

### 5.3 Armature voltage control

In this method of speed control, armature is supplied from a separate variable Ac voltage source, while the field is separately excited with fixed rate dc voltage as shown in figure. Here the armature resistance and field current are not varied. Since the no load speed the speed versus  $I_a$  characteristic will shift parallel as shown in figure for different values of  $V_a$ .

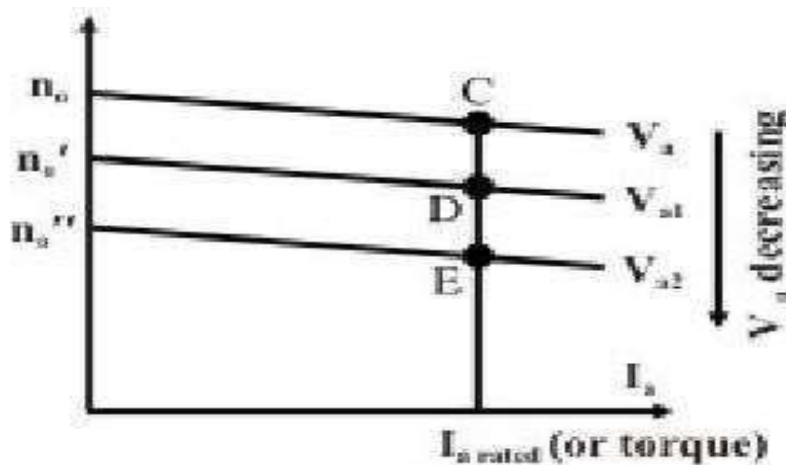
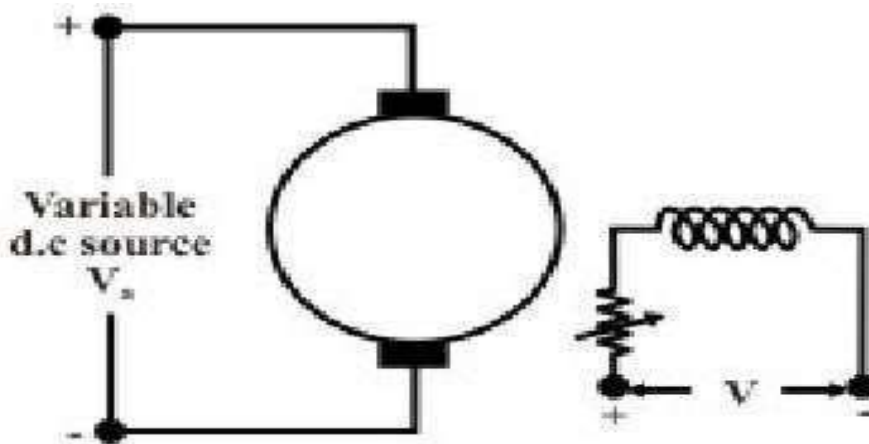


Figure 5.3.1 Armature voltage control

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*(Source: "Fundamentals of Electrical Drives" by G.K.Dubey, page-242)*

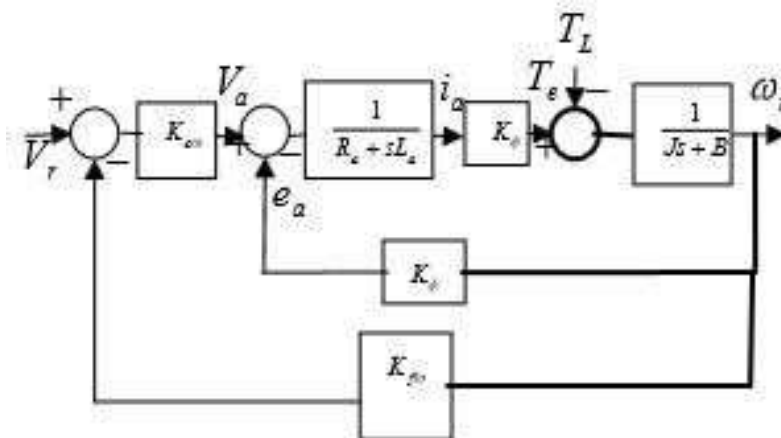
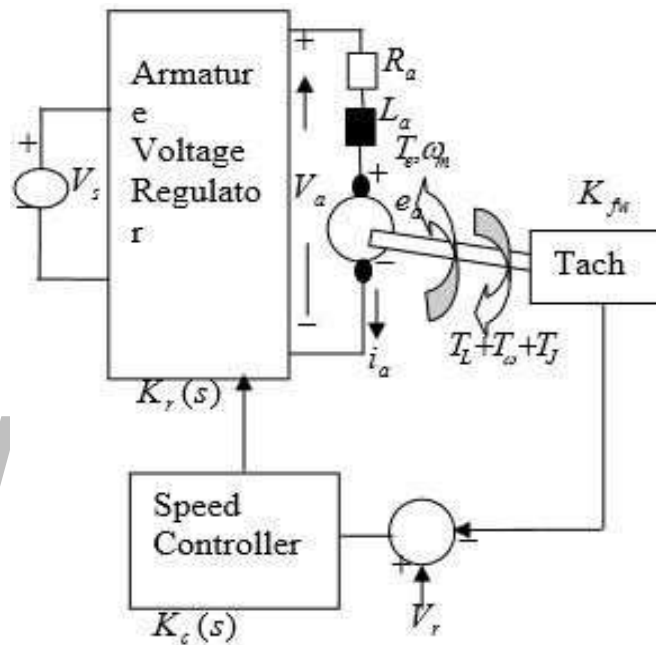
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As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method dissimilar to that of armature resistance control method except that the former one is much superior as next re-power loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed, as one should not apply a cross the armature a voltage, which is higher than the rated voltage.

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## 5.2 Closed Loop Control with Current and Speed Feedback

Closed loop control improves on the drives performance by increasing speed of response and improving on speed regulation. So the functions of closed loop control is that  $\omega_n$  is increased,  $\epsilon$  is reduced,  $t_s$  is reduced, and Speed Regulation(SR) is reduced. A closed loop speed control scheme is shown below



**Figure 5.2.1 Closed Loop Speed Control**

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey, page-192)

Where,

$K_{fGD}$  is the tachometer feed back gain

$K_c(s)$  is the speed controller gain

$K_r(s)$  is the armature voltage regulator gain

The dynamic equation by mason's rule is,

$$\begin{pmatrix} V_r \\ T_L \end{pmatrix} \frac{K_\phi K_{cap}(B)K_{cap}(s)}{-(R_a + sL_a)K_\phi K_{f\omega}(s)K_{cap}(s)D_o(s)}$$

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$$\begin{pmatrix} \omega_m \\ i_a \end{pmatrix} = \frac{\begin{pmatrix} (Js + B)K_{cap} & K_\phi K_{f\omega} K_{cap} \end{pmatrix} \begin{pmatrix} T_L \end{pmatrix}}{D_o(s)}$$

Where,

$$D_o(s) = s^2 J L_a + (R_a J + B L_a) s + R_a B + K_\phi^2 + K_\phi K_{f\omega} K_{cap}$$

$$D_o(s) = J L_a \left[ s^2 + \left( \frac{R_a J + B L_a}{J L_a} \right) s + \frac{R_a B + K_\phi^2}{J L_a} \right] + \text{ve.}$$

Last Equation is a second order system

The Natural Frequency of Oscillation,  $\omega_n$  is,

$$\omega_n = \sqrt{\frac{R_a B + K_\phi^2 + K_\phi K_{f\omega} K_{c\omega p}}{J L_a}}$$

$$\varepsilon = \frac{R_a J + B L_a}{2 \omega_n J L_a}$$

This is always higher than the open loop case due to the factor  $K_\phi, K_{f\omega}, K_{c\omega p}$

The Damping Ratio,  $\varepsilon$ , is

$$SR = \frac{-R_a}{R_a B + K_\phi^2 + K_\phi K_{f\omega} K_{c\omega p}}$$

This is lower than in the open loop case due to the increase in  $\omega_n$  Speed Regulation

(SR) is also derived as

$$\begin{pmatrix} \omega_m \\ i_a \end{pmatrix} = \frac{\begin{pmatrix} K_\phi K_{c\omega} K_{c\omega p} & -(R_a + s L_a + K_{c\omega} K_{f\omega}) \\ (J s + B) K_{c\omega} K_{c\omega p} & K_\phi + K_{f\omega} K_{c\omega} K_{c\omega p} \end{pmatrix} \begin{pmatrix} V_r \\ T_L \end{pmatrix}}{D_o}$$

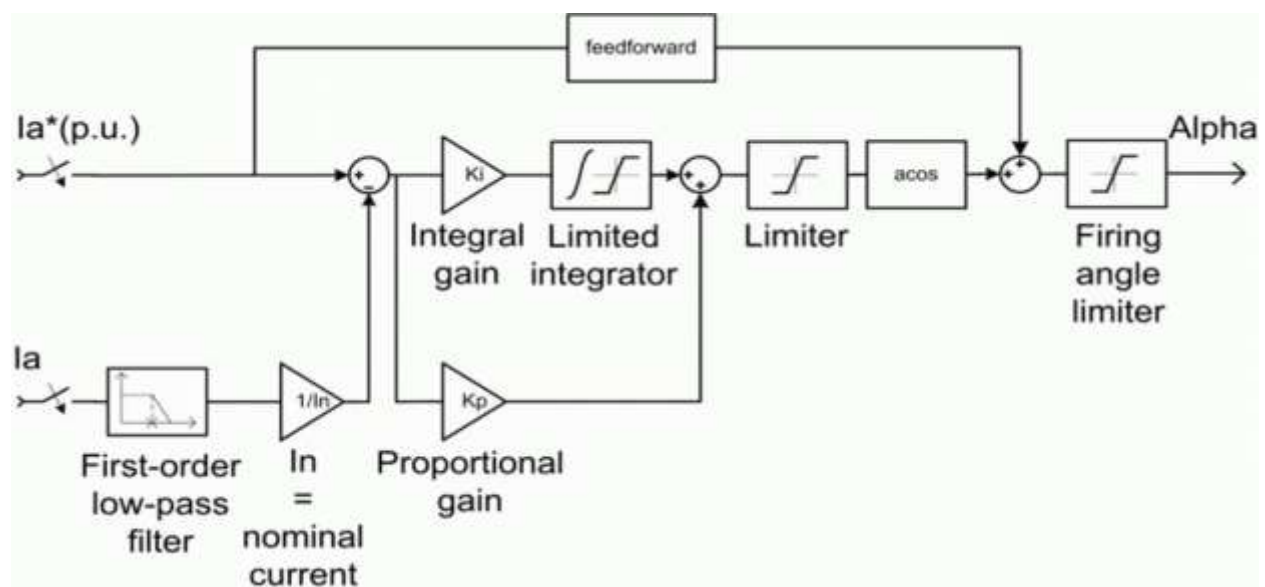
SR is also lower than in the open loop case due to the factor  $K_\phi, K_{f\omega}, K_{c\omega p}$ . This is an indication of a better drive performance.

## 5.5 Current Controller

The armature current regulator in the following figure is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angle. This generates the rectifier output voltage needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (input) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation.

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system during continuous conduction. To compensate non linearities appearing during discontinuous conduction, a feed forward term is added to the firing angle.



**Figure 5.5.1 Speed Controller**

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey, page-342)

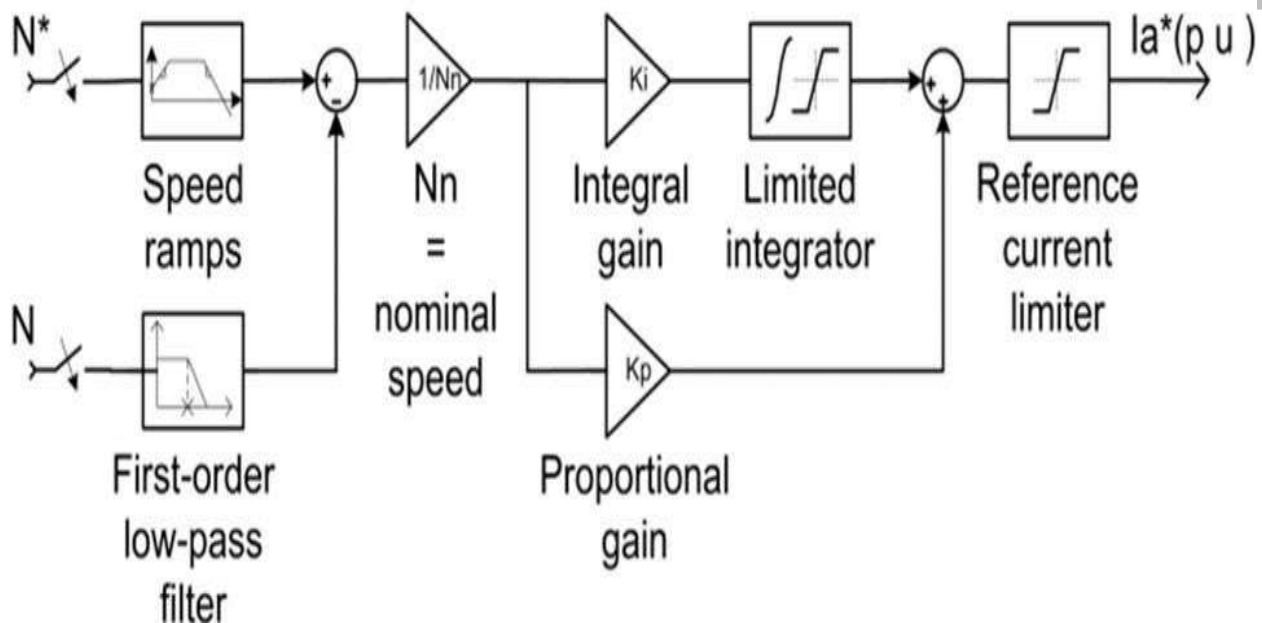
## 5.6 Speed Controller

The speed regulator in the following figure uses a PI controller. The controller outputs the armature current reference (input) by the current controller in order to obtain the electromagnetic torque needed or each the desired speed. During torque

regulation is used , the speed controller is disabled The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system.

The speed

measurement is filtered by a first-order low-pass filter.



**Figure 5.6.1 Speed Controller**

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey, page-347)



## 5.4 Flux-field Weakening Control Design and Analysis

In order to produce the maximum torque, which main component is proportional to q-axis component of the armature current, it is convenient to control the inverter-fed PMSM by keeping the direct, d-axis, current component to be  $i_d$  as long as the inverter output voltage doesn't reach its limit.

At that point, the motor reaches its maximum speed, so-called rated speed (called also base speed when talking about flux-weakening). Beyond that limit, the motor torque decreases rapidly toward its minimum value, which depends on a load torque profile. To expand the speed above the rated value, the motor torque is necessary to be reduced. A common method in the control of synchronous motors is to reduce the magnetizing current, which produces the magnetizing flux. This method is known as field-weakening. With PM synchronous motors it is not possible, but, instead, the air gap flux is weakened by producing a negative d-axis current component,  $i_d$ .

Because nothing has happened to the excitation magnetic field and the air gap-flux is still reduced, so is the motor torque, this control method is called flux-weakening. As a basis for this analysis, the PMSM current and voltage d-q vector diagrams from the previous section Fig are used. During flux-weakening, because the demagnetizing (negative)  $i_d$  current increases, a phase current vector is rotated toward the negative d-semi-axis. The rotation of the phase voltage vector is determined by a chosen flux weakening strategy, but at the end of flux-weakening it always rotates toward the positive q-semi axis because of  $i_q$  current, i.e.  $v_d$  voltage magnitude decrease.

Hence ,the voltage-to-current phase shift decreases to zero and increases in negative direction either to the inverter phase shift limit (usually  $30^0$ ), or a load torque dictated steady-state (zero acceleration), or to the zero motor torque condition (no load or generative load). A big concern of flux-weakening control is a danger of permanent demagnetization of magnets. However, large materials such as Samarium-Cobalt, allows significant  $i_d$  current which can extend the motor rated speed up to two times. Three commonly used flux-weakening control strategies are :

1) Constant-voltage-constant-power(CVCP)control

2) Constant-current-constant-power(CCCP)control

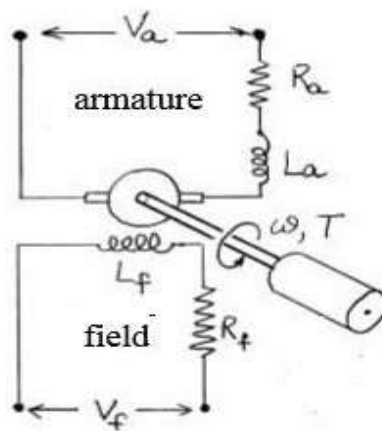
3)Optimum-current-vector(OCV or CCCV-constant-current-constant-voltage)control.

## 5.1 Transfer Function for DC Motor

Consider a separately excited DC motor with armature voltage control. In armature

The figure at the right represents a DC motor attached to an inertial load. The voltages applied to the field and armature sides of the motor are represented by  $V_f$  and  $V_a$ . The resistances and inductances of the field and armature sides of the motor are represented by  $R_f$ ,  $L_f$ ,  $R_a$ , and  $L_a$ . The torque generated by the motor is proportional to  $i_f$  and  $i_a$ , the currents in the field and armature sides of the motor.

$$T_m = K i_f i_a$$



**Figure 5.1.1 Speed Controller**

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey, page-142)

### Field-Current Controlled:

In a field-current controlled motor, the armature current  $i_a$  is held constant, and the field current is controlled through the field voltage  $V_f$ . In this case, the motor torque increases linearly with the field current. We write

$$T_m = K_{mf} i_f$$

For the field side of the motor the voltage/current relationship is

$$\begin{aligned} V_f &= V_R + V_L \\ &= R_f i_f + L_f \left( \frac{di_f}{dt} \right) \end{aligned}$$

The transfer function from the input voltage to the resulting current is found by taking Laplace transforms of both sides of this equation.

$$\frac{I_f(s)}{V_f(s)} = \frac{(1/L_f)}{s + (R_f/L_f)} \quad (1^{\text{st}} \text{ order system}) \quad ;i.z)$$

The transfer function from the input voltage to the resulting motor torque is found by combining equations (1.2) and (1.3).

$$\frac{T_m(s)}{V_f(s)} = \frac{K L_f}{s + (R_f/L_f)} \quad (1^{\text{st}} \text{ order system}) \quad (1.4)$$

So, a step input in field voltage results in an exponential rise in the motor torque.

An equation that describes the rotational motion of the inertial load is found by summing moments

$$M - T_p - cv - JR \quad (\text{counterclockwise positive})$$

$$J\dot{w} + cw = T_m$$

$$\frac{W(s)}{T_m(s)} = \frac{(1/J)}{s + (c/J)} \quad (1^{\text{st}} \text{ order system}) \quad (1.5)$$

Combining equations (1.4) and (1.5) gives the transfer function from the input field voltage to the resulting speed change

$$\frac{W(s)}{V_f(s)} = \frac{W(s) T_m(s)}{T_m(s) V_f(s)} = \frac{(K_m/L_f J)}{(s + c/J)(s + R_f/L_f)} \quad (2^{\text{nd}} \text{ order system}) \quad (1.6)$$

Finally, since  $lv = dq/dt$ , the transfer function from input field voltage to the resulting rotational position change is

$$\frac{Q(s)}{V_f(s)} = \frac{Q(s) W(s)}{W(s) V_f(s)} = \frac{K_m/L_f J}{(s + c/J)(s + R_f/L_f)} \quad (3^{\text{rd}} \text{ order system}) \quad (1.7)$$