Electric Machine Control

Chapter 7

Current Regulation in Power Converters

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7.1 Introduction

- Field orientation controller
  - Most systems provide **current commands** and thus require power converters which function as controllable current sources
    - Stator dynamics can be eliminated
    - The function of Inner current loops in ac machine is similar to the current loop in a high performance dc machine except the amplitude and phase control

7.2 Current Regulated Inverters

- Current regulator for ac drives
  - Stator dynamics (effects of resistance, inductance and induced emf) can be eliminated
  - Both the amplitude and phase of the stator current must be controlled
    - More complex than dc drives
- CSI/ PWM
  - CSI
    - A natural current supply and can readily be adapted to the controlled current operation
  - PWM
    - Higher bandwidth
    - Elimination of current harmonics as compared to the CSI

7.2.1 The current regulated CSI inverter

- Problems in CSI
  - Commutation delay
  - Significant harmonics
  - At low frequency
    - Torque pulsation
    - Speed oscillations (cogging) → improved by PWM technique
- CSI operation
  - Above 10-20Hz

CSI with dc-link current regulator

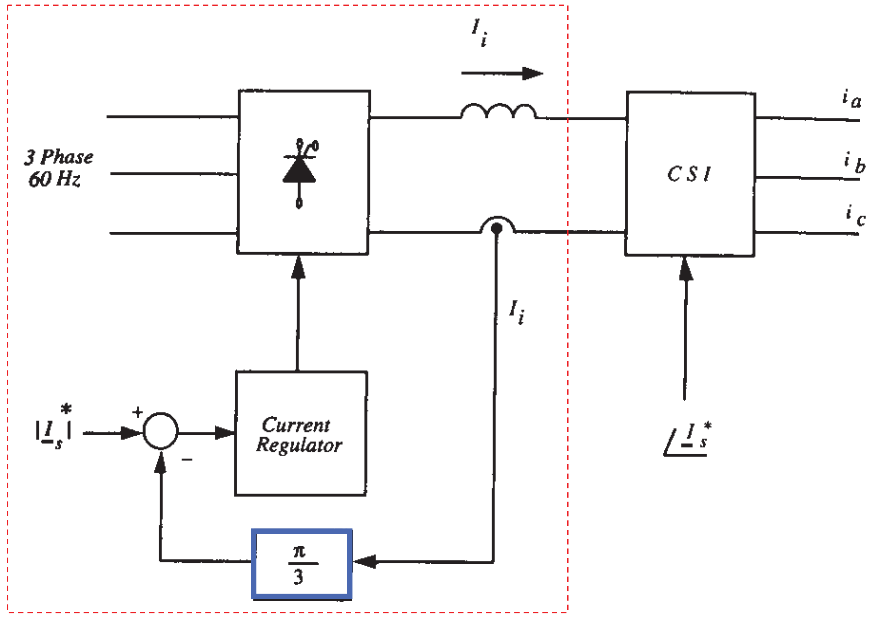


Figure 7.1 CSI inverter with dc link current regulator as a three phase regulated source

CSI with dc-link current regulator and commutating delay compensation

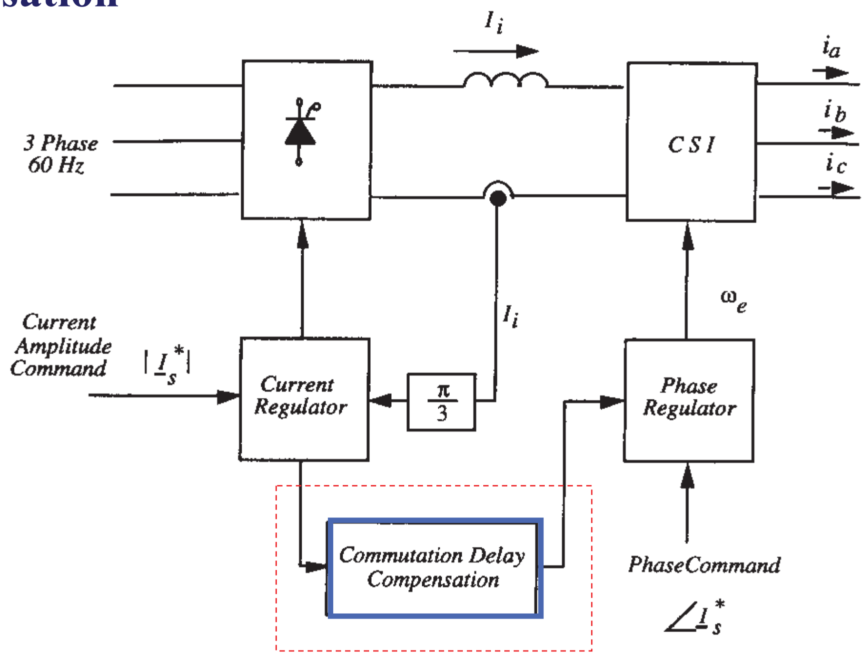


Figure 7.2 Current regulated CSI inverter with commutation delay compensation

7.2.2 The current regulated PWM inverter

- Several fundamental differences from the CSI system
  - Autual time domain reference in PWM inverter (amplitude and phase references required in the CSI)
  - Harmonic current reduction
  - Ac current regulation (dc current regulation in the CSI)
  - Wide bandwidth current sensor is necessary
- The PWM current regulator can be classified into three groups
  - Hysteresis regulator
  - Ramp comparison
  - Predictive controllers

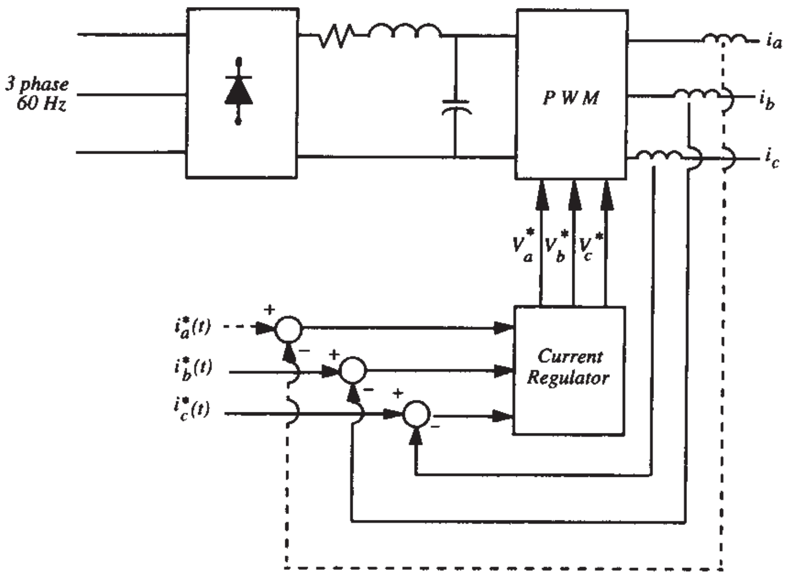


Figure 7.3 PWM system with current regulation to produce a controlled three phase current source

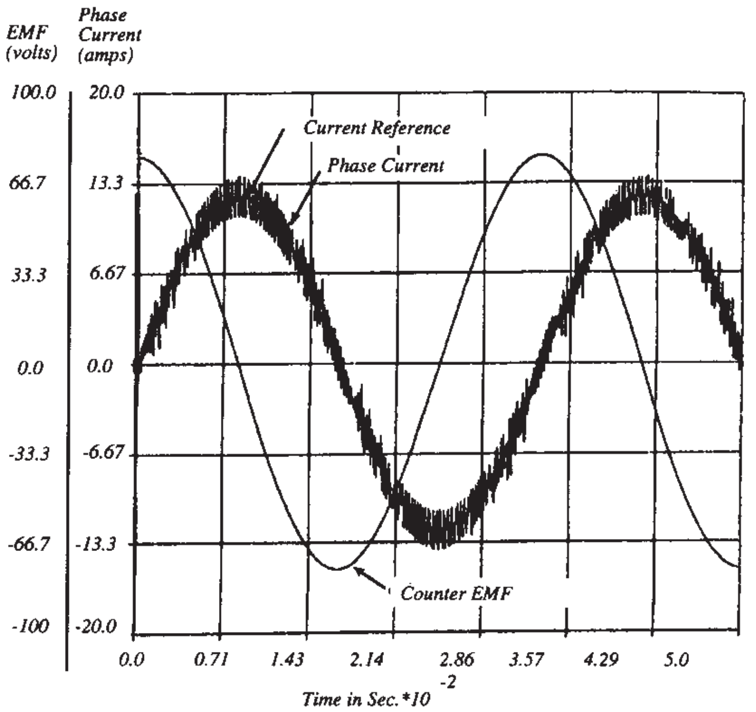


Figure 7.4 Simulated waveforms of a PWM inverter with current regulation using three independent hysteresis controllers

7.3 Hysteresis Regulators

- Advantages:
  - Simple and good current amplitude control
- Disadvantages:
  - Highly variable PWM switching rate
    - Opposite to the needs for good current control
  - The current is limited to twics the hysteresis band

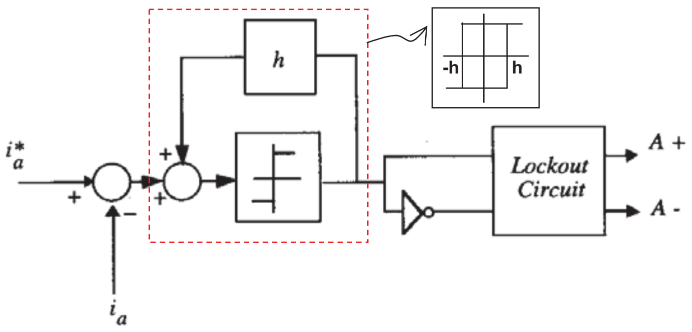
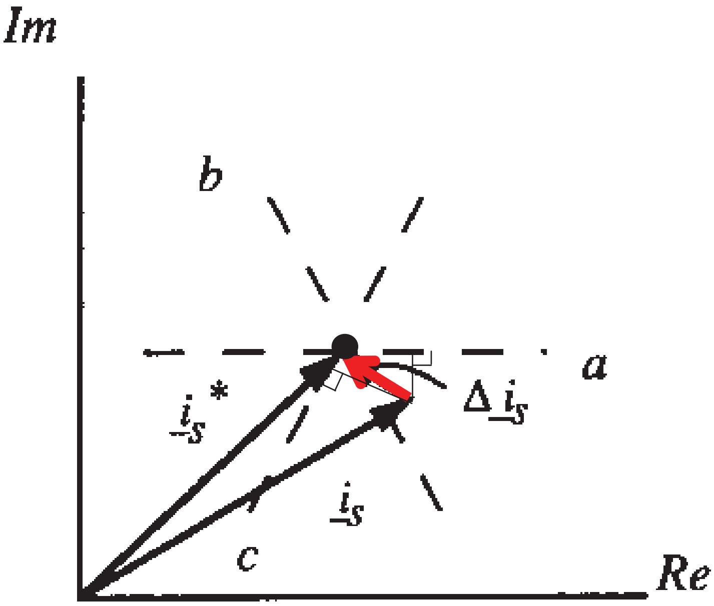


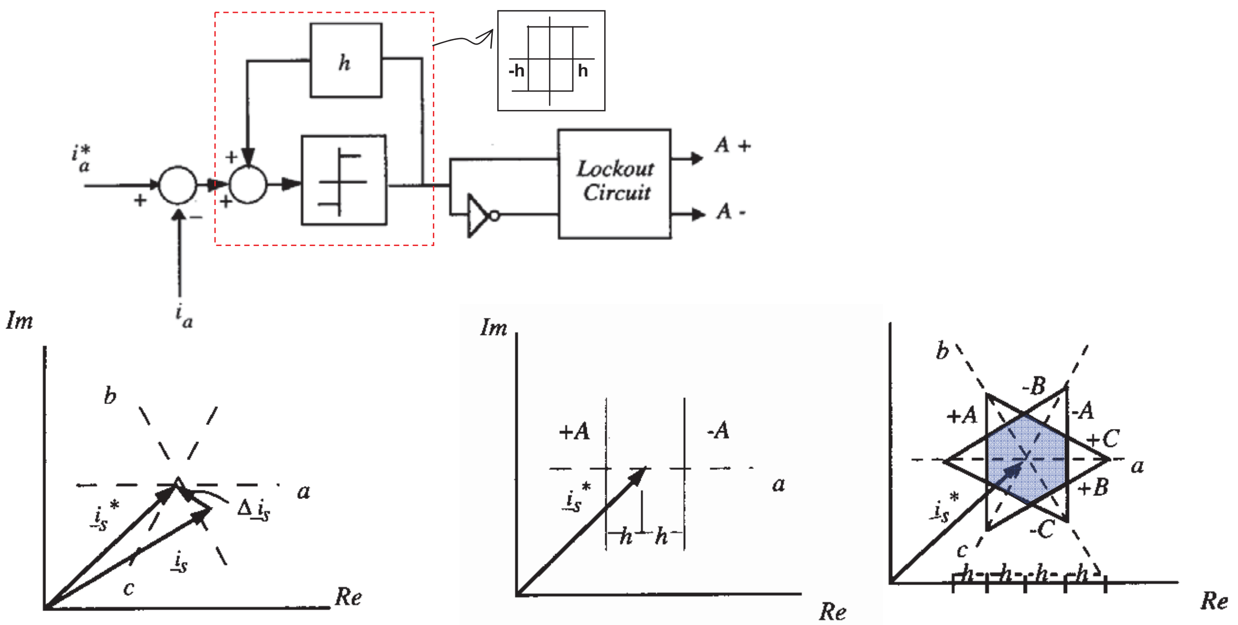
Figure 7.5 Hysteresis current controller for one phase

Behavior of the hysteresis controller



a) Current Vectors in the Complex Plane.

Behavior of the hysteresis controller



a) Current Vectors in the Complex Plane. *b) Switching Lines for Phase a.* *) Complete Switching Diagram.*

Figure 7.6 Hysteresis controller switching diagrams – three independent controllers

An error of 2h, twice the expected value equal to the hysteresis band

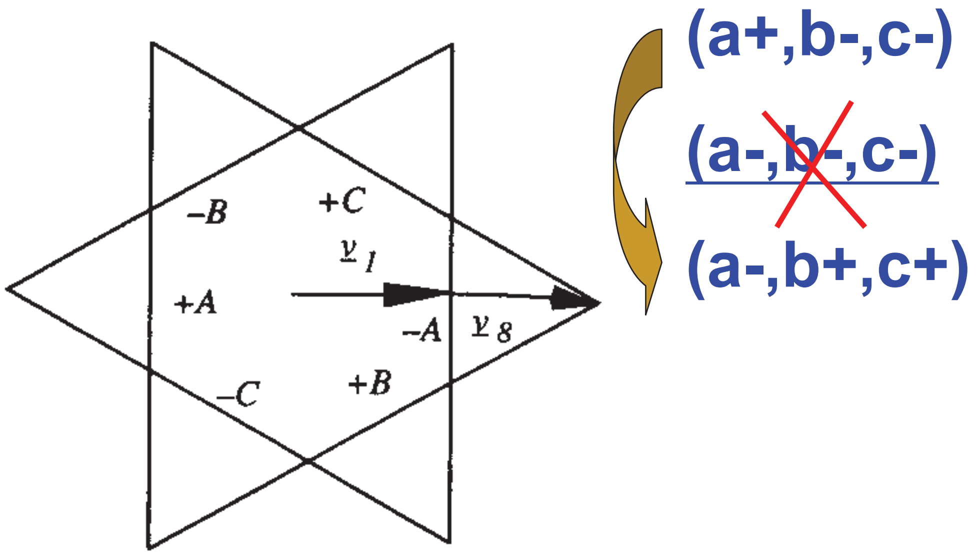


Figure 7.7 Hysteresis controller current trajectory resulting in error equal to twice the hysteresis band

High frequency limit cycle oscillations when the load counter emf is low

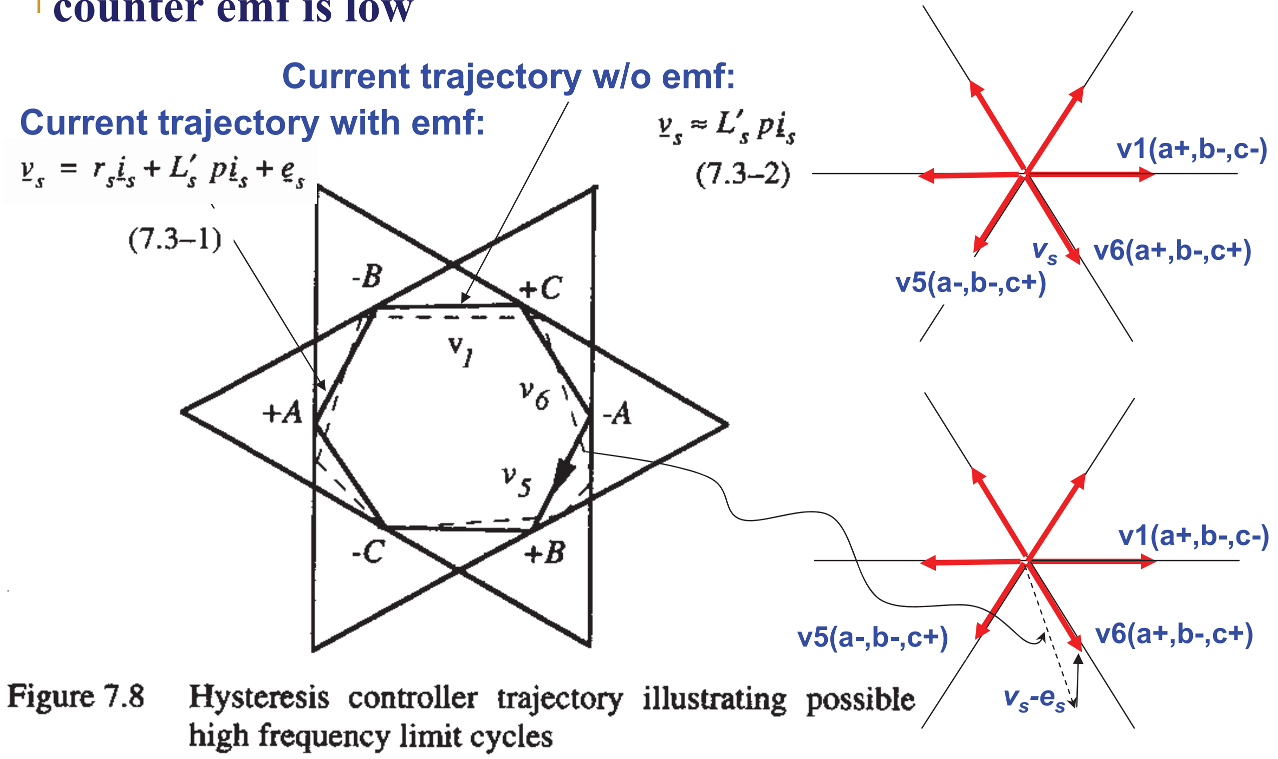


Figure 7.8 Hysteresis controller trajectory illustrating possible high frequency limit cycles

h=1.5

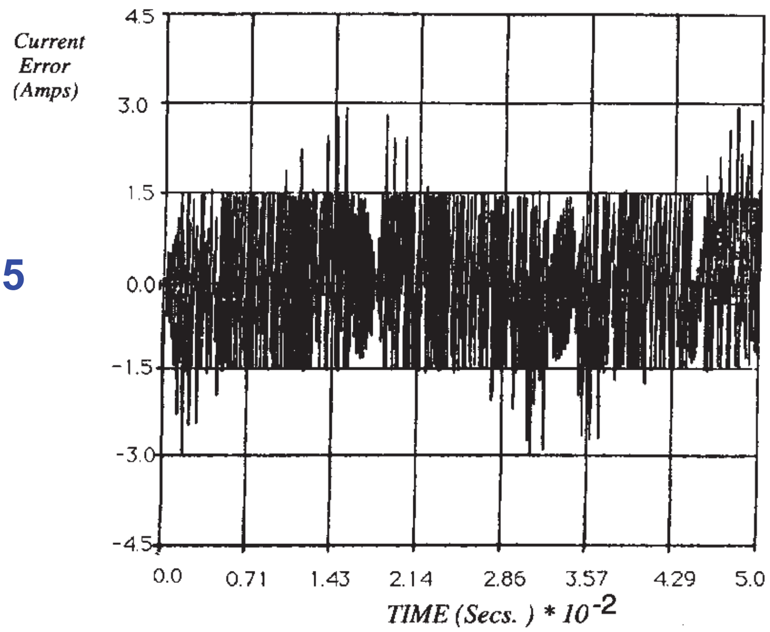


Figure 7.9 Simulation results for hysteresis controller driving a typical 10 HP induction motor at 30 HZ. and no load showing random large current errors

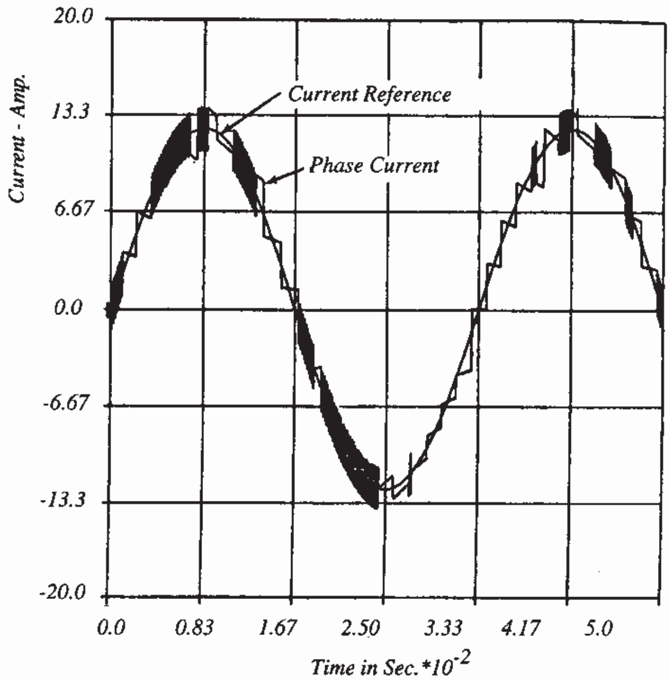


Figure 7.10 Simulation results for hysteresis controller driving a typical 10 hp induction motor at zero speed showing sporadic high frequency limit cycles in the motor phase current

Estimation of limit cycle oscillation frequency

- For zero counter emf, the velocity in am,peres per second is approximately

$$\text{velocity} = \frac{di_s}{dt} \approx \frac{2}{3}\frac{V_{dc}}{L'_s} \qquad (7.3\text{–}3)$$

- The distance (in amperes) travelled in a complete limit cycle is approximately

$$\text{distance} = \Delta i_s \approx 6h \qquad (7.3\text{–}4)$$

- The inverter switching frequency is then

$$f_s = \frac{\text{velocity}}{\text{distance}} = \frac{V_{dc}}{9hL'_s} \qquad (7.3\text{–}5)$$

- For Vdc=300V, L's=3.36mH, h=1.5 amperes

$$f_s = \frac{300}{9\text{x}1.5\text{x}3.36\text{x}10^{-3}} = 6610\text{Hz} \quad (7.3\text{–}6)$$

7.4 Ramp-Comparison Controllers

- For the purpose of constant switching frequency
- Basic concept:

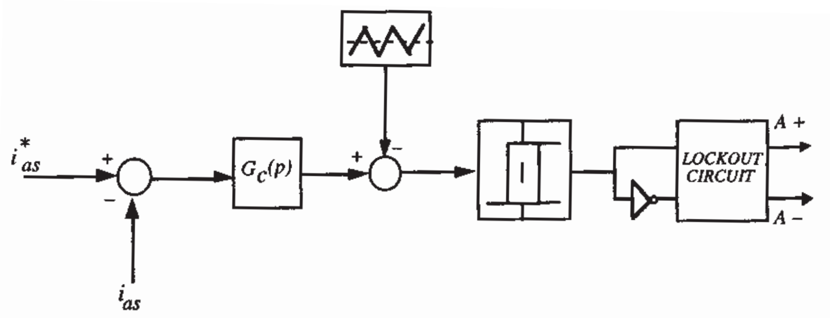


Figure 7.12 One phase of basic ramp comparison controller

✓**The inverter switches at the frequency of the triangle wave and produces an output voltage which is proportional to the error signal**

$$v_{out} = \frac{2}{\pi} V_i \frac{v_{in}}{V_\Delta} \quad (v_{in} \to V_{dc})$$

$$\begin{cases} = K_\Delta v_{in} & = \dfrac{2V_i}{\pi} m_i \qquad m_i \le 1 \\ = m_i \dfrac{V_{dc}}{\pi} \left[\sin^{-1}(1/m_i) + (1/m_i)\sqrt{1-(1/m_i)^2} \right] & m_i > 1 \end{cases}$$

where $K_\Delta = (2/\pi)(V_i/V_\Delta)$

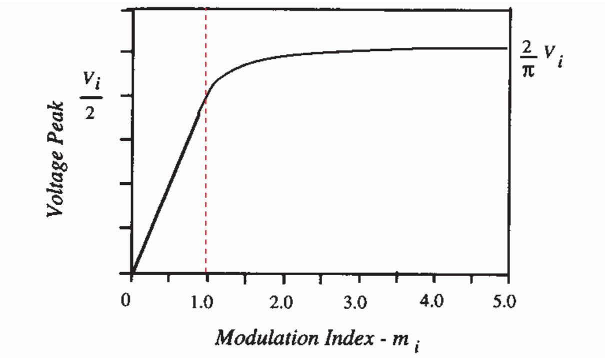


Figure 7.13 Fundamental component of phase voltage versus modulation index m_i

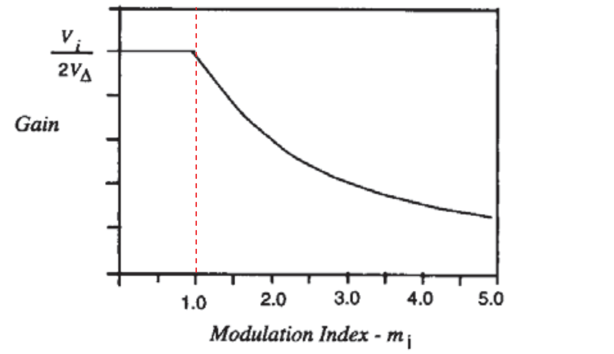


Figure 7.14 Fundamental component gain versus modulation index m_i

7.5 Stationary Frame Regulators

- For steady state operation, the equivalent ckt of IM can be used to relate $\underline{i}_s^s$ and $\underline{v}_s^s$
  - Arbitrary R.F.

$$\underline{v}_s = r_s \underline{i}_s + (p + j\omega)\underline{\lambda}_s \qquad (7.5\text{–}2)$$

$$0 = r_r \underline{i}_r + [p + j(\omega - \omega_r)]\underline{\lambda}_r \qquad (7.5\text{–}3)$$

  - Stationary R.F.

$$\underline{v}_s^s = [r_s + pL_s'] \underline{i}_s^s + \frac{L_m}{L_r} p \underline{\lambda}_r^s \qquad (7.5\text{–}10)$$

$$0 = -\frac{L_m}{\tau_r} \underline{i}_s^s + \left[p - j\omega_r + \frac{1}{\tau_r} \right] \underline{\lambda}_r^s \qquad (7.5\text{–}11)$$

$$\Rightarrow \quad \underline{v}_s^s = \underline{i}_s^s \underline{Z}_{in}(j\omega_e, jS\omega_e) \qquad (7.5\text{–}12)$$

where $\underline{Z}_{in}(j\omega_e, jS\omega_e) = \dfrac{p^2 L_s' + p(r_s + L_s/\tau_r - j\omega_e L_s') + r_s[1/\tau_r - j\omega_e(1-S)]}{p + 1/\tau_r - j\omega_e(1-S)}$

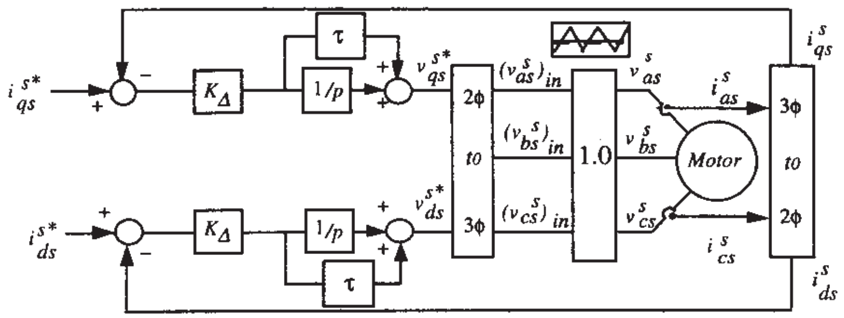
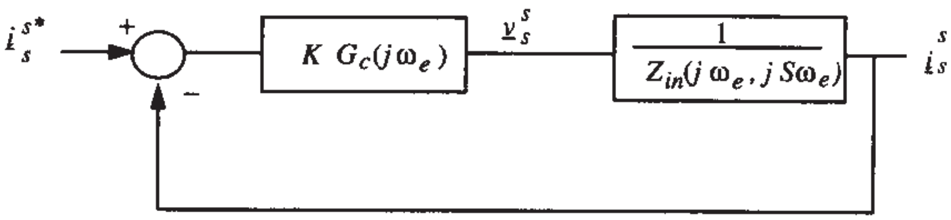
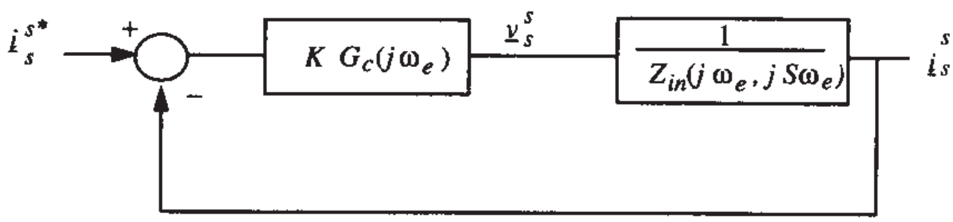


Figure 7.15 System diagram of stationary d,q frame ramp comparison current regulator using PI controllers



$$\frac{\underline{i}_s^s}{\underline{i}_s^{s*}} = \frac{1}{1+\underline{Z}_{in}(j\omega_e, jS\omega_e)/K_\Delta \underline{G}_c(j\omega_e)} \quad (7.5\text{–}14)$$



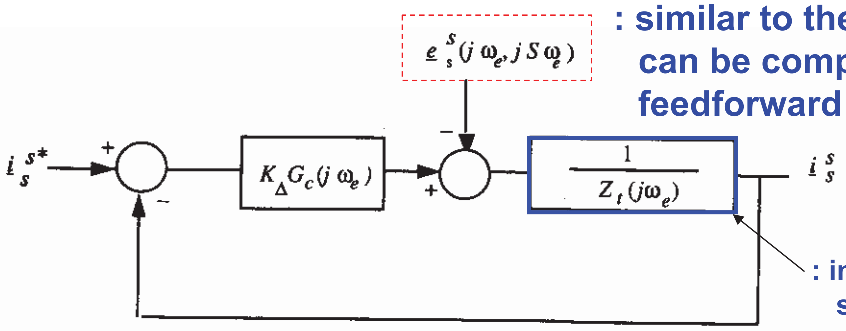
$$\frac{\underline{i}_s^s}{\underline{i}_s^{s*}} = \frac{1}{1+\underline{Z}_{in}(j\omega_e, jS\omega_e)/K_\Delta \underline{G}_c(j\omega_e)} \quad (7.5\text{–}14)$$

- **(7.5-14) shows that the system of Fig.7.15 can result a significant phase and magnitude errors if the frequency curve of $G_c(j\omega_e)$ does not maintain sufficiently high gain at higher frequencies.**

Transient model

$$\underline{v}_s^s = [r_s + pL'_s]\,\underline{i}_s^s + \frac{L_m}{L_r}p\underline{\lambda}_r^s \qquad (7.5\text{–}15)$$

$$\Rightarrow \quad \underline{v}_s^s = [r_s + j\omega_e L'_s]\,\underline{i}_s^s + \underline{e}_s^s \qquad (7.5\text{–}16)$$



: similar to the dc machine and can be compensated by the feedforward compensator

: independent of rotor speed

Note: $Z_t(j\omega_e) = r_s + j\omega_e L'_s$: transient impedance

Figure 7.17 Steady state frequency domain block diagram for the current regulator of Figure 7.15 using the 'transient' model of the machine

7.6 Syn. Frame Regulators

- Stationary R.F. Regulator
  - Regulating ac signals: does not produce current error because of the frequency dependent PI controllers
- High performance applications
  - Guaranteed zero steady state error
  - Require more hardware for implementation
  - Require explicit knowledge of the frequency ω_e

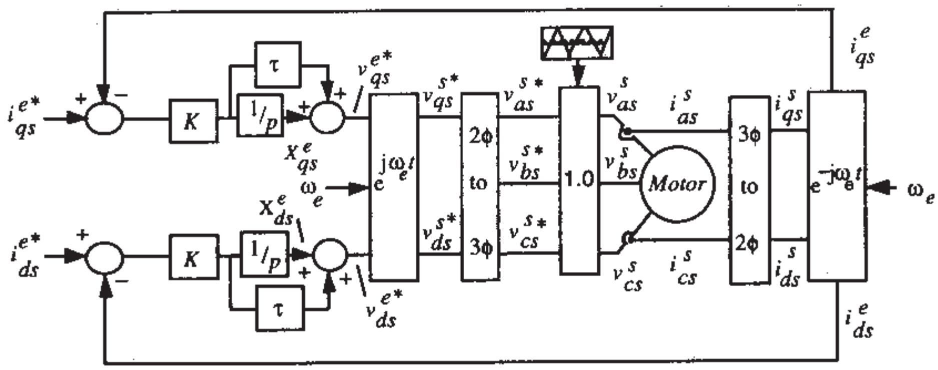


Figure 7.18 System diagram of synchronous frame ramp comparison current regulator using PI controllers

Transform stationary R.F. to synchronous R.F.

$$\underline{v}_s^{s*} = K\tau(\underline{i}_s^{s*} - \underline{i}_{qs}^{s}) + \underline{x}_s^s \qquad (7.6\text{–}1)$$

$$p\underline{x}_s^s = K(\underline{i}_s^{s*} - \underline{i}_s^s) \qquad (7.6\text{–}2)$$

$$\underline{f}_s^s = e^{j\omega_e t}\underline{f}_s^e \qquad (7.6\text{–}3)$$

$$\underline{v}_s^{e*} = K\tau(\underline{i}_s^{e*} - \underline{i}_s^e) + \underline{x}_s^e \qquad (7.6\text{–}4)$$

$$(p + j\omega_e)\underline{x}_s^e = K(\underline{i}_s^{e*} - \underline{i}_s^e) \qquad (7.6\text{–}5)$$

$$\Rightarrow \quad \underline{x}_s^e = \frac{1}{p}[K(\underline{i}_s^{e*} - \underline{i}_s^e) - j\omega_e \underline{x}_s^e] \qquad (7.6\text{–}6)$$

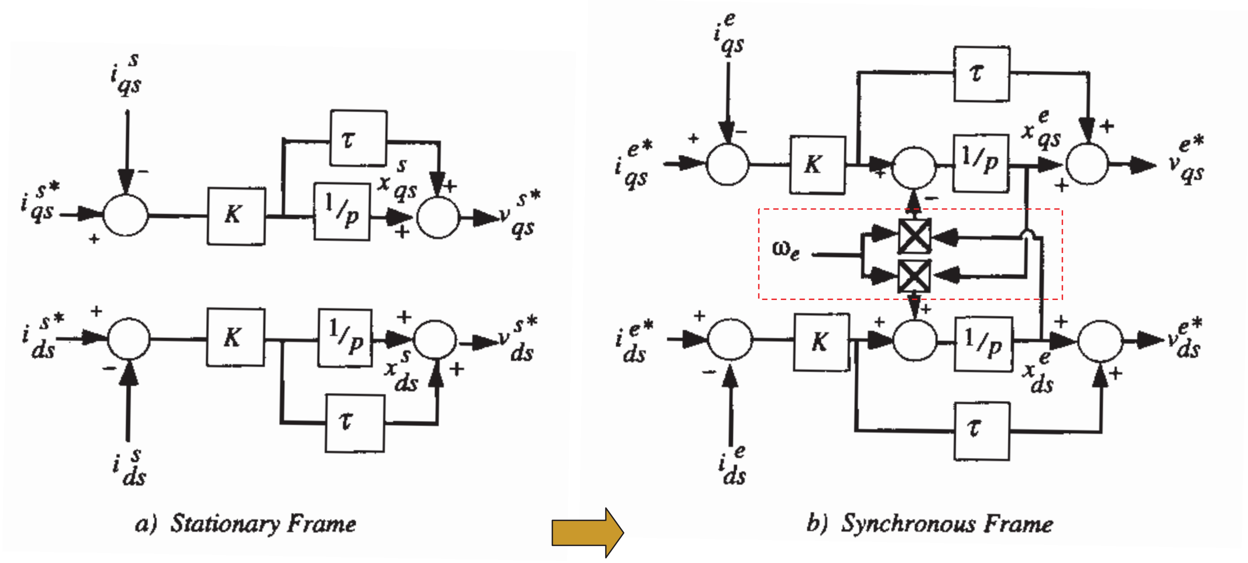
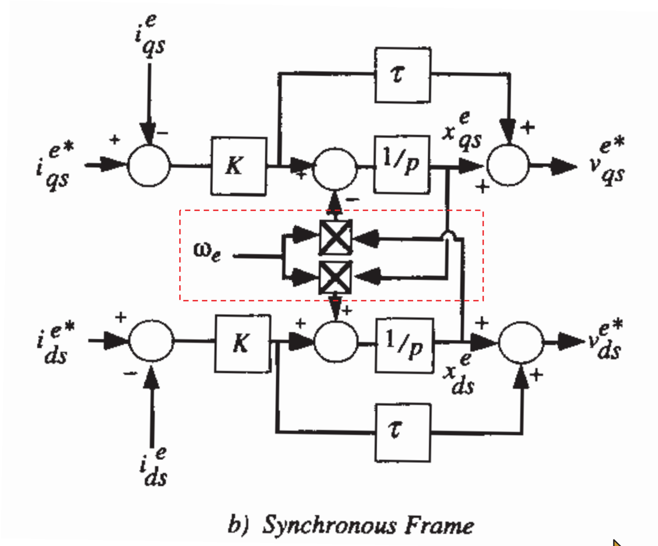


Figure 7.19 Models of the stationary frame PI controller current regulator in a) the stationary frame and b) the synchronous frame

Cross coupling for a stationary frame PI current regulator in synchronous frame



- Nonzero steady state
- q-axis current will not follow the q-axis if there is an error in the direct channel.
- Resonant phenomena

$$\begin{cases} px^e_{qs} = -\omega_e x^e_{ds} & (7.6\text{–}7) \\ px^e_{ds} = \omega_e x^e_{qs} & (7.6\text{–}8) \end{cases}$$

$$\begin{cases} x^e_{qs} = A\cos(\omega_e t + \varphi) & (7.6\text{–}10) \\ x^e_{ds} = A\sin(\omega_e t + \varphi) & (7.6\text{–}11) \end{cases}$$

$$\underline{x}^s_s = e^{j\omega_e t}\underline{x}^e_s = e^{j\omega_e t}Ae^{-j(\omega_e t + \varphi)} = Ae^{-j\varphi} \qquad (7.6\text{–}12)$$

Oscillations can be initiated only in transient and will die out according to the damping properties.

Cross coupling for a stationary frame PI current regulator in stationary frame

$$\underline{v}_s^{s*} = K\tau(\underline{i}_s^{s*} - \underline{i}_s^s) + \underline{x}_s^s \qquad (7.6\text{–}13)$$

$$\underline{x}_s^s = \frac{1}{p}[K(\underline{i}_s^{s*} - \underline{i}_s^s) + j\omega_e \underline{x}_s^s] \qquad (7.6\text{–}14)$$

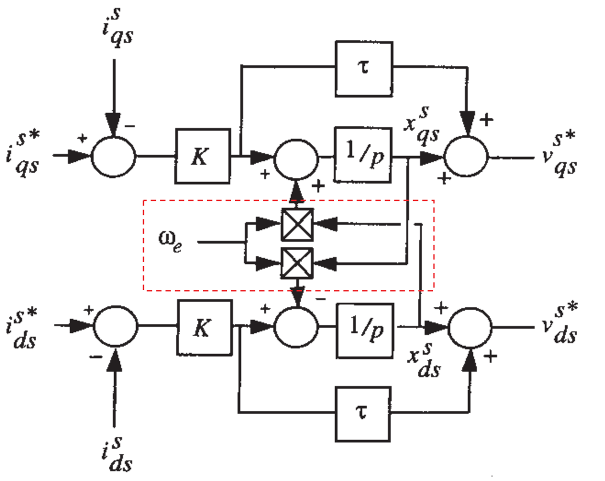
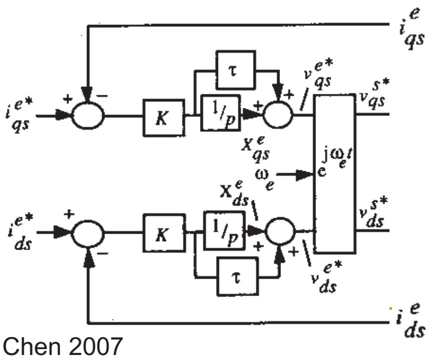


Figure 7.20 The stationary frame equivalent of a PI controller synchronous frame regulator

$$p(\underline{x}_s^s) = p(e^{j\omega_e t}\underline{x}_s^e)$$

$$= e^{j\omega_e t} p\underline{x}_s^e + \cancel{j\omega_e \underline{x}_s^s} = \left[K\left(\underline{i}_s^{s*} - \underline{i}_s^s\right) + \cancel{j\omega_e \underline{x}_s^s}\right]$$

$$\Rightarrow p\underline{x}_s^e = K\left(\underline{i}_s^{e*} - \underline{i}_s^e\right)$$



7.7 Feedforward Compensation

- Regulators
  - Series compensation
  - Feedback compensation
  - Feedforward compensation

Series compensation

Series compensator : hysteresis and ramp comparison

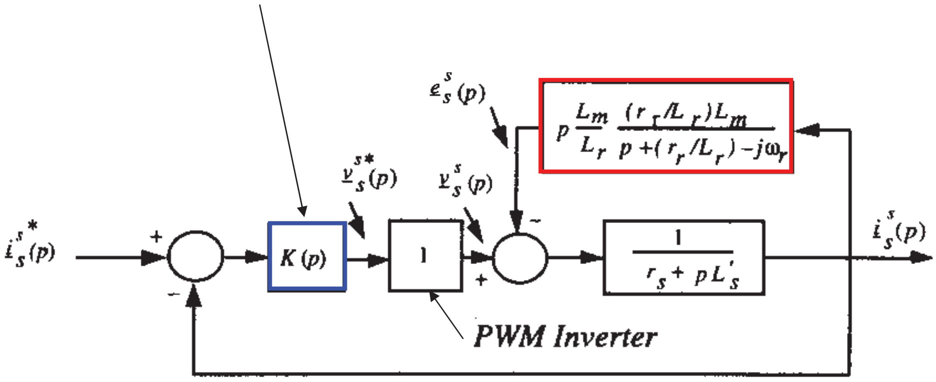


Figure 7.21 Block diagram of series compensated current regulated induction motor

$$\begin{cases} v_s^s = [r_s + pL_s']\, i_s^s + \overbrace{\boxed{\frac{L_m}{L_r}p\lambda_r^s}}^{e_s^s(p)} & (7.5\text{–}10) \\ 0 = -\frac{L_m}{\tau_r} i_s^s + \left[p - j\omega_r + \frac{1}{\tau_r}\right]\lambda_r^s & (7.5\text{–}11) \end{cases}$$

Feedforward compensation

When all of the parameters of the machine are accurately known, it is possible to regulate the stator currents w/o any feedback of the motor current by using a feedforward compensator.

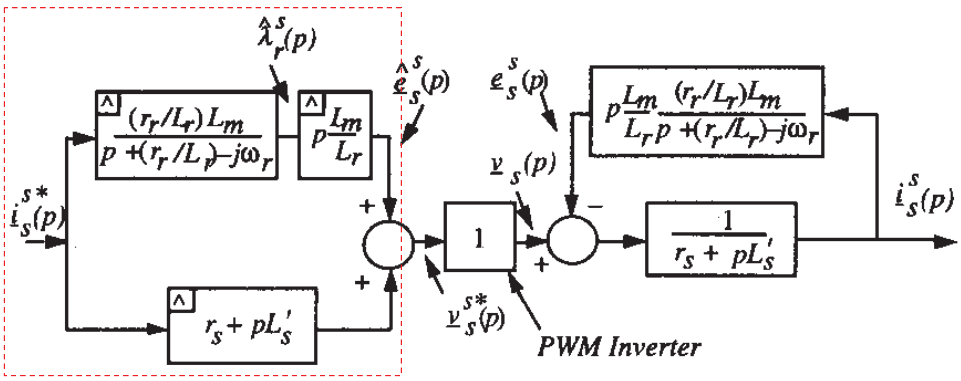


Figure 7.22 Block diagram of induction motor current controller with ideal feedforward compensation. The carot symbol '^' denotes an estimate of the quantity

Feedforward compensation

The difficulty of computing rotor flux linkage can be improved by measuring the air gap flux linkage from flux coils.

$$\underline{\lambda}_r^s = \frac{L_r}{L_m}\underline{\lambda}_m^s - (L_r - L_m)\,\underline{i}_s^s \qquad (7.7\text{–}1)$$

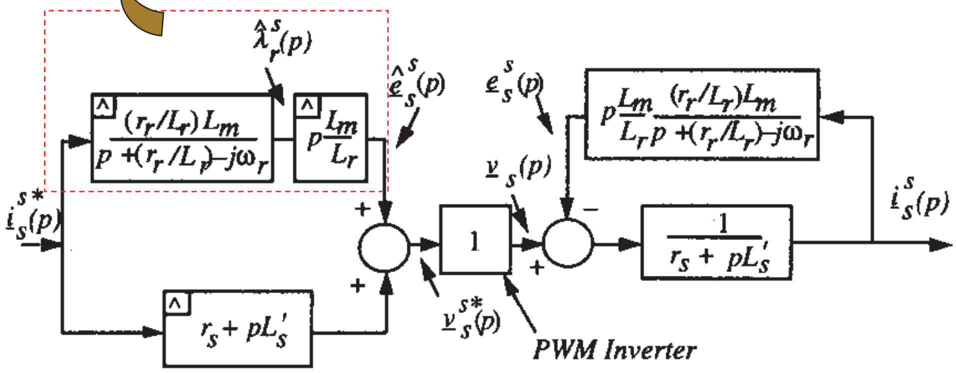


Figure 7.22 Block diagram of induction motor current controller with ideal feedforward compensation. The carot symbol '^' denotes an estimate of the quantity

7.8 Augmented Feedforward Compensation

- Augmented feedforward compensation (AFC)
  - Series compensator + Feedforward compensator
- Feedforward compensator in AFC
  - Open loop control
  - Rough estimate of the voltage command
    - Impoved by the series compensator (PI controller)
- Series compensator in AFC
  - Since the major portion of the voltage command is provided by the feedforward compensator, thereby **permitting a reduced gain in series compensator**
    - **Less sensitive to random errors and injected noise**

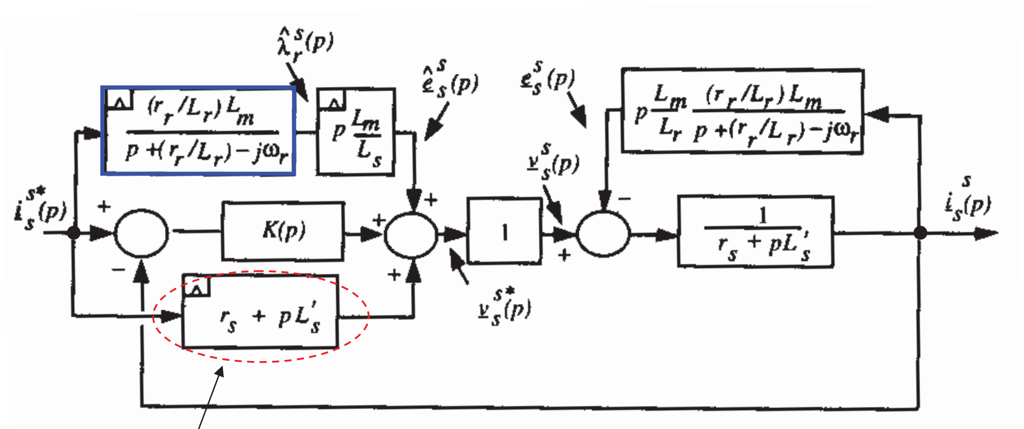


Figure 7.23 Block diagram of current regulator using series compensation augmented by feedforward compensation. The symbol '^' denotes an estimate of the quantity

The voltage drop term can be omitted or be replaced by only an estimate of the drop contributed by the transient inductance.

7.9 Augmented Feedforward Compensation with Decoupling

$$
\begin{cases}
v_s^{s*} = K\tau(i_s^{s*} - i_s^s) + x_s^s & (7.6\text{–}13) \\
x_s^s = \frac{1}{p}[K(i_s^{s*} - i_s^s) + j\omega_e x_s^s] & (7.6\text{–}14)
\end{cases}
$$

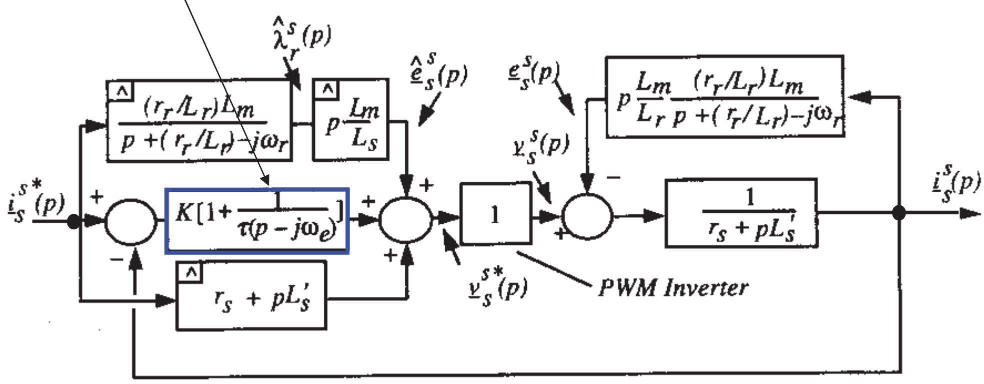


Figure 7.24 Block diagram of current regulator using cross coupled series compensation augmented by feedforward compensation. The symbol '^' denotes an estimate of the quantity

7.10 Predictive Control

$$\frac{d}{dt}\underline{i}_s^s(t) \cong \frac{1}{L'_s}[\underline{v}_s^s(t) - \underline{e}_s^s(t)] \qquad (7.10\text{–}1)$$

Assume T is sufficiently small

$$\underline{i}_s^s(\mathrm{T}) - \underline{i}_s^s(0) \cong \frac{\mathrm{T}}{L'_s}[\underline{v}_s^s(0) - \underline{e}_s^s(0)] \qquad (7.10\text{–}2)$$

$$\because \quad \underline{i}_s^s(\mathrm{T}) = \underline{i}_s^{s*}(\mathrm{T})$$

$$\underline{v}_s^{s*}(0) = \frac{L'_s}{\mathrm{T}}[\underline{i}_s^{s*}(\mathrm{T}) - \underline{i}_s^s(0)] + \underline{e}_s^s(0) \qquad (7.10\text{–}3)$$

Assume the position of the command $\underline{v}_s^{s*}(0)$ is instantaneously located between vectors v1 and v2

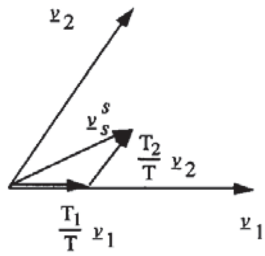


Figure 7.25 Space vector synthesis of a voltage $\underline{v}_s^s$.

$$\int_0^{\mathrm{T}} \underline{v}_s^{s*}(0)\,dt = \int_0^{\mathrm{T}} \underline{v}_1 dt + \int_{\mathrm{T}_1}^{\mathrm{T}_1+\mathrm{T}_2} \underline{v}_2 dt + \int_{\mathrm{T}_1+\mathrm{T}_2}^{\mathrm{T}} \underline{v}_7 dt \qquad (7.10\text{–}4)$$

Zero voltage switching state

$$\underline{v}_s^{s*}(0) = \frac{\mathrm{T}_1}{\mathrm{T}}\underline{v}_1 + \frac{\mathrm{T}_2}{\mathrm{T}}\underline{v}_2 + \frac{\mathrm{T}_3}{\mathrm{T}}\underline{v}_7 \qquad (7.10\text{–}5)$$