AN APPROACH TO CLOSED-LOOP DESIGN OF A CURRENT SOURCE INVERTER/RELUCTANCE MOTOR DRIVE

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Summary

Prior investigations of the steady-state[1] and open-loop dynamic characteristics[2] of a current source inverter/reluctance motor drive has revealed that closed-loop control is necessary for practical application. In this paper two practical closed-loop feedback schemes are presented which have desirable performance characteristics for adjustable speed applications.

Introduction

Conventional electric machines are generally designed to operate with a nominal flux operating point slightly above the knee of the magnetization characteristic. This criterion, generally, yields good overall performance with a near optimum utilization of the magnetic material and with losses held to a reasonable minimum. Operation beyond the knee of the magnetization characteristic tends to result in diminishing returns for increasingly higher increments of excitation current. When a reluctance machine is supplied from a current source inverter (CSI) it has been shown that the overexcitation which exists at light loads not only incurs higher core and winding losses, but also results in severe torque pulsations.[1] This drawback points to the need for a closed-loop control which provides a suitable stability margin yet maintains air gap flux near the design value. This paper describes the development of two types of closed-loop systems which satisfy this basic requirement.

A number of computer-aided control design methods are presently available. Graphical techniques such as root-locus, however, often have greater appeal to practicing engineers. The transfer function combined with the root-locus approach is a well understood classical design technique which has been used with great success in the closed-loop design of traction drives.[4,5] This paper outlines a procedure for the design of adjustable speed ac drives. Specifically, it is shown how transfer function/root locus techniques have been used to obtain conventional performance characteristics from a current source inverter / reluctance motor system.

System Requirements

It is apparent that numerous suitable control designs can be devised if based solely on technical specifications. Selection of a best design will be determined by economic and reliability factors as well as by a set of specific technical requirements; a task too complicated to consider fully here. Instead, this paper will outline a design technique incorporating only those basic considerations typically encountered in conventional adjustable speed drive applications.

The reluctance motor/voltage source type of static ac drive has found wide acceptance in low horsepower, multi-motor applications where high accuracy speed control is of primary importance. The reluctance motor is particularly attractive in such cases since precise synchronous speed operation is possible without the need for rotor excitation or sensing of rotor variables. In order that a CSI/reluctance motor drive be practical for such applications rotor variables cannot be sensed since the cost involved in instrumentation would result in a prohibitively expensive system. Also, since these low horsepower applications are typically multi-motor configurations, the feedback structure should accomodate situations wherein two or more motors are supplied from the same inverter.

For some applications, dynamic or regenerative braking capability is a useful system feature. The CSI/ac motor drive is unique in that it has inherent regeneration capability. Since regenerative power flow is achieved by a natural reversal of the inverter terminal voltage, and not by a reversal of current flow as for voltage inverters, a smooth, controlled transition from motoring to braking is possible. It is desirable that this inherent feature be preserved or perhaps even enhanced by use of feedback.

To fully utilize machine capacity, adjustable speed drives must be capable of producing rated torque over a range of operating speed. In practice, a minimum speed is set by the process and is typically 0.1 to 0.3 pu of rated speed. Maximum speed at rated torque may be limited either by the need for proper commutation of the inverter or by the power rating of the rectifier bridge. Assuming that by proper design the limit is set by the latter condition, torque output will be limited by a maximum power constraint such as shown in Fig. 1. The closed-loop control must be sufficiently rapid to ensure good dynamic response and provide full rated torque capability at rotor speeds up to this design limit. In some applications it is desirable that operation be extended into the power limit region. In this mode of operation the rectifier voltage becomes constant so that use of this variable is lost as a control input. However, stability must be maintained up to the power limit.

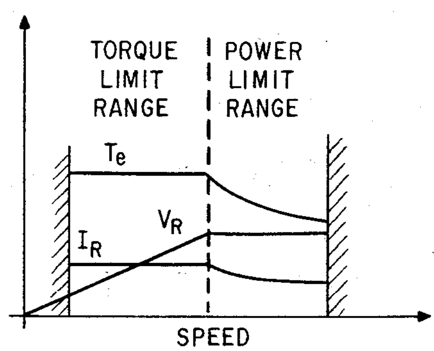


Fig. 1 Performance characteristics of an adjustable speed drive.

Design Study

Thusfar, guidelines have been established for improving open-loop performance based on an analysis of the steady-state characteristics of a CSI/reluctance motor drive[1] and also from an investigation into the instability mechanisms which occur during motoring and regeneration.[2] In particular, it has been observed from the stability analysis that the CSI/reluctance machine system is stable for loads not exceeding the pull-out torque capability of the machine. Compared with results obtained for conventional voltage inverter sources it can be concluded that operation in this mode indeed enhances the stability performance of the drive. However, it has also been shown that losses in the machine, torque pulsations and reverse voltage stresses on the thyristors can be held at reasonable levels only if motor line current is maintained at a suitable minimum level required to support a given load.[1] This level, of course, depends upon the loading of the drive. Such a minimum level of excitation may be difficult to derive without feedback if it is not practical or possible to predetermine the loading of the drive. A more attractive alternative is clearly to utilize feedback to regulate the operation of the machine about a desirable flux condition.

It has been shown that constant current excitation results in a stable system whereas voltage excitation is inherently unstable. It follows that a regulated current source will have a stability profile somewhere between these two extremes. The minimum control loop gain required to ensure stability is one of the important factors to be determined from a control study.

Closed-Loop Design

In a companion paper, the small-displacement equations for the basic open-loop system have been derived and are listed in Appendix I therein.[2] In general, three inputs to this system of equations can be identified namely, the change in rectifier voltage ΔV_R, the change in inverter frequency $\Delta\omega_e$, and the change in load torque ΔT_L. Other inputs, however, are possible. For example, a change of filter reactance $p\Delta X_F$ can also be viewed as a system input. This rate of change of filter reactance can be implemented with a controllable saturistor in place of the filter choke. Control is best effected, however, by means of the rectifier voltage and inverter frequency. Five state variables appear in the system equations. Of these, only three are readily measurable namely, $\Delta\delta_I$, $\Delta\omega_e$ and Δi_{ds}^e $[i_{ds}^e = (2\sqrt{3}/\pi)I_R]$. In addition, however, it is possible to define output variables expressed as linear combinations of the state variables such as ΔV_s, $\Delta\Psi_s$, ΔT_e and Δv_{ds}^e $[v_{ds}^e = (\pi/3\sqrt{3})V_I]$. Although the list of candidate output variables is endless, those typically available as feedback signals are Δi_{ds}^e (dc link current), Δv_{ds}^e (dc link voltage), ΔV_s (ac voltage amplitude), and $\Delta\Psi_s$ (ac flux linkage amplitude).

In order to evaluate the nature of the system to be controlled the open-loop transfer function between one variable of the output set $(\Delta i_{ds}^e, \Delta v_{ds}^e, \Delta V_s, \Delta\Psi_s)$ and another variable from the input set $(\Delta V_R, \Delta\omega_e)$ can be obtained.[3] Table 1 shows the poles and zeros of four typical transfer functions for the open-loop system for motoring and generating conditions at a per unit frequency ratio $f_R = 1.0$. The system parameters, given in Appendix I, are identical to those used in the companion paper.[2] It can be observed from these transfer functions that stabilization of the drive is more effectively achieved by use of the rectifier voltage input than by means of inverter frequency.

It has already been established that current regulation tends to improve system stability.[2] Utilizing negative current feedback, the perturbation equations relating the change of rectifier voltage to an error in rectified current can be obtained. Examination of the transfer function $\Delta i_{ds}^e/\Delta V_R$ in Table 1 indicates that a simple proportional gain is sufficient for feedback compensation. If the algebraic compensator equation is combined with the basic open-loop system equations, the resulting equations define system transfer functions with current feedback. The details of this derivation can be found in Ref. 6. Negative current feedback has the effect of modifying the source dynamic characteristic towards that of a current source by increasing the apparent source resistance. The poles of the system with current feedback are given in Table 2 for the selected gain, $K_I = 1.0$. The minimum gain K_I required to ensure stability for this system was 0.6. Note that stability of the system is considerably improved although the feedback gain is relatively modest.

Although a satisfactory stability margin is secured by the current loop, it has also been established that operation over a wide range of load without overexcitation, requires flux or volts per hertz regulation. The working flux or volts per hertz of the machine can be regulated to within acceptable limits by incorporating closed-loop regulation of flux magnitude Ψ_s or volts per hertz V_s/f_e. In practice, stator flux may be

		MOTORING Te = 0.52		GENERATING Te = -0.52	
		Re	Im	Re	Im
	Poles	-4.82E+01	± 5.38E+01	-9.36E+01	0.
		2.75E+01	0.	1.52E+01	± 4.46E+01
		-8.97E+00	0.	-8.73E+00	0.
		-1.23E+00	0.	-1.14E+00	0.
$\Delta i_{ds}^e/\Delta V_R$	Gain	-1.57E+00		1.19E+00	
	Zeros	-2.50E+00	± 2.14E+01	-2.50E+00	± 2.14E+01
		-8.50E+00	0.	-8.61E+01	0.
		-1.21E+00	0.	-1.21E+00	0.
$\Delta v_{ds}^e/\Delta V_R$	Gain	1.09E+00		9.35E-01	
	Zeros	-3.09E+01	± 6.37E+02	-2.61E+01	± 6.27E+02
		-8.75E+00	± 3.23E+00	-1.04E+01	± 2.95E+00
		1.88E-01	0.	-1.63E-01	0.
$\Delta i_{ds}^e/\Delta\omega_e$	Gain	2.70E-03		2.06E-03	
	Zeros	-8.52E+00	0.	-8.57E+00	0.
		8.26E+04	0.	-8.36E+04	0.
		-7.09E-01	0.	7.16E-01	0.
		-1.23E+00	0.	-1.19E+00	0.
$\Delta v_{ds}^e/\Delta\omega_e$	Gain	-1.48E-04		-1.13E-04	
	Zeros	-3.25E+01	± 2.75E+01	1.31E-02	0.
		-1.29E+01	0.	2.40E+00	0.
		-1.16E+00	0.	-1.18E+01	0.
		1.34E-02	0.	-7.65E+01	0.

Table 1 Poles and zeros of open-loop system transfer functions at $f_R = 1.0$ and $I_R = 0.8$ pu.

		MOTORING Te = 0.52		GENERATING Te = -0.52	
	Poles	-5.71E+02	0.	-9.89E-01	± 2.79E+01
		-4.69E+00	± 1.20E+00	-5.71E+02	0.
		-7.98E+00	0.	-8.66E+00	0.
		-1.18E+00	0.	-1.18E+00	0.
$\Delta\Psi_s/\Delta I_R^*$	Gain	2.35E+01		4.62E+00	
	Zeros	-5.38E+01	0.	-5.38E+01	0.
		-7.63E-01	± 2.51E+01	-7.63E-01	± 2.51E+01
		-7.03E+00	0.	-7.03E+00	0.
$\Delta V_s/\Delta I_R^*$	Gain	2.32E+01		4.67E+00	
	Zeros	-1.04E+01	± 1.42E+00	-8.43E+00	± 4.54E+00
		-1.25E+03	0.	-2.00E+00	0.
		1.94E+00	0.	-1.38E+03	0.
		6.81E+02	0.	8.19E+02	0.
$\Delta v_{ds}^e/\Delta I_R^*$	Gain	-1.92E+00		4.67E+00	
	Zeros	-2.86E+02	0.	8.19E+02	0.
		-8.89E+00	± 3.15E+00	-1.38E+03	0.
		1.88E-01	0.	-8.43E+00	± 4.54E+00
				2.00E+00	0.

Table 2 Poles and zeros of system transfer function with current feedback; $f_R = 1.0$, $I_R = 0.8$ pu and $K_I = 1.0$

derived by integrating the output voltage of search coils embedded on the stator core or by Hall Effect sensors. The volts per hertz can be derived from measurements of the stator voltage and frequency. Table 2 gives the transfer functions for the required feedback variables. In principle either voltage or flux could be used for regulation. However, note the favorable location of the system zeros for flux feedback $\Delta\Psi_s/\Delta I_R^*$ compared to those for voltage feedback $\Delta V_s/\Delta I_R^*$.

Figure 2 shows the block diagram of the rectifier control with flux regulation and dc link current feedback. The choice of compensator for the flux loop can be determined by examining the root-loci of possible pole-zero configurations. The root-loci for a near-optimum compensator with a pole at the origin and zero at -1.25 is shown in Fig. 3. The perturbation equations for the composite system with flux regulation and negative current feedback are again supplied in Ref. 6 and can be obtained by incorporating the equations for the flux controller in the system equations. The poles and zeros of several pertinent closed loop system transfer functions are given in Table 3 for $K_\psi = 3.2$, $\tau_\psi = 0.8$ and $K_I = 1.0$. It can be noted that although stability has been preserved, the flux controller has introduced an additional pole near the origin which is now the dominant factor limiting transient response of the system.

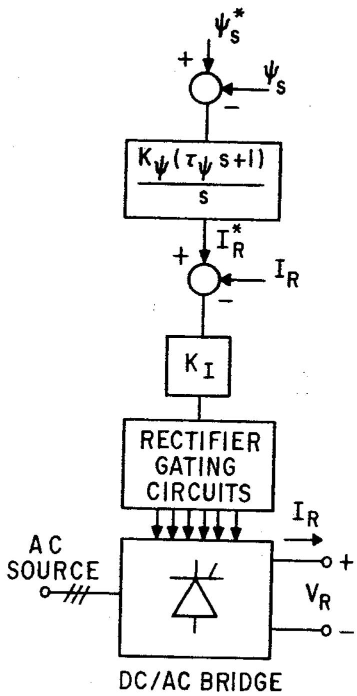


Fig. 2 Block diagram of rectifier control with current feedback and flux regulation.

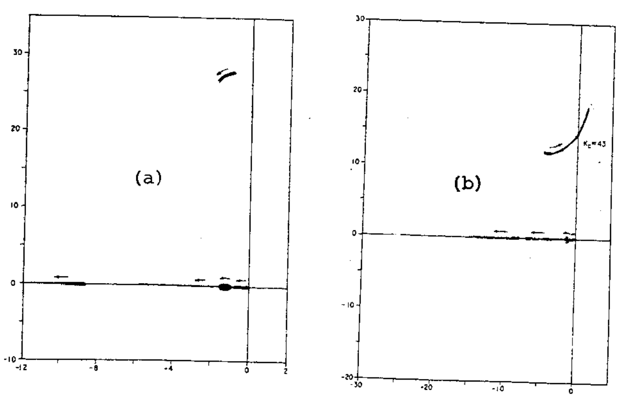


Fig. 3 Root loci for flux controller with compensator $K_\psi(0.8s + 1)/s$. (a) Motoring, $T_e = 0.52$ pu, (b) Generating, $T_e = -0.52$ pu.

		MOTORING Te = 0.52		GENERATING Te = -0.52	
		Real	Im	Real	Im
	Poles	-5.72E+02	0.	-9.94E-01	± 2.79E+01
		-4.56E+00	± 1.20E+01	-5.72E+02	0.
		-7.98E+00	0.	-8.67E+00	0.
		-1.16E+00	0.	-1.18E+00	0.
		-3.51E-01	0.	-6.69E-02	0.
$\Delta i_{ds}^e/\Delta\omega_e$	Gain	-1.27E-02		-1.27E-02	
	Zeros	-8.53E+00	0.	-8.57E+00	0.
		8.25E+04	0.	-8.37E+04	0.
		-6.39E-01	0.	6.48E-01	0.
		-1.23E+00	0.	-1.19E+00	0.
		-3.16E-04	0.	2.19E-04	0.
$\Delta\omega_r/\Delta\omega_e$	Gain	1.00E+00		1.00E+00	
	Zeros	-8.38E+00	0.	-9.48E+02	0.
		-1.97E+02	0.	-1.18E+00	0.
		-1.11E+00	0.	-8.52E+00	0.
		-3.49E-01	0.	-6.69E-02	0.
$\Delta\delta_I/\Delta\omega_e$	Gain	-9.22E-02		9.22E-02	
	Zeros	-4.10E-08	0.	2.79E-08	0.
		-5.92E-01	0.	-1.04E+00	± 1.91E+00
		-8.72E+00	± 2.58E+00	-1.04E+01	0.
		-5.72E+02	0.	-5.72E+02	0.
$\Delta v_{ds}^e/\Delta\omega_e$	Gain	1.73E-03		-1.73E-03	
	Zeros	-5.74E+02	0.	-1.08E+01	0.
		-8.02E+00	± 2.52E+00	-5.70E+02	0.
		3.72E-01	0.	-1.77E+00	± 1.66E+00
		-6.00E-01	0.	2.64E-01	0.
		-8.95E-02	0.	-8.43E-02	0.
$\frac{\Delta(v_{ds}^e/\omega_e)}{\Delta\omega_e}$	Gain	9.46E-06		-8.89E-06	
	Zeros	1.56E+03	0.	1.53E+03	0.
		-2.15E+03	0.	-2.11E+03	0.
		-4.28E+00	0.	-1.65E+00	-1.25E+00
		4.85E-01	0.	-1.65E+00	1.25E+00
		-6.17E-01	0.	5.93E-01	0.
		-1.38E-01	0.	-7.61E-02	0.
$\Delta V_s/\Delta\omega_e$	Gain	3.87E-03		3.87E-03	
	Zeros	-5.73E+02	0.	-5.72E+02	0.
		-9.40E+00	± 1.58E+00	-3.22E-02	± 2.93E+00
		1.66E+00	0.	-1.09E+01	0.
		-5.87E-01	0.	-1.46E+00	0.
		3.59E-02	0.	-2.16E-02	0.
$\frac{\Delta(V_s/\omega_e)}{\Delta\omega_e}$	Gain	2.06E-06		2.04E-06	
	Zeros	-2.93E+02	± 1.27E+03	-2.91E+02	± 1.10E+03
		1.55E+00	0.	-5.06E-01	-3.21E+00
		-4.99E+00	0.	-5.06E-01	3.21E+00
		-5.80E-01	0.	-1.37E+00	0.
		8.01E-02	0.	-3.25E-02	0.
$\Delta\Psi_s/\Delta\omega_e$	Gain	-6.37E-07		-4.42E-07	
	Zeros	-5.35E-06	0.	3.71E-06	0.
		-5.97E-01	0.	-2.96E+00	0.
		-7.25E+00	0.	5.15E+00	0.
		-5.73E+01	0.	-4.43E+01	0.
		-1.89E+03	0.	6.91E+02	0.

Table 3 Poles and zero of candidate damping signals. Transfer functions with current feedback and flux regulation, $K_I = 1.0$, $K_\psi = 3.2$, $\tau_\psi = 0.8$.

In addition to stability considerations, system performance must generally also meet requirements on transient response. An appropriate amount of additional damping can be introduced into the system by proper choice of feedback. By limiting transient swings of the machine, stability will also be improved. The inverter frequency control is a convenient point at which to introduce a damping signal. In order to avoid steady-state error in machine speed a rate feedback circuit can be used. Damping signals introduced into the rectifier dc voltage are also possible but are limited by the time constant of the dc filter choke.

Krause[7] has investigated the stabilization of a reluctance machine fed from a voltage source, whereby damping is introduced by controlling the effective value of the inverter output voltage. It was shown that variables such as deviation in rotor speed and the rate of change in instantaneous power provides very effective damping. Similar conclusions have been obtained from a study of the poles and zeros of the corresponding transfer functions.[6] The use of variables such as change in rotor angle, rotor speed and higher order derivatives of speed as excitation control signals to improve transient response of power generating units is well known.

Although variables associated with rotor speed are appropriate quantities to use, measurement is difficult. Moreover, for low and medium power drive applications, increases in the complexity and cost of instrumentation are seldom justified. However, by computing appropriate transfer functions, other satisfactory feedback signals can be identified. Transfer functions for a variety of potential damping signals are tabulated in Table 3. The two operating points shown in Table 3 are typical of the numerous operating conditions which must be examined during a typical design study. It can be observed from this list that practical damping signals include the variables $\Delta\delta_I$, $\Delta\omega_r$, $\Delta v_{ds}^e(\Delta V_I')$, and ΔV_s. Of these variables the change in inverter dc voltage Δv_{ds}^e is easily measured. A practical feedback scheme employing Δv_{ds}^e is shown in Fig. 4. Desirable dc gain characteristics can be obtained by dividing v_{ds}^e by the inverter angular frequency ω_e. The suitability of $\Delta(v_{ds}^e/\omega_e)$ as a feedback damping signal is illustrated by the root locus plots for motor and generating conditions in Fig. 5. Since the inverter terminal voltage changes polarity from motoring to generating, a reversal in the damping signal is required to maintain stability. It can be noted that a reversal in the sign of the steady-state gain of $\Delta(v_{ds}^e/\omega_e)$ is inherent. The gain of the controller of Fig. 4 can be adjusted to give uniformly damped transient response for motoring and generating operation.

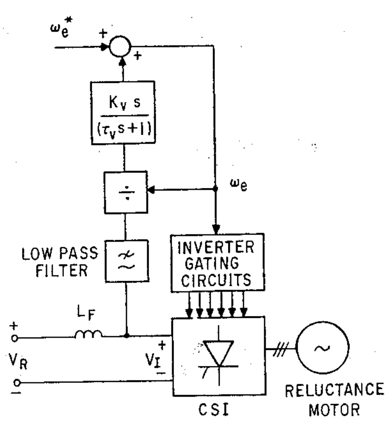
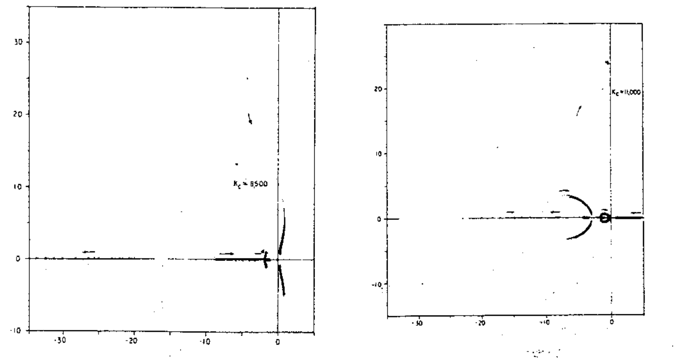


Fig. 4 Block diagram of feedback damping loop.



(a) (b)

Fig. 5 Influence of feedback signal $\Delta(v_{ds}^e/\omega_e)$ on system damping. (a) Motoring, T_e=0.52, (b) Generating, T_e=-0.52

Closed-Loop System Response

In the preceding section it was shown how various control loops can be designed to stabilize as well as improve steady-state and transient performance of a CSI/reluctance motor drive. When assembled, the complete design is shown in Fig. 6. For convenience, this system shall be referred to as Design A. As mentioned, an alternative to flux control is regulation of the volts per hertz applied to the machine. Stator voltage control is, in fact, particularly desirable since voltage is more readily measured than motor flux. Design B is given in Fig. 7 and shows such a system wherein the operating point is regulated about a desired value of volts per hertz. System feedback parameters were selected in the same manner as Design A.

Although suitable control configurations can be devised by considering only small perturbations in operating point, evaluation of a final control design depends ultimately upon closed-loop response to large-signal system inputs. System design also involves the optimization of control parameters to obtain the best closed-loop performance. Often the synthesis procedure is too involved for a purely analytical approach because of coupling effects, sampling effects and system nonlinearities. As a check of the analytical approach it is particularly convenient to employ an analog computer simulation. In this manner the sensitivity to parameter changes and effects of large amplitude disturbances can be rapidly checked without resorting to system hardware.

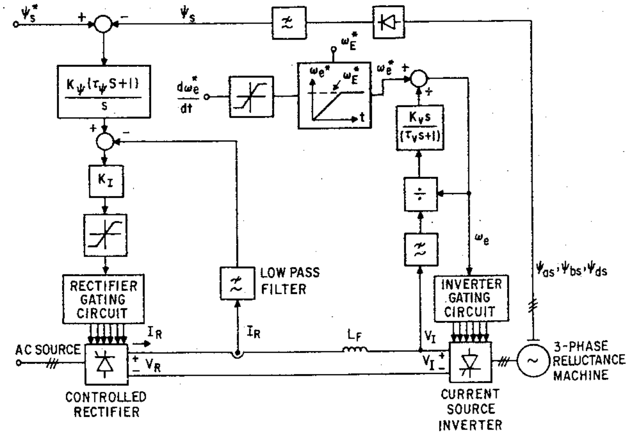


Fig. 6 Block diagram of Design A. ω_e= instantaneous angular frequency, ω_e^* = angular frequency set point, ω_E = angular frequency target point.

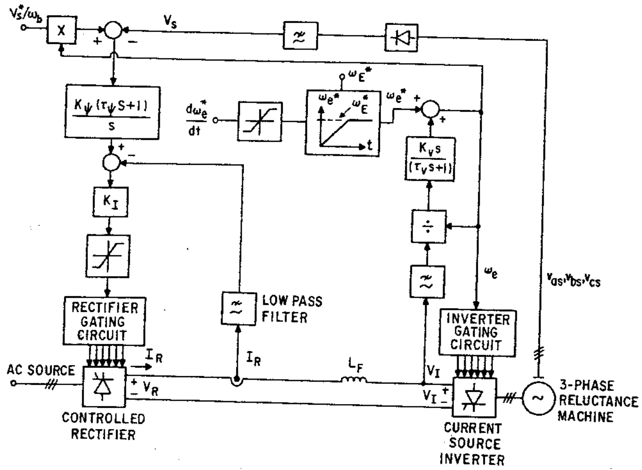


Fig. 7 Block diagram of Design B.

In order to evaluate the system transient behavior, a step load torque of 0.5 pu was applied to the simulated system which was initially at no-load. Pull-out torque for the motor design considered was 0.62 so that the step load is sufficiently large to demonstrate stability of the system over a wide load range. In addition to the step load test at various frequencies, a test was made to check system behavior when the ceiling of the rectifier voltage is reached during the transient.

The closed-loop response of both designs are given in Figs. 8 and 9. For brevity, only the closed-loop response of Design A will be discussed in detail. The response of Design A as shown in Fig. 8 is for compensator parameters K_I = 0.9, K_ψ = 2.5, τ_ψ = 2.0, K_v = 5.7E+04 and τ_v = 20. Closed-loop response to a step load torque for motoring and generating conditions at rated frequency (f_R=1.0) is shown in Fig. 8(a). It is noted that almost uniform transient behavior is obtained. The magnitude of the stator current i_{as} remains fairly constant over the duration of the load switching test. An increase in the fundamental component of the stator voltage v_{as} is noted during motoring operation; vice-versa a decrease occurs for generating operation. It can be seen that the inverter terminal dc voltage changes polarity as the machine switches from no-load to generating operation. The maximum rotor speed deviation following the step change in load is about two percent. Figure 8(b) shows the response of the system when operating at f_R= 0.5 pu for similar load switching tests. Note that at this speed the transient response has even less overshoot. Similar results were obtained over a wide range of operating frequencies.

Stability studies[2] have indicated that a current source reluctance motor drive becomes unstable when the rectifier becomes inoperative. Figure 8(c) shows the response to a step motoring load torque when the rectifier has a ceiling level just above its nominal steady-state operating value. During the transient period when the rectifier voltage is at its ceiling level, a rapid decay of stator current and torque is evident. Even though the motor is out of control during this period the system is able to recover although with large fluctuations in stator current and torque. A noticable speed drop of about five percent is observed during the transient period. A similar constraint on the minimum (maximum negative) value of rectifier voltage during regeneration shows considerably less fluctuations in current and torque. Similar results are obtained for

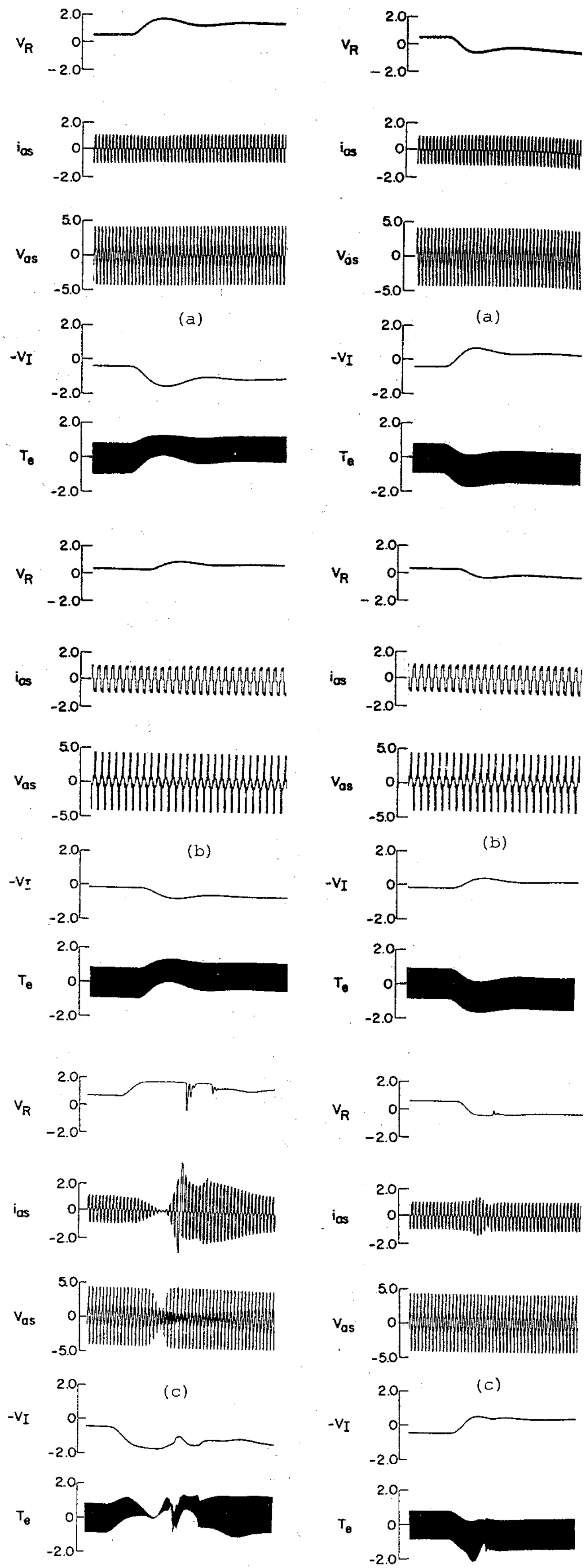


Fig. 8 Load torque switching response of Design A. Step load changes from 0 to ±0.5 pu. (a) f_R=1.0, (b) f_R=0.5, (c) f_R= 1.0, V_R(limit) = 1.4 pu.

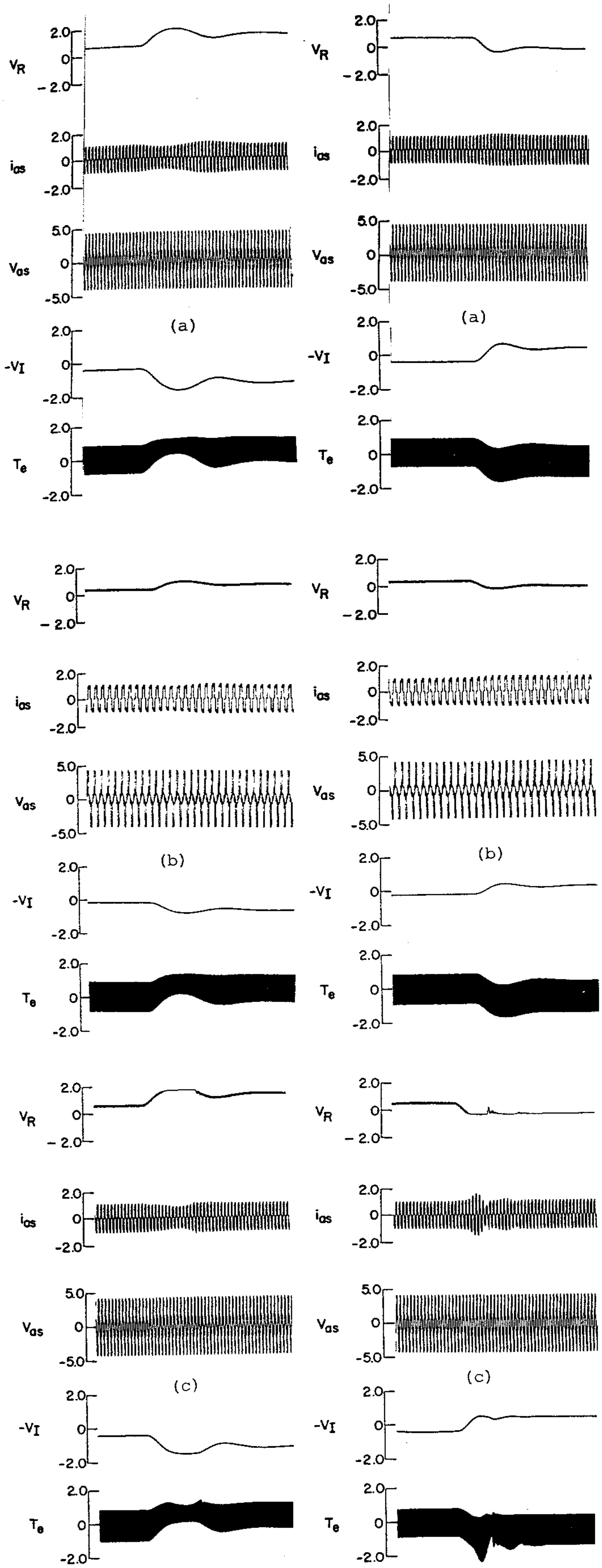


Fig. 9 Response during load torque switching for Desing B. Step load changes from 0 to ±0.5 pu. (a) f_R=1.0, (b) f_R= 0.5, (c) f_R= 1.0, V_R(limit) = 1.4 pu.

Design B. The parameters employed in Design B for the responses of Fig. 9 are $K_I = 0.9$, $K_\psi = 2.7$, $\tau_\psi = 2.0$, $K_V = 5.7E+04$ and $\tau_V = 20$. It is interesting to note that less fluctuations occur in this case when the rectifier voltage is at its ceiling.

It appears that the results obtained from these tests are not sufficient to clearly determine the superiority of one design over the other since similar performance can be obtained with the appropriate selection of parameters. The main drawback to the use of flux as a feedback variable is the cost and reliability problems associated with a search coil and flux integrator. At present, an embedded search coil for flux measurement is not a standard feature in commercially available machines. In contrast, stator voltage is readily available from terminal measurements. Unfortunately, this signal becomes less and less accurate a measure of flux as line frequency decreases due to stator IR drop. Hence, system performance tends to deteriorate without IR compensation. Since stator resistance changes appreciably with temperature, such a compensation signal is difficult to derive.

Conclusion

In this paper a procedure has been described for the synthesis of a closed-loop current source inverter/reluctance motor drive using established transfer function and root locus techniques. Two related system configurations which provide stable operation with good transient response over a wide speed range have been presented. The object of this paper is not to obtain a design meeting specific requirements but to establish guidelines for future design of similar systems. Suitable modifications will clearly be necessary to implement current limit, dynamic braking, fault protection and other specialized system requirements.

It has been shown that the transfer function/root locus technique is a particularly convenient approach to design of complex ac adjustable speed drives. This paper should aid the designer in proceeding with confidence towards a well-performing system design. Since the approach is analytical rather than experimental in nature parameters can be readily optimized without resorting to time consuming trial and error adjustments on system hardware.

Principal Symbols

All quantities are in per unit unless noted.

- f_R - frequency ratio ω_e/ω_b
- i_{as} - stator a phase current
- i_{ds} - stator d-axis current
- i_{qs} - stator q-axis current
- I_s - stator current amplitude
- I_R - dc link current
- K_I - gain of current controller
- K_V, τ_V - gain and time constant of feedback damping signal, K_V in 1/s., τ_V in s.
- K_ψ, τ_ψ - gain and time constant of flux regulator, K_ψ in 1/s., τ_ψ in s.
- R_F, X_F - filter resistance and reactance
- T_e - electromagnetic torque
- T_L - load torque
- v_{as} - stator a phase voltage
- v_{ds} - stator d-axis voltage

v_{qs} - stator q-axis voltage

V_I - inverter dc voltage

V_R - rectifier dc voltage

V_s - stator phase voltage amplitude

δ_I - torque angle for current source (Rad.)

Ψ_s - stator flux linkage amplitude

ω_b - base electrical angular frequency (Rad/s.)

ω_e - electrical angular frequency of inverter (Rad/s)

Δ - to indicate a small change from a steady-state operating point

Superscripts

e - to denote a variable expressed in the synchronously rotating reference frame

' - to indicate a dc link variable referred to the stator

* - commanded or set-point value of the variable

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Appendix I

Motor Parameters

$r_s = 0.045$

$r'_{qr} = 0.015$

$r'_{dr} = 0.030$

$x_{\ell s} = 0.100$

$x'_{\ell dr} = 0.100$

$x'_{\ell qr} = 0.100$

x_{aq}(unsat) = 0.500

x_{ad}(unsat) = 2.000

Filter Parameters

$R_F = 0.100$

$X_F = 1.200$

Base quantities are peak rated motor phase voltage and line current.[2] Base frequency, $\omega_b/2\pi$, is 60 Hz.