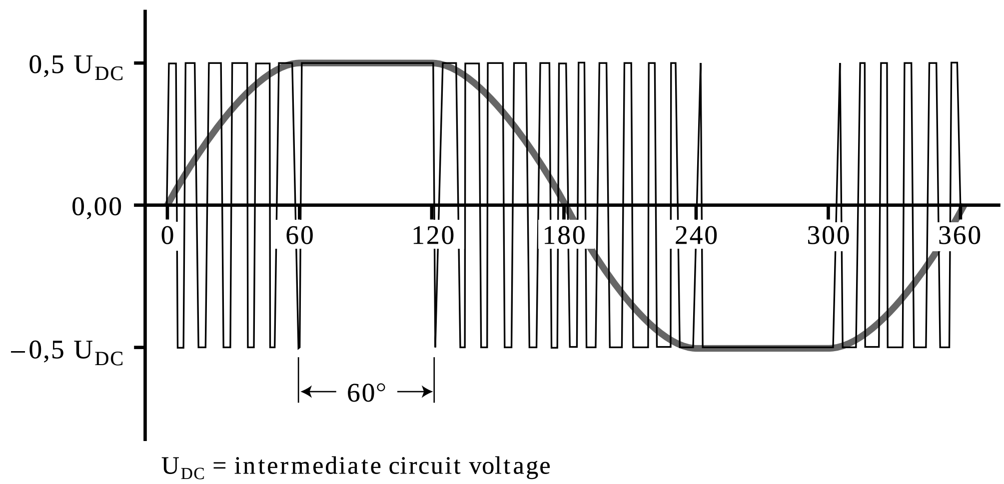

Fig. 2.31 Synchronous 60° PWM (Danfoss VVC control) of one phase

Unlike sine-controlled PWM, VVC is based on a digital generation of the required output voltage. This ensures that the frequency converter output reaches the rated value of the supply voltage, the motor current becomes sinusoidal and the motor operation corresponds to those obtained in direct mains connection.

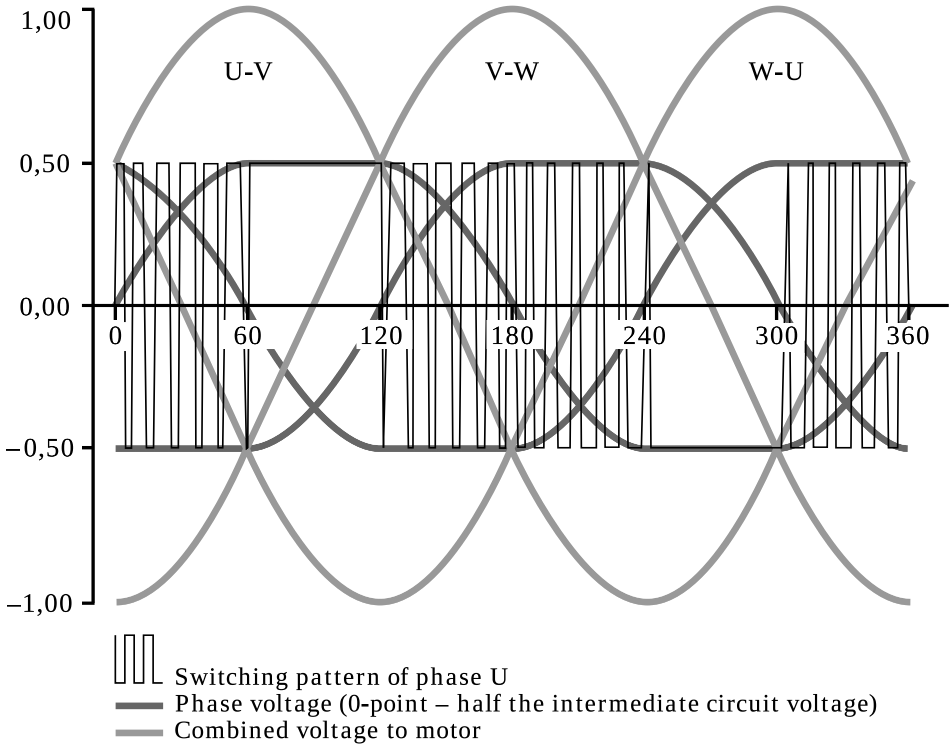

Fig. 2.32 With the synchronous 60° PWM principle the full output voltage is obtained directly

Optimum motor magnetisation is obtained because the frequency converter takes the motor constants (stator resistance and inductance) into account when calculating the optimum output voltage.

As the frequency converter continues to measure the load current, it can regulate the output voltage to match the load, so the motor voltage is adapted to the motor type and follows load conditions.

VVC^plus control principle

The VVC^plus control principle uses a vector modulation principle for constant, voltage-sourced PWM inverters. It is based on an improved motor model which makes for better load and slip compensation, because both the active and the reactive current components are available to the control system and controlling the voltage vector angle significantly improves dynamic performance in the 0-10 Hz range where standard PWM U/F drives typically have problems.
The inverter switching pattern is calculated using either the SFAVM or 60° AVM principle, to keep the pulsating torque in the air gap very small (compared to frequency converters using synchronous PWM).
The user can select his preferred operating principle, or allow the inverter to choose automatically on the basis of the heat-sink temperature. If the temperature is below 75°C, the SFAVM principle is used for control, while above 75° the 60° AVM principle is applied.

Table 2.01 gives a brief overview of the two principles:

Selection	Max. switching frequency of inverter	Properties
SFAVM	Max. 8 kHz	1. low torque ripple compared to the synchronous 60° PWM (VVC) 2. no "gearshift" 3. high switching losses in inverter
60°-AVM	Max. 14 kHz	1. reduced switching losses in inverter (by 1/3 compared to SFAVM) 2. low torque ripple compared to the synchronous 60° PWM (VVC) 3. relatively high torque ripple compared to SFAVM

Table 2.01 Overview: SFAVM versus 60° AVM

The control principle is explained using the equivalent circuit diagram (Fig. 2.33) and the basic control diagram (Fig. 2.34).
It is important to remember that in the no-load state, no current flows in the rotor ($i_\omega = 0$), which means that the no-load voltage can be expressed as:

$$\underline{U} = \underline{U}_L = (R_S + j\omega_S L_S) \times i_s$$

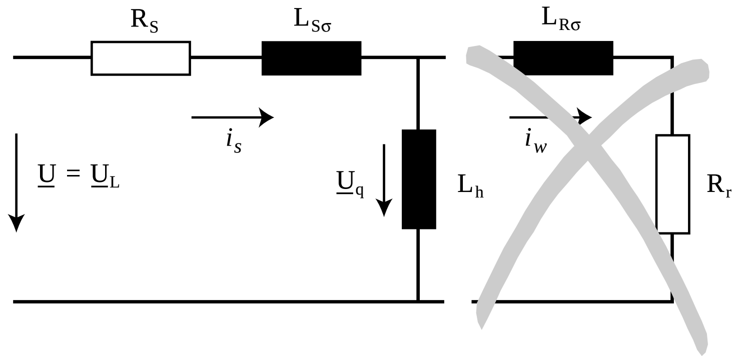

Fig. 2.33a Equivalent circuit diagram of three-phase AC motor loaded)

in which:
R_S is the stator resistance,
i_s is the motor magnetisation current,
$L_{S\sigma}$ is the stator leakage inductance,
L_h is the main inductance,
L_S ($=L_{S\sigma} + L_h$) is the stator inductance, and
ω_s ($=2\pi f_s$) is the angular speed of the rotating field in the air gap
The no-load voltage ($\underline{U}_L$) is determined by using the motor data (rated voltage, current, frequency, speed).

Under a load, the active current (i_w) flows in the rotor. In order to enable this current, an additional voltage ($\underline{U}_{Comp}$) is placed at the disposal of the motor:

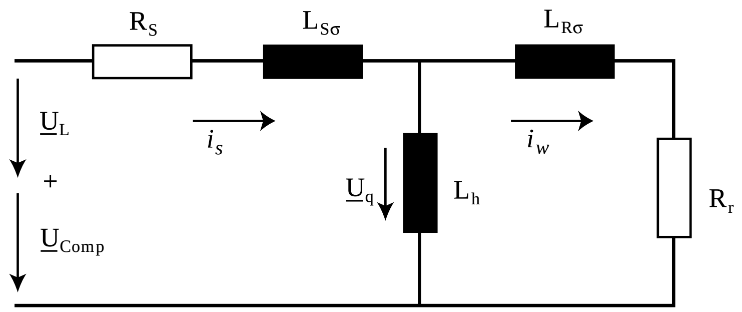

Fig. 2.33b Equivalent circuit diagram for three-phase AC motors (loaded)

The additional voltage $\underline{U}_{Comp}$ is determined using the no-load and active currents as well as the speed range (low or high speed). The voltage value and the speed range are then determined on the basis of the motor data.

f	frequency (internal)	U_{DC}	voltage of DC intermediate circuit
f_s	preset reference frequency	$\underline{U}_L$	no- load voltage vector
Δ_f	calculated slip frequency	$\underline{U}_S$	stator voltage vector
I_{SX}	reactive current components (calculated)	$\underline{U}_{Comp}$	load- dependent voltage compensation
I_{SY}	active current components (calculated)	U	motor supply voltage
I_{SX0}, I_{SY0}	no- load current of x and y axes (calculated)	X_h	reactance
I_u, I_v, I_w	current of phases U, V and W (measured)	X_1	stator leakage reactance
R_s	stator resistance	X_2	rotor leakage reactance
R_r	rotor resistance	ω_s	stator frequency
θ	angle of the voltage vectors	L_S	stator inductance
θ_0	no- load value theta	L_{Ss}	stator leakage inductance
$\Delta\theta$	load-dependent part of theta (compensation)	L_{Rs}	rotor leakage inductance
T_C	Temperature of heat conductor/ heat sink	i_s	motor phase current (apparent current)
		i_w	active (rotor) current

Explanations for Fig. 2.33 (page 87) and Fig. 2.34 (page 89)

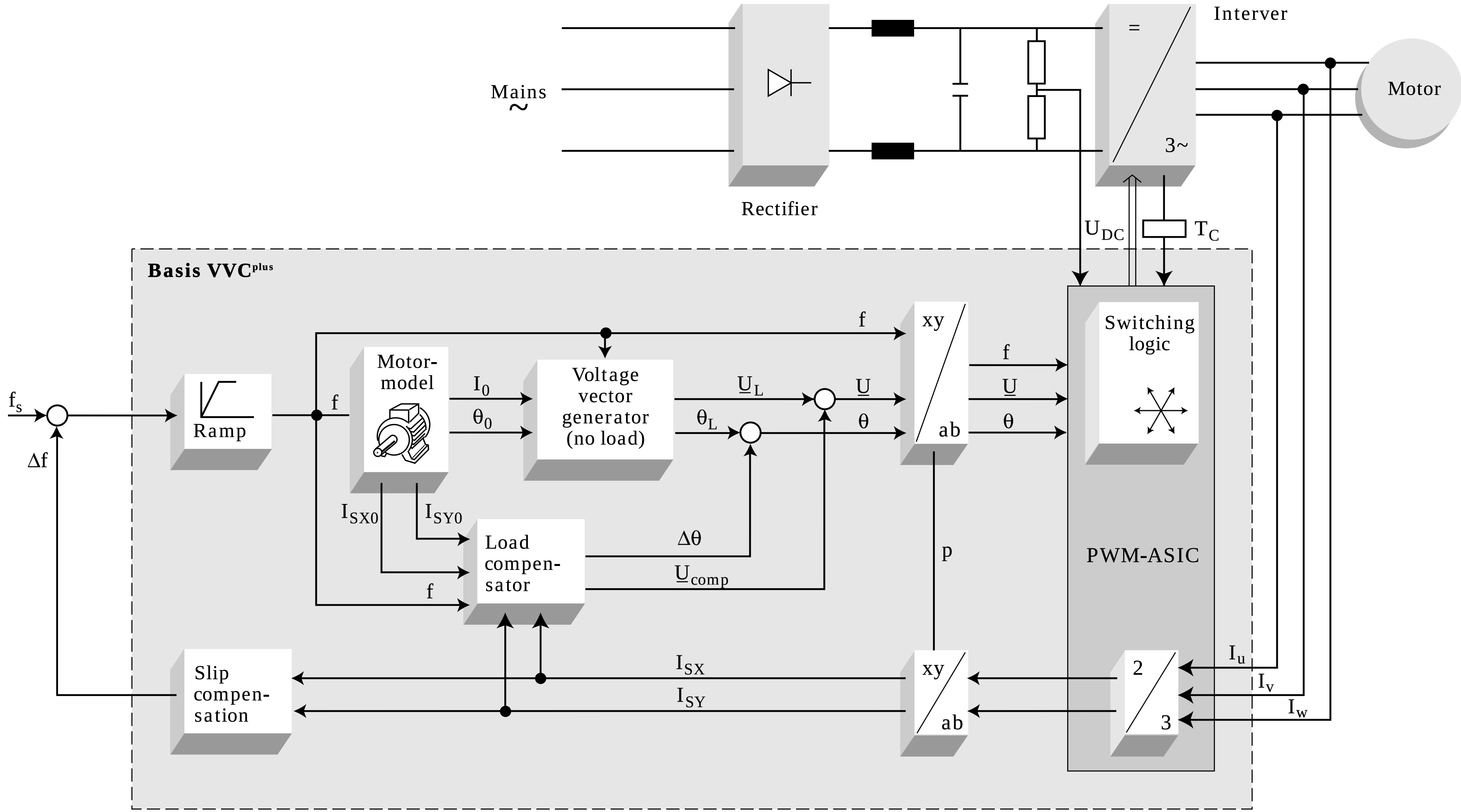

Fig. 2.34 *Basis of VVC*[plus] *control*

As shown in Fig. 2.34, the motor model calculates the rated no-load values (currents and angles) for the load compensator (I_{SX0}, I_{syo}) and the voltage vector generator ($I_{o,}$ θ_o). Knowing the actual no load values makes it possible to estimate the motor shaft torque load much more accurately.
The voltage vector generator calculates the no-load voltage vector ($\underline{U}_L$) and the angle (θ_L) of the voltage vector on the basis of the stator frequency, no-load current, stator resistance and inductance (see Fig. 2.33a). The resulting voltage vector amplitude is a composite value having added start voltage and load compensation voltage. The voltage vector θ_L is the sum of four terms, and is an absolute value defining the angular position of the voltage vector.
As the resolution of the theta components (θ) and the stator frequency (F) determines the output frequency resolution, the values are represented in 32 bit resolution. One (θ) theta component is the no load angle which is included in order to improve the voltage vector angle control during acceleration at low speed. This results in a good control of the current vector since the torque current will only have a magnitude which corresponds to the actual load. Without the no load angle component the current vector would tend to increase and over magnetise the motor without producing torque.
The measured motor currents (I_u , I_v and I_w) are used to calculate the reactive current (I_{SX}) and active current (I_{SY}) components.
Based on the calculated actual currents and the values of the voltage vector, the load compensator estimates the air gap torque and calculates how much extra voltage (U_{Comp}) is required to maintain the magnetic field level at the rated value. The angle deviation (Δθ) to be expected because of the load on the motor shaft is corrected. The output voltage vector is represented in polar form (p). This enables a direct overmodulation and facilitates the linkage to the PWM-ASIC.

The voltage vector control is very beneficial for low speeds, where the dynamic performance of the drive can be significantly improved, compared to V/f control by appropriate control of the voltage vector angle. In addition, steady stator performance is obtained, since the control system can make better estimates for the load torque, given the vector values for both voltage and current, than is the case on the basis of the scalar signals (amplitude values).

Field-oriented (Vector) control

Vector control can be designed in a number of ways. The major difference is the criteria by which the active current, magnetising current (flux) and torque values are calculated.

Comparing a DC motor and three-phase asynchronous motor (Fig. 2.35), highlights the problems. In the DC, the values that are important for generating torque – flux (Φ) and armature current – are fixed with respect to size and phase position, based on the orientation of the field windings and the position of the carbon brushes (Fig. 2.35a).

In a DC motor the armature current and flux-generating current are at right angles and neither value is very high. In an asynchronous motor the position of the flux (Φ) and the rotor current I_1 depends on the load. Furthermore unlike a DC motor, the phase angles and current are not directly measurable from the size of the stator.

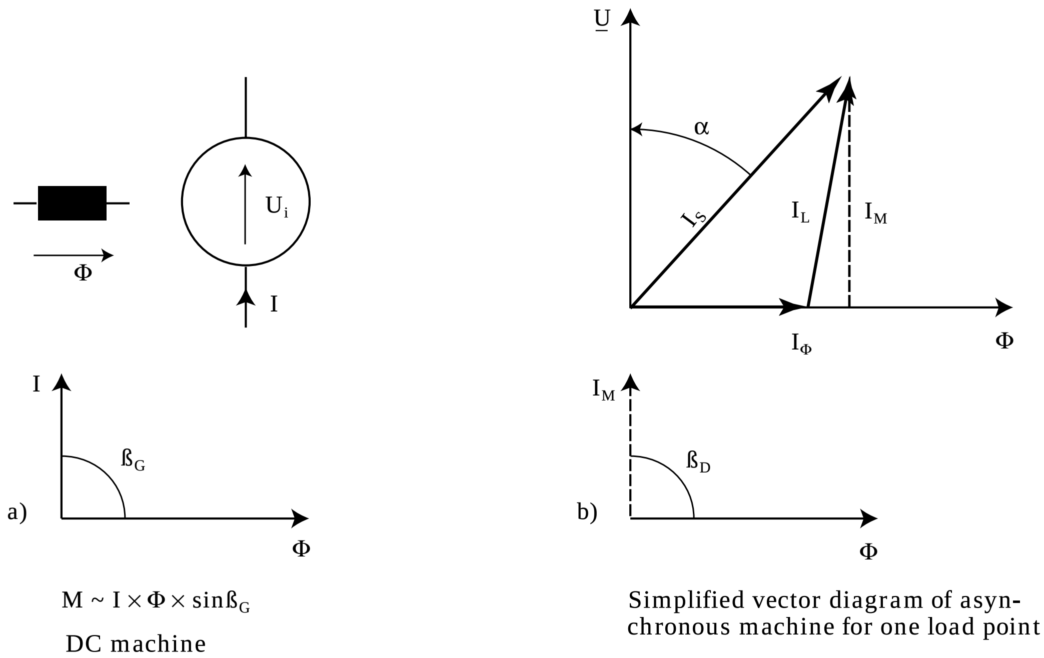

Fig. 2.35 Comparison between DC and AC asynchronous machines

Using a mathematical motor model, the torque can, however, be calculated from the relationship between the flux and the stator current.

The measured stator current (I_S) is separated into the component that generates the torque (I_L) with the flux (Φ)at right angles to these two variables (I_B). These generate the motor flux (Fig. 2.36).

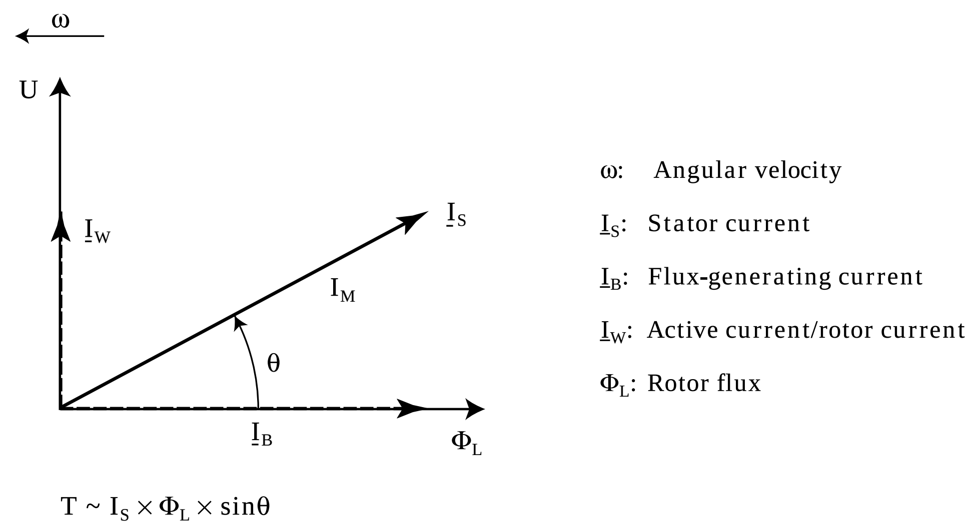

Fig. 2.36 Calculation of the current components for field-oriented regulation

Using the two current components, torque and flux can be influenced independently. However, as the calculations, which use a dynamic motor model, are quite complicated, they are only financially viable in digital drives.

As this technique divides the control of the load-independent state of excitation and the torque it is possible to control an asynchronous motor just as dynamically as a DC motor – provided you have a feedback signal. This method of three-phase AC control also offers the following advantages:

- good reaction to load changes
- precise speed regulation
- full torque at zero speed
- performance comparable to DC drives.

V/f characteristic and flux vector control

The speed control of three-phase AC motors has developed in recent years on the basis of two different control principles:

normal V/f or SCALAR control, and
flux vector control.

Both methods have advantages, depending on the specific requirements for drive performance (dynamics) and accuracy.

V/f characteristic control has a limited speed regulation range of approximately 1:20 and at low speed, an alternative control strategy (compensation) is required. Using this technique it is relatively simple to adapt the frequency converter to the motor and the technique is robust against instantaneous loads throughout the speed range.

In flux vector drives, the frequency converter must be configured precisely to the motor, which requires detailed knowledge. Additional components are also required for the feedback signal.

Some advantages of this type of control are:

- fast reaction to speed changes and a wide speed range
- better dynamic reaction to changes of direction
- it provides a single control strategy for the whole speed range.

For the user, the optimum solution lies in techniques which combine the best properties of both strategies. Characteristics such as robustness against stepwise loading/unloading across the whole speed range - a typical strongpoint of V/f-control - as well as fast reaction to changes in the reference speed (as in field-oriented control) are clearly both necessary.

Danfoss VVC^{plus} is a control strategy that combines the robust properties of V/f control with the higher dynamic performance of the field-oriented control principles and has set new standards for drives with speed control.

VVC^plus Slip compensation

Independently of the actual load torque, the magnetic field strength of the motor and the shaft speed are maintained at the speed reference command value. This is done using of two equalising functions: slip compensation and the load compensator.

The slip compensation adds a calculated slip frequency (Δf) to the rated speed signal in order to maintain the required reference frequency (Fig. 2.31). The rise in stator frequency is limited by a user-defined run-up time (ramp). The estimated slip value is taken from the estimated value of the torque load and the actual magnetic field strength – so the magnetic field weakening is also taken into consideration.

The stationary behaviour of the control system is illustrated together with the torque/speed graphs in Fig. 2.37.

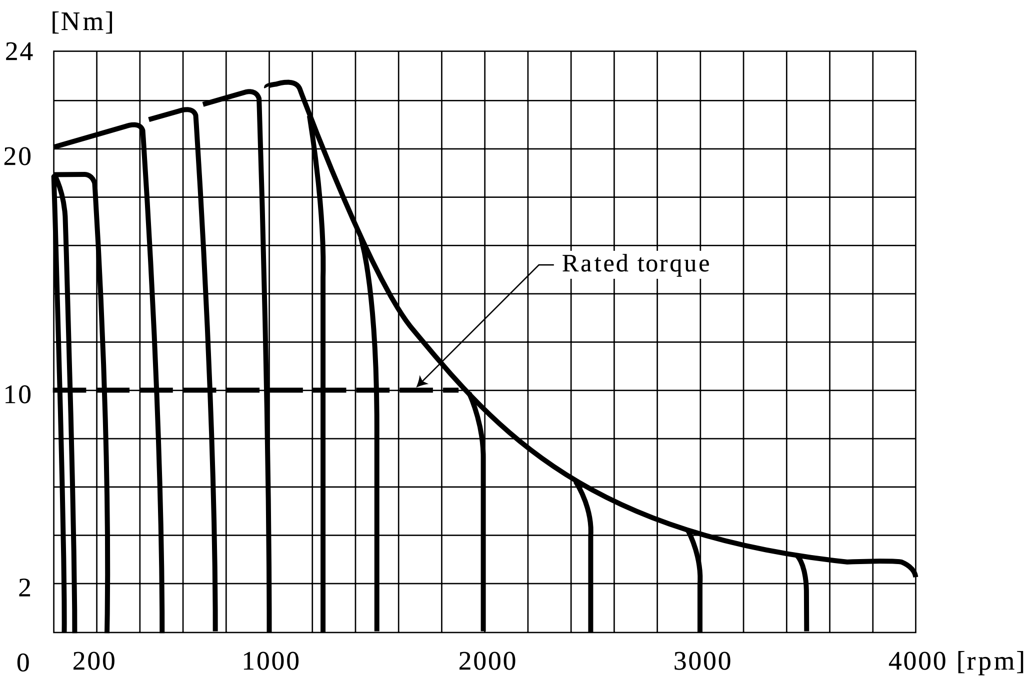

Fig. 2.37 Torque/speed characteristics (Rated torque 10 Nm)