SV9000 Closed Loop

What does closed loop deliver to the customer?

Closed loop vector drives provide better product quality and increased output through precise and responsive control of motor speed and torque. Low speed torque control and smooth transitions of both torque and direction makes the SV9000 closed loop drive ideal for machine tool, web handling and winder applications. When the speed of a spindle or press must be maintained as a tool is engaged, the SV9000 closed loop drive maintains constant process speed during the shock load conditions found in machine tool applications. Consistent motion regardless of load, while following a speed profile results in better quality and more throughput. Production time is saved because the customer's process doesn't need to come to a complete stop when switching from line operation to inverter operation or during power loss ride through.

The SV9000 closed loop vector drive delivers all this by providing;

- ♦ Precise speed control
- ♦ Precise torque control
- ♦ High performance, low speed operation of both speed and torque
- ♦ Smooth transition between forward and reverse operation under load

What is closed loop Vector control?

Closed loop vector control utilizes a shaft-mounted encoder to accurately determine the motor rotor position. For precise control of speed, it is first necessary to have precise control of torque. As such, the closed loop vector control is not recommended for applications with multiple motors per drive because only one rotor position feedback is available and the torque control of additional motors with one inverter section is impractical.

By closing the loop with continuous rotor position feedback, the vector control algorithm quickly and accurately delivers the required flux producing current (also called direct current $\mathbf{i_d}$), and torque producing (also called quadrature current $\mathbf{i_q}$). Appendix A provides a brief treatment of the closed loop theory of operation.

Closed loop control strategy

Standard closed loop control provides performance comparable to a DC closed loop converter. This is ideal for retrofits where a DC system is being upgraded. Vector control utilizes a closed loop motor model with encoder feedback to provide precise speed and torque control performance. The following performance benchmarks are useful in comparison to other types of drive controllers:

- Frequency regulator operates with a 5 ms update rate
- I_q and I_d regulators operate with a 1 ms update rate
- Speed regulation 0.01%

Encoder connection with option boards.

Encoder feedback signal quality and frequency are central to high performance operation. A good quality optical encoder is recommended. Each application should be analyzed to determine the optimal pulse count. The highest pulse count possible provides the best angular resolution for low speed regulation. However, when selecting a pulse rate it is also necessary to consider the maximum input frequency (pulses per second) of the drive and the maximum and minimum motor speed. For example, if the top motor speed is 1740 revolutions per minute (rpm) and the minimum speed is 10 rpm, then the following calculation produces the maximum encoder pulse rate.

$$\frac{maximum\ pulses}{revolution} = \frac{110{,}000\left(\frac{pulses}{second}\right)\times 60\left(\frac{seconds}{minute}\right)}{1740\left(\frac{revolutions}{minute}\right)}$$
$$= 3793\left(\frac{pulses}{revolution}\right)$$

However, a standard encoder pulse rate should be selected reasonably close to the above calculation with some margin for over-speed. In this case, a 2500 pulses per revolution (ppr) encoder is a good choice. While this may seem to be a high pulse rate, remember that the drive performance at low speed is influenced by the number of pulses sampled per update period. For example, if a .005 second speed update is assumed, then at 10 rpm, the pulses per period (ppp) is calculated as follow;

$$\frac{pulses}{period} = \frac{10\left(\frac{revolutions}{minute}\right)}{60\left(\frac{seconds}{minute}\right)} \times 2500\left(\frac{pulses}{revolution}\right) \times .005\left(\frac{seconds}{period}\right)$$
$$= 2.1\left(\frac{pulses}{period}\right)$$

If a 600 ppr encoder is substituted the resulting resolution at 10 rpm is 0.500 ppp. The granularity of this feedback, directly affects the torque regulator as position uncertainty, and the speed regulator as speed uncertainty. For practical purposes, avoid using encoders above 10,000 ppr. Encoder technology is continuing to improve, but remember that these devices are mounted on a motor accessory shaft, sometimes within the vector motor blower housing, and may experience temperatures as high as 80° C. It is difficult to find commercially available encoders at these high ppr with such a high temperature specification. Other important encoder requirements and specifications are listed below;

- 110kHz maximum pulse frequency
- 90° ±5% quadrature
- shielded twisted pair cable, use quantity 3, 2 conductor twisted pair, 18 gauge, Belden #8770 or equivalent
- two supply voltages available
  24 V "0" ≤ 10 V, "1" ≥ 18V, Ri=2.2KΩ
  5V "0" ≤ 2 V, "1" ≥ 3V, Ri=330Ω

Closed loop option boards

Closed loop control is available with the standard encoder option, expanded I/O options, or fieldbus option boards in the following configurations:

- Option designator –01, SV9IO100, expanded I/O with 5 digital inputs, 2 analog voltage inputs, analog voltage output, thermistor input, encoder input. Requires system software Sm00099c.bin and application software Smf091ca.hex for closed loop operation.
- Option designator –03, SV9IO102, expanded I/O with 5 digital inputs, 2 analog inputs (1 voltage, 1 current), analog current output, thermistor input, encoder input, encoder direction output, 1/64 encoder pulse train output. Requires system software Sm00099c.bin, and application software Smf091ca.hex for closed loop operation.
- Option designator –05, SV9IO104, encoder input, encoder direction output, 1/64 encoder pulse train output. Requires system software Sm00099c.bin, and application software Smf091ca.hex for closed loop operation.
- Option designator –31, SV9NCPB(CN), Profibus and expanded I/O with 4 digital inputs, 1 relay, 2 open collector outputs, thermistor input,

encoder input, encoder direction output, 1/64 encoder pulse train output. Requires system software Sm00099c.bin, application software Smf091ca.hex and option software Smpb001o.bin for closed loop operation.

- Option designator –32, SV9NCMB(CN), Modbus and expanded I/O with 4 digital inputs, 4 open collector outputs, thermistor input, encoder input. Requires system software Sm00099c.bin, application software Smf091ca.hex and option software Smmb001j.bin for closed loop operation.
- Option designator –33, SV9NCIB(CN), Interbus S and expanded I/O with 4 digital inputs, 4 open collector outputs, thermistor input, encoder input. Requires; system software Sm00099c.bin, application software Smf091ca.hex and option software Smib001h.bin for closed loop operation.
- Option designator –34, SV9NCLW(CN), Lon Works and expanded I/O with 4 digital inputs, 4 open collector outputs, thermistor input, encoder input. Requires; system software Sm00099c.bin, application software Sma046xx.hex and option software Smab001a.bin for closed loop operation.

Fieldbus with closed loop

- Frequency or torque controlled operation mode
  - 2500Hz as maximum frequency
- Can be used with or without fieldbus connection

Application/Performance Matrix

Industry/ Application	Volts/ Hz	Open Loop Vector	Closed Loop Vector
Textile			
(Range Drives)/			
Tenter			✕
Printing			✕
Dying & Bleach			✕
Non Woven			✕
Warper			✕
Spinning			✕
Spin-Draw			✕
Tow-stretch			✕
Extruders		✕	
Take-ups			✕
Machine Tool			
Punch Press		✕	
Spindle			✕
Table feed		✕	
Milling	✕		
Drilling	✕		
Lathe			✕

Industry/ Application	Volts/ Hz	Open Loop Vector	Closed Loop Vector
Gear Hobing		✕	
Gear Honing	✕	✕	
Grinder	✕	✕	
Material Handling			
Conveyors	✕		
Feeders	✕		
Converting			
Slitter		✕	
Laminators			✕
Unwind/Rewind			✕
Coater			✕
Treater			✕
Calendar			✕
Dryers	✕		
Embosser			✕
Pull roll			✕
Printer			✕

Vector Control of Squirrel Cage Induction Motors

This appendix takes a closer look at the three-phase squirrel cage AC motor. Electromagnetic induction allows the squirrel cage AC motor to convert electrical power into mechanical power.

Magnetic fields are created in a circular flux pattern when current flows through a conductor. The flux pattern is at a right angle to the direction of the current flow. When a current-carrying conductor is placed in an external magnetic field, this magnetic field and the field created by the current in the conductor will distort. A force will be exerted on the conductor at right angles to both the current flow and the external magnetic field.

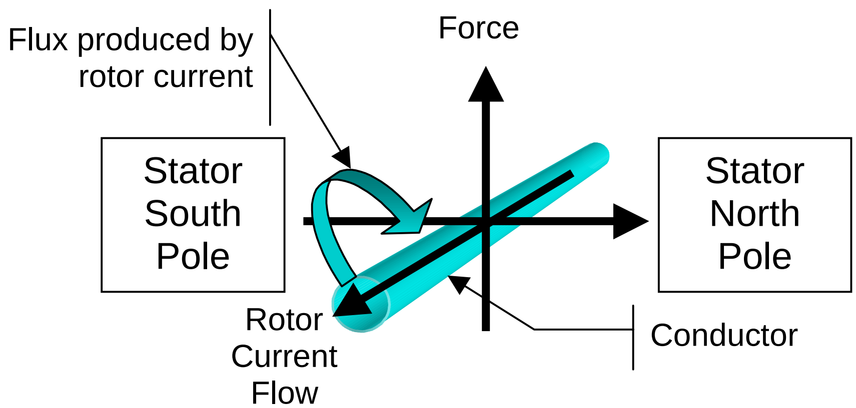

figure 1: Force exerted on a conductor in a magnetic field

The design of a squirrel cage induction motor takes advantage of this basic principle. First, the stator windings of the motor are excited with an alternating voltage source. This in turn causes current to flow in the proper sequence, to produce a rotating magnetic field around the motor axis. This field rotates at a rate based on the synchronous frequency of the exciting voltage. The magnetic flux induces currents to flow in the rotor resulting in north and south magnetic poles. At no load the rotor magnetic poles tend to align with the stator magnetic poles. and no force is produced. The rotor rotation is close to synchronous speed at no load as it follows the rotation of the stator magnetic field. As a mechanical load is applied to the motor shaft, the rotor will begin to slip with respect to the stator magnetic field rotation. This slip results in a portion of the current in the rotor conductor to cross the magnetic poles established by the stator at a right angle. Figure 1 illustrates the resultant force applied to the rotor conductors with the motor under load. This force produces torque and rotary motion due to the rotation of the stator magnetic poles.

A frequency converter takes advantage of this basic principle to control the speed or torque developed by the motor. By high speed switching a DC bus across the motor windings, the frequency converter creates three outputs; voltage, current and frequency. If the motor shaft position is known, the rotor slip from synchronous frequency can be measured and these outputs can be regulated to produce the desired speed and torque. A motor mounted encoder provides the shaft position information and the resulting control is referred to as "closed loop vector control."

The vector control algorithm performs a series of transformations of the measured three phase motor currents and voltages. This enables the control algorithm to control direct and quadrature currents without the complexity of dealing with sinusoidal 3 phase quantities. (See figures: 1, 2, and 3) First, in *Equation (1)* the vector sum of the line currents ($\mathbf{I_s}$) is calculated and projected onto the fixed reference of the stator axis, resulting in $\mathbf{i_\alpha}$ and $\mathbf{i_\beta}$. This frame of reference can be thought of as a single-phase representation of the three phase quantities.

Equation (1) $$I_s = \overline{i_a + i_b + i_c} = \overline{i_\alpha + i_\beta}$$

The same transformation is applied to the vector sum of the measured three phase voltages as expressed in *Equation (2)*.

Equation (2) $$V_s = \overline{v_a + v_b + v_c} = \overline{v_\alpha + v_\beta}$$

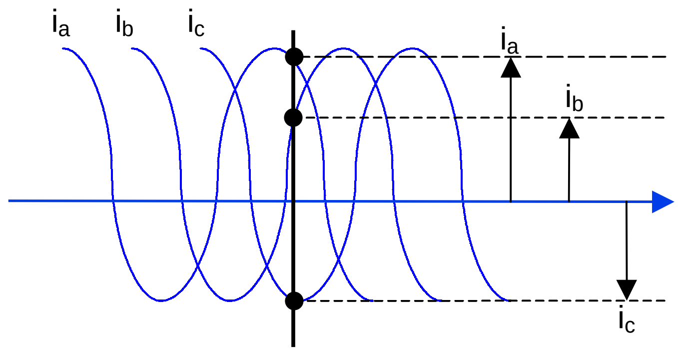

Figure 1
Instantaneous magnitude of 3 phase currents

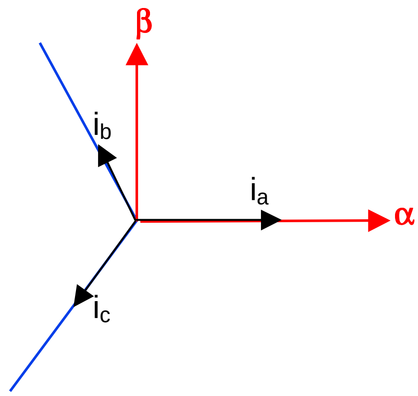

Figure 2
Three phase currents projected onto the α, β *coordinate axis*

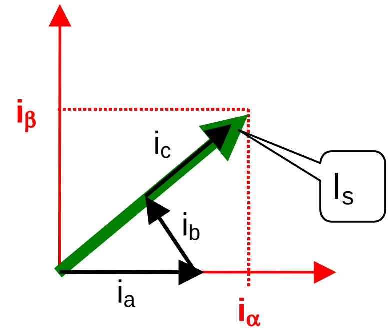

Figure 3
Vector sum of three phase currents and resulting $\boldsymbol{i_\alpha}$ *and* $\boldsymbol{i_\beta}$

The vectors $\mathbf{I_s}$ and $\mathbf{V_s}$ are rotating at synchronous speed ω_s with respect to the stator axis. (See figure 4.) The angle θ_s is rotating at an angular velocity of ω_s, the frequency impressed on the motor terminals. An (x, y) coordinate axis is now defined which rotates with nominal frequency, $k\omega_s$. The transformation to the x,y axis can be thought of as the direct current representation of the alternating currents $\mathbf{i_\alpha}$ and $\mathbf{i_\beta}$ (See equations 3 and 4). The k term is a result of the number of motor poles. The currents are then resolved into their x and y components (See figure 5).

Equations (3,4) $\quad i_x = i_\alpha \cos\theta + i_\beta \sin\theta \; , \quad i_y = -i_\alpha \sin\theta + i_\beta \cos\theta$

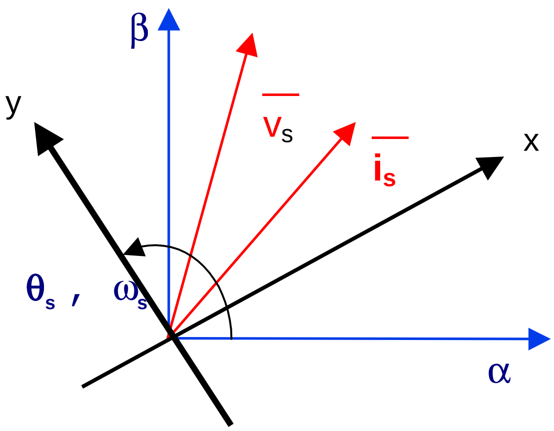

Figure 4
Rotating vectors $\boldsymbol{I_s}$ *and* $\boldsymbol{V_s}$ *with respect to the stator axis.*

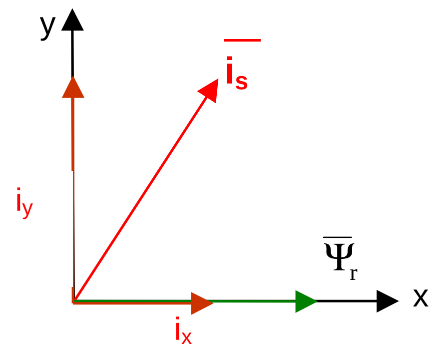

Figure 5
Quadrature and Direct axis showing the motor flux

The closed loop vector control algorithm provides reference signals to the Vector Modulator which adjust the output voltage, current and frequency to create the desired output torque and speed.

Control Block Diagram Signal Flow

Figures 6 and *7* show the block diagrams of the vector control both below and above synchronous frequency. Below synchronous frequency, the algorithm uses voltage control. Above synchronous frequency, the algorithm uses frequency control. A separate block diagram above synchronous frequency is a result of the change from voltage control to frequency control. Above synchronous frequency, the difference between the motor's counter emf voltage and DC bus voltage is reduced. This in turn reduces the voltage regulator response. The change to frequency control above synchronous speed helps maintain consistent response in the constant horsepower range of operation.

Definitions

f	Inverter output frequency	$\mathbf{v_{dref}}$	Direct voltage reference
$\mathbf{f_n}$	Motor synchronous frequency	$\mathbf{v_{qref}}$	Quadrature voltage reference
$\mathbf{f_{ref}}$	Frequency reference	$\mathbf{K_{sl}}$	Slip gain
$\mathbf{f_{sl}}$	Slip frequency	$\mathbf{L_s}$	Programmed V/F pattern
$\mathbf{\Delta f}$	Frequency error	**PI**	Proportional integral regulator
$\mathbf{f_r}$	Rotor frequency	**V/F**	Voltz per Hertz
$\mathbf{i_{dref}}$	Direct current reference	$\boldsymbol{\theta_r}$	Rotor position
$\mathbf{i_{qref}}$	Quadrature current reference	$\mathbf{d(\theta_r)/dt}$	Rotor velocity
$\mathbf{i_a, i_b, i_c}$	Phase a,b and c currents		

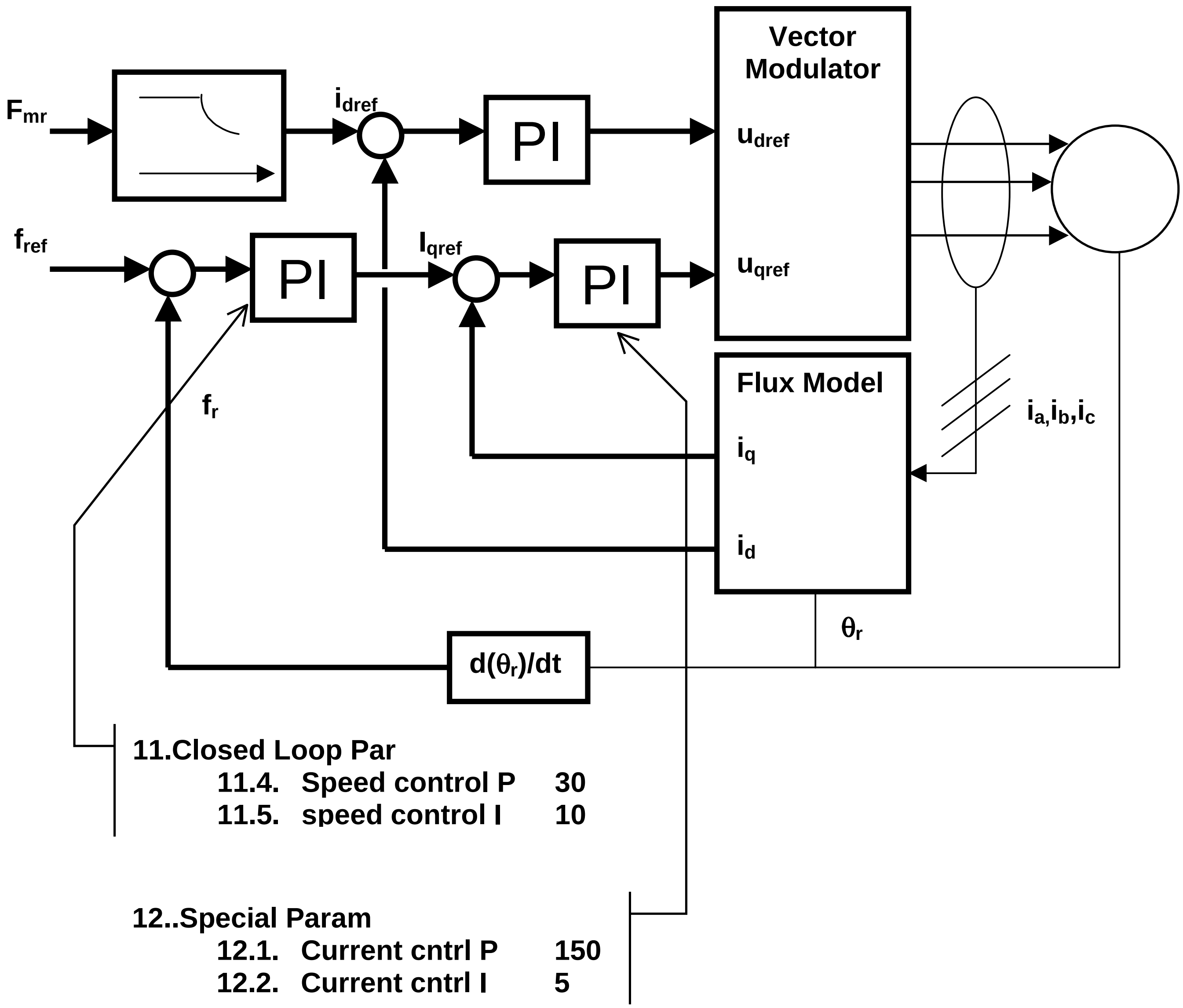

Figure 6
Closed Loop Block Diagram $f<f_n$

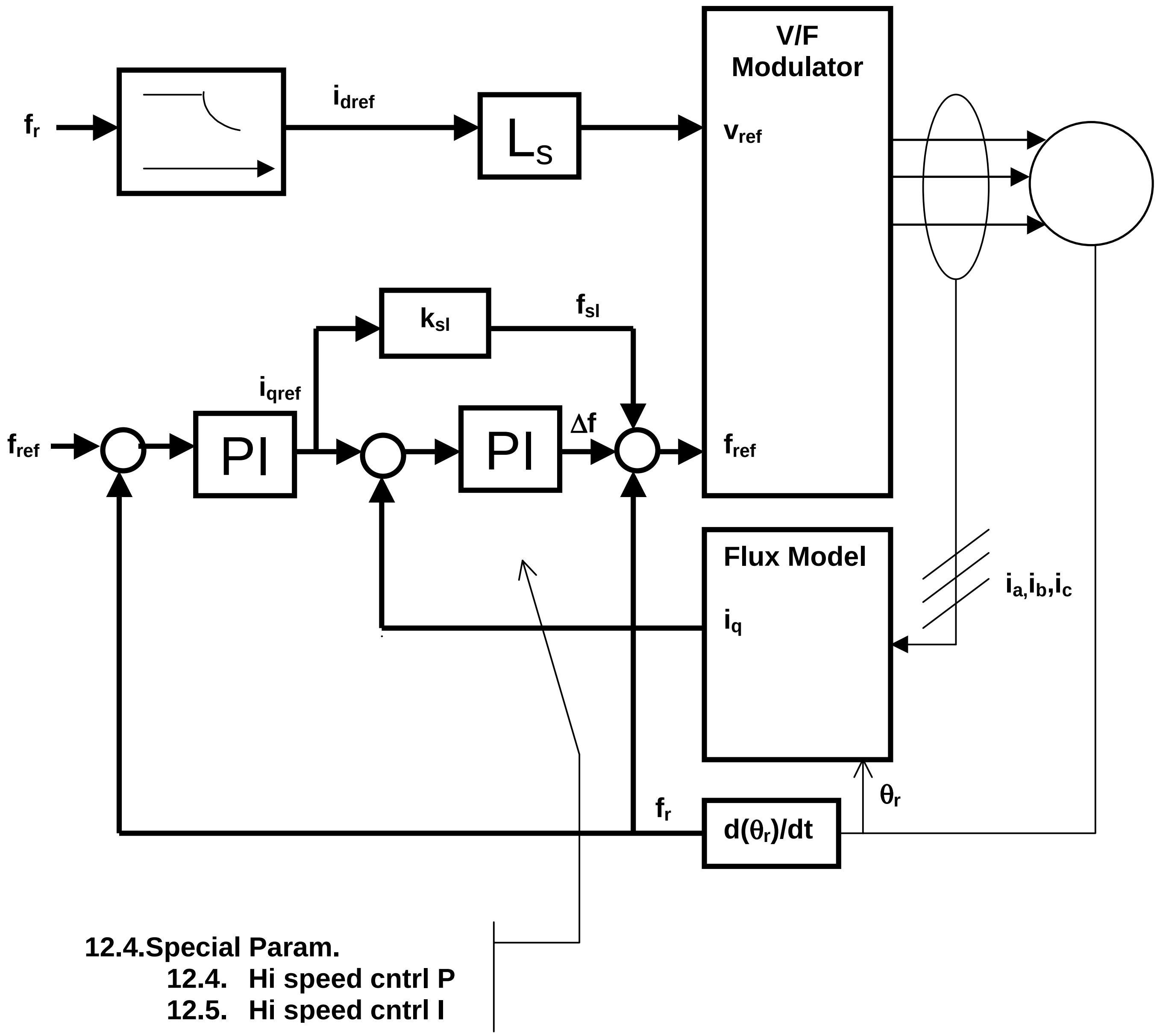

Figure 7
Closed Loop block Diagram $f>f_n$