BNL-104812-2014-TECH

AGS/AD/Tech Note No. 396;BNL-104812-2014-IR

POWER CONTROLLER FOR AGS MAIN MAGNET POWER SUPPLY

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June 1994

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U.S. Department of Energy

USDOE Office of Science (SC)

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Technical Note

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June 6, 1994

Introduction

The drive power for the AGS Main Magnet is characterized as a pulsed electrical load. The peak power swing for each pulse can be as large as ± 72 MVA and the losses can reach 9 Megawatts. The Main Magnet Power Supply (MMPS) drives the pulsating load. It provides adequate energy storage to isolate the power swing from the power grid thereby preventing disturbances to other users. The power grid provides only the losses in a constant-valued non-pulsating mode. Depending on the AGS cycle the power grid loading can vary from 1 MW (no load) to 9 MW (maximum rating of motor).

This report is a system description of the AGS Main Magnet Power Supply Power Regulator and recommendations for upgrading its performance to accommodate mixed cycles, i.e., a sequence of different AGS cycles. The system consists of a 12,000 HP (9 Megawatt) wound rotor induction motor, a salient pole synchronous generator rated 50 MVA continuous or 95 MVA peak, and a rigid shaft coupling the rotors of the two machines. The combination of rigid shaft and rotors is characterized by a high value of inertia and functions as a "flywheel". The major component of drive power for the generator is derived from the stored energy of the "flywheel". The power regulation system has been designed to efficiently utilize the energy stored in the flywheel by operating the induction motor in a constant-power mode.

The input power to the induction motor is regulated on a dynamic basis by a three phase cycloconverter which injects currents of appropriate magnitude and phase at slip frequency into the rotor windings. The rotor current is controlled by a fast feedback loop, forcing the motor to draw a nearly constant value of line power during each AGS cycle. This results in a constant-power drive and maximizes the slip and power flow from the "flywheel". In addition, the loop maintains a constant electrical power input to the stator. The controller also regulates the reactive power flow, such that the motor is a unity power factor load. This system is the electronic equivalent of the classical Scherbrus and Krämer drives. Control is exercised below, above, and at synchronous speed. By comparison, the Westinghouse MG set can be controlled only below synchronous speed.

The parameters relating to the power flow through the motor-"flywheel" generator combination (MG set) are given in Table I.

Table I

Power and Energy Parameters for MG Set and Magnet Load

Motor		
	Rating	12,000 HP 9 MegaWatts
	Synchronous Speed	1,200 RPM
	Slip	± .02
	Windage and Friction Losses	850 Kilo Watts
Generator	Rating	50 MVA continuous 95 MVA peak
Flywheel		
	Moment of Inertia	40,000 Kg M^2
	Nominal Angular Velocity	125.66 radians per second
	Stored Energy	315 Mega Joules
	Energy Transfer for Rated Slip(S=±.02)	±12.6 Mega Joules
AGS Main Magnet		
	Inductance	.75 Henries
	Series Resistance	.26 Ohms
	Current for 33 GeV	6,000 A
	Stored Energy @ 6000A	13.5 Mega Joules
	Peak Power @ 6000A	±72 Mega Watts
	Power for Flattop @ 6000A	9.36 Mega Watts
	Current for 28 GeV	5,050 A
	Stored Energy	9.6 Mega Joules
	Power at Flattop	6.6 Mega Watts

System Description

The block diagram of the existing motor, cycloconverter, and power regulator is given in Figure 1. Associated with Figure 1 is an elementary phasor diagram, Figure 2, giving the relationship between stator and rotor current.

The power regulator uses a reference signal derived from the speed error. The shaft speed is measured at the beginning of each AGS cycle and compared to a reference speed, generating a speed error. The error is measured at a specific time within each AGS cycle (termed pre-pulse) and retained as a voltage on a capacitor over the entire AGS cycle. The power reference signal P* is generated by combining two signals derived from this stored error voltage. One signal is formed by integrating the error voltage; the second signal is proportional to the error voltage.

In the steady state, where the input power equals the average losses, the speed error and resulting error voltage are zero. Thus, the power reference depends only on the output of the integrator, which is at a constant value of voltage. The steady state input power is proportional to the integral of the error voltage. The input power is constant over the cycle, but the shaft power and speed are not constant. Shaft power depends on the motor power and the "flywheel" effect of the rigid shaft. The shaft speed is controlled, i.e., specified, at only one point within each AGS cycle. Thus, allowing the "flywheel" to slow up and discharge energy or to speed up and absorb energy.

During the energizing phase of the magnet cycle the "flywheel" slows up and contributes to the drive power of the generator. During the de-energizing phase of the magnet cycle the "flywheel" speeds up and absorbs the energy stored within the magnets. To a first approximation the energy stored in the magnet is obtained from the "flywheel" and is returned to the "flywheel" at the end of the cycle. In the steady state the energy dissipated by the magnet and rectifiers is obtained from the motor; the "flywheel" speed at the time of pre-pulse in each AGS cycle equals the reference speed. If the motor input energy fails to balance the dissipated energy of the cycle, the "flywheel" does not return to the reference speed resulting in an error voltage and a perturbation of the integrator. The integrator output voltage adjusts the motor power in the successive cycles to achieve a power balance or steady state operation. The transient response depends on the gain-settings of the controller and with the present speed regulator the transient response is typically in the range of 5 to 15 AGS cycles or periods.

The duration of the transient response is determined by the gain of the integral and proportional controllers. The duration of the transient response has an inverse relationship with the disturbances produced on the power line. The present design is very conservative. The maximum power line disturbance has been calculated for a speed error corresponding to the cycloconverter rating (s = ±.02) and the gain-control potentiometers at their mid-points as 1.9 MW and .41 MW/sec. Based on the parameters of substation transformer #3 at Temple Place, the RF pulsating load (also powered from this transformer), and the unity power factor operation of the motor, a power swing of 7 MW can be permitted for the motor.

To control the speed variation or slip of an induction motor the rotor must be energized (operation above synchronous speed) or loaded (operation below synchronous speed). The rotor interfaces to a three phase cycloconverter. The cycloconverter is the source or sink for the rotor power and, thus, is the controller for the stator power. The ratio between the rotor and stator power is equal to the motor slip.

The cycloconverter output is at slip frequency and the output magnitude is established by the power reference. Current feedback is employed to hold the line current at a nearly constant value. This results in a constant value of input power over the AGS cycle. The rotor power is dependent on the slip and varies over the cycle, thus the current-feedback loop must be fast compared to the AGS cycle time. Constant power operation of the motor results in the most efficient employment of the stored energy of the "flywheel".

The torque-speed characteristic of a typical wound rotor induction motor is shown in Figure 3 with and without feedback to the rotor. With the rotor short-circuited variation of load power is proportioned between increments of torque and speed (slip). Voltage feedback, i.e., the rotor voltage is controlled by the shaft speed, results in a constant speed and a variable torque characteristic. Current feedback, i.e., the rotor current is controlled by the input power, maintains a constant torque and results in a variable speed. For a given variation of load power maximum slip variation is achieved with current feedback, maximizing power transfer from the "flywheel". In this mode the input power is constant, and the variation of load power over a cycle is balanced by power flow from the "flywheel".

In principle current feedback can be employed to provide either a constant torque or a constant power mode. If the feedback variable is the stator power then a constant torque mode results and the stator power is held constant. If the feedback variable is the line power a constant power mode results. In the second mode the developed shaft power and the drive power, sum of stator and rotor powers, are held constant. Siemens description[1] of the controller refers to a constant torque mode. The wiring diagrams and field observations of the installation reveals that the controller operates in a constant power mode. Analysis of the difference between the two modes indicates that for the rated slip of ±2% the differences are negligible. In the constant power mode the torque variations are less than ±2%. In the constant torque mode the line power variations are less than ±2%.

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(1) New Main Magnet Power Supply for the AGS, Contract 139000, Description of the Automatic Power Control Systems, Siemens, November 9, 1970.

The current injected into the rotor is phased to contain a real and a reactive component. The reactive component of rotor current leads the line voltage and is used to compensate the lag component of stator current. See the phasor diagram in Figure 2. The magnitude of the reactive component of rotor current is controlled by a second feedback loop controlling the reactive stator power. The reference signal for this loop is zero reactive power. The two feedback loops are independent; the motor is operated at a nominal power factor of unity.

The power regulator can be readily modified to control the power on a cycle to cycle basis, allowing for mixed cycle operation. The basic modification is a second input signal to the integrator, that will initialize the integrator at the time of pre-pulse. This modification will allow the power reference P* to vary on a cycle to cycle basis without involving a transient response. The maximum power step size must be less than the allowable power swing at the substation transformer of 7 MW.

In summary, the MG set supplies a pulsed load. During any cycle the speed of the machines will constantly vary since the power regulator is forcing a fixed input power. If the input power equals the average power drawn by the load plus all other losses the machine will start each successive cycle at the reference speed. If there is a change in speed caused by an incorrect power balance the speed error will modify the power reference P* and reduce this error to zero in the following cycles.

Fixed Cycle Operation

The characteristic response of the controller driving motor and "flywheel" have been calculated with the AGS operating in its most common modes. The modes correspond to FEB, SEB (2 second flattop), SEB with a dwell time (front porch), and a 4 second cycle with a 1 second injection time from the Booster. The peak magnet current was held constant at 6 kA (33 GeV) for each mode. The magnet current and shaft speed waveforms are given in Figure 4 for ach mode. From this analysis the energy dissipated per cycle U, the steady state stator power P, and the maximum "flywheel" slip $|\Delta s|$ are given in Table II. In this analysis the reference speed is held constant at 125 radians per second (1200 RPM). A discussion of the techniques for calculating the response of the MG set to periodic cycles is included as Appendix A.

Mode	Period	Energy Loss Per Cycle U	Stator Power P	Maximum "flywheel" Slip $\|\Delta s\|$
FEB	1 SEC	3.94 MJ	3.94 MW	2%
SEB	3 SEC	23.74 MJ	7.91 MW	2.32%
SEB (with front porch)	3 SEC	20.48 MJ	6.83 MW	2.60%
4 Second cycle	4.05 SEC	24.83 MJ	6.13 MW	3.13%

Table II

Response of MG Set to Common Cycles

This analysis is performed for the maximum AGS energy of 33 GeV. More realistic, the AGS operates on a 28 GeV cycle, 5050 Ampere peak value of magnet current. For the second energy value the response is approximately 70% of the tabulated values. For all cycles and energies the "flywheel" slip is well within the allowable slip window of 4%. The reference speed n* adjustment centers the speed waveform within the window.

It is interesting to calculate the maximum capability of the MG set in driving the rectifiers and magnet. Operating within the allowable slip window of 4% the stored energy of the "flywheel" limits the magnet current to 8.2 KA, exceeding the current capability of the rectifiers of 6 KA. With a 6 KA current pulse the flattop duration is limited by the 9 MW drive motor to 6.05 seconds for periodic operation. This value of flattop duration will exceed the cooling capability of the magnet and bus bars. The present performance of the MG set and cycloconverter does not limit the performance of the MMPS. It will be shown later in this report that the cycloconverter is capable of driving the motor and load within a slip window of ± 2%, and is marginal for the ± 4% service speed slip of the motor.

Transient Response

The transient response of the MG set has not been an issue to this point in time. The AGS has been operated on a fixed AGS cycle basis and the power reference P* has been at a constant value. With mixed cycle operation the power reference P* is a cycle-cycle variable and if generated by the controller will involve its transient response. If the values of P* have been calculated as a function of the cycle parameters by the AGS control system and is an external input to the MG set controller, then the transient response vanishes. Successive values of P* are limited by the maximum allowable power swing (or surge) at the 13.8 Kv substation transformer to within 7 MW.

The closed loop transient response has been calculated for two perturbations of a basic AGS cycle. The cycle chosen for analysis has a period of 2 seconds and absorbs 10 Mega Joules of electrical energy. The perturbations are:

1. With the cycle invariant, increment the value of the speed reference n* by 1 radian per second.
2. With the speed reference n* invariant, increment the peak magnet current and increase the stored energy by 2 Mega Joules.

The responses have been calculated with the two gain-adjustment poteniometers at their mid-point and are given in Figures 5 and 6. In each figure the slip, integrator output voltage, and stator reference power are plotted to a common time scale. The first case corresponds to the impulse response; the second, to a step response. Note that the duration of the transient is approximately 15 AGS periods.

The parameters used in these calculations are taken from the circuit schematic Fig. 7 and are given in Table III. A discussion of the techniques involved in calculating the transient response of the controller is included as Appendix B.

Tachometer Sensitivity	.8356 Volts/radian per second
Integrator Time Constant	.15 seconds
Gain of Integrator to Output	1.314
Gain of Proportional Amplifier	2
Sensitivity of Power Reference P*	0.9 MW/volt
Attenuation of Integrator Loop	1/40
Attenuation of Proportional Loop	½
Energy Sensitivity of "flywheel"	5.04 MJ/radian per second

Table III
Parameters Relevant to the Transient Response of the Controller

The power reference P* responds to the speed error Δn at the time of prepulse and is given by $\Delta P^* = -(.1647t + .752)\,\Delta n$

where P* is in MW

Δn is the speed error (=n-n*)

t is time in seconds measured from pre-pulse

Typically, for a cycle of 2 seconds the energy response due to the integrator is 0.3294 Mega Joules/radian per second. The energy required to correct the speed error of the "flywheel" is 5.04 Mega Joules/radian per second. Thus, 15 cycles are required for the integrator to reach a new steady state once it is disturbed.

The slow response is satisfactory for fixed cycle operation as the loop is required to correct only for slow perturbations due to power line regulation, magnet heating, ambient temperature, etc. The slow response could interfere with pulse to pulse modulation. Rather than redesign the controller, the integrator can be initialized at prepulse for each new cycle in the chain.

For the transient response, as well as for the steady state, the slip must be limited to lie within the speed - field excitation control window of the generator. This will assure that the rectifier output is insensitive to motor speed variations. Though the allowable slip of the generator is greater than $\pm$ 4%, the present arrangement of generator, field exciter, and controls limit the slip to $\pm$ 2%. The service speed of the motor is 1200 RPM $\pm$ 4%, the speed of the generator is 1200 RPM $\pm$ 2%. Thus, the maximum allowable slip is $\pm$ 2%. The width of the slip window is 4% and controls a maximum energy transfer from the "flywheel" of 25.2 Mega Joules.

Cycloconverters

The cycloconverter injects rotor current controlling the stator current and power. On a normalized basis, the rotor and stator currents are equal; the rotor and stator voltages are in the ratio of the motor slip. Thus, the stator and rotor powers are in the ratio of 1/s. The shaft and rotor powers are in the ratio of $\left(\frac{1-s}{s}\right)$,s is positive below and is negative above synchronous speed.

The wound rotor induction motor with rotor injection can be considered an (mechanical) amplifier. The rotor current or power controls the stator and shaft power. The gain is in the slip and not in the current; analogous to a grounded gird or common base amplifier. In addition, the injected rotor current can contain a lead component, thereby compensating the lag component of stator current and providing power factor correction.

The rotor current is composed of two independent quadrature related components, see Figure 2. The component in phase with the line voltage sets the stator real power and is controlled by P*. The component in quadrature with he line sets the stator reactive power and is controlled by Q*. The value of Q* is zero, correcting to unity power factor.

The cycloconverter can marginally control the motor within its service speed of ± 4%. It operates well within its rating to control the motor within the slip window of ± 2%.

The ratings of the cycloconverter are 115 Volts line to neutral and 1800 Amperes per phase. The performance of the cycloconverter at a slip of +4% and -4% has been calculated. The calculation is based on the induction motor parameters given in Table IV.

Rating	12,000 Horsepower
Line Voltage	13.8 Kilo Volts
Line Current	394.3 Amperes
Stator Power Factor	0.95
Stator Real Power	8953 Kilo Watts
Stator Reactive Power	2943 Kilo Vars
Blocked Rotor Voltage	4.45 Kilo Volts
Rotor Winding Resistance to Neutral	5.6×10^{-3} Ohms

Table IV
Motor Parameters

By neglecting stator winding and core losses the power delivered to the air gap is 8953 Kilo Watts. The performance at a slip of ± 4% is given in Table V. Details of the calculations are included as Appendix C.

	S = .04	S = -.04
Power Delivered to Air Gap	8953 KW	8953 KW
Power Delivered to Shaft	8596 KW	9311 KW
Power Delivered by air Gap to Rotor	358 KW	
Power Added to Air Gap from Rotor		358 KW
Rotor Current	1223 A	1223 A
Rotor Dissipation (3 ϕ)	25 KW	25 KW
Rotor Power Delivered to Line	333 KW	
Rotor Power Absorbed from Line		383 KW
Rotor Voltage	96.3 Volts	109.35 Volts
Lead Angle	19.5°	17.1°
Power Factor	.94	.96
Reactive Power, Lead	118 KVAR	118 KVAR

Table V
Performance of Cycloconverters at ± 4% Slip

From Tables IV and V note that the stator reactive power (2943 KVAR) multiplied by the slip (.04) equals the rotor reactive power (118 KVAR); the stator real power (8953 kW) multiplied by the slip (.04) equals the rotor real power (358 kW).

These calculations have neglected the voltage drop in the slip rings, brushes, and power cables which would increase the rotor resistance. The increased resistance would increase the injected rotor voltage beyond the calculated value of (109 Volts). The ratings are more than adequate for a ± 3% slip. The width of the slip window is limited by the field-current regulator of the generator. At present, the ±2% limit in slip window is acceptable.

Induced Power Grid Disturbances

The MG set is powered from the 13.8 KV port of transformer number 3 at Temple Place substation. Two other major loads are powered from the same port. They are:

1. the apartment area, a 2 MW fixed load,
2. the AGS RF system. With the upgraded RF system operational, it is estimated that the load has a 4 MW, pf = 0.95 lag, pulsed component plus a fixed 1.5 MW component.

In addition, a number of smaller pulsed and fixed loads are powered from this transformer. Only the pulsed components contribute to the power line flicker.

The parameters of the transformer and power grid affecting the MG set are given in Table VI.

Transformer Rating	30 MVA
Leakage	7.5 %
13.8 KV Port	
Capacity	335 MVA
R to x ratio	0.11
69 KV Port at Temple Place	
Capacity	1920 MVA
LILCO Port Lab Entrances	
Capacity	2310 MVA

Table VI
Parameters of Power Grid

The flicker induced by a pulsating load is given by

$$\frac{\Delta V}{V} = \frac{P\left(\frac{R}{x}\right) + Q}{scc} + j\,\frac{p - Q\left(\frac{R}{x}\right)}{scc}$$

where $\frac{\Delta V}{V}$ = power line flicker

scc = short circuit capacity of port

R = resistance of power

x = inductive reactance of port

P = power of load

Q = reactive power of load, lagging load is positive

The maximum allowable pulsed motor load is limited by an induced flicker (design limit) of 0.8%. The allowable load is 7 MW, and is corrected for unity power factor. The RF system and main magnet power supply are synchronized. Thus, the pulsed loads are linearly combined to give

P = 11 MW

Q = 1.32 MVAR, lag

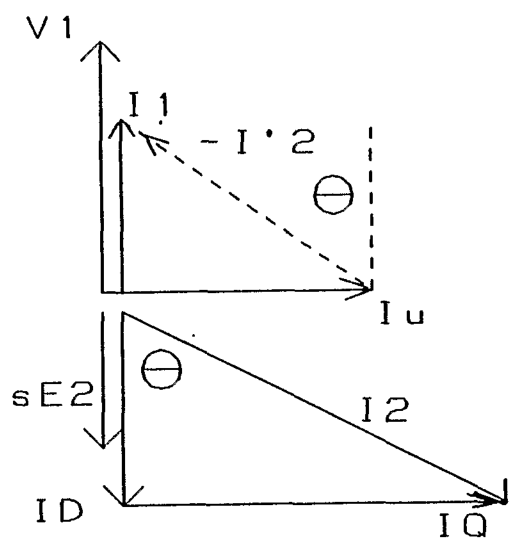
The amplitude flicker on the 13.8 KV line is 0.8% and the phase flicker is 1.84°.

The effect of flicker on the connected power line loads decrease as the frequency of the pulsating load is reduced. In the range of the AGS cycles (period of 1 to 5 seconds) LILCO allows a 1.3 to 1.5% flicker. Figure 8 gives the LILCO flicker curve. The power limit is set for sixty percent of the LILCO limit.

The value of induced amplitude flicker has been projected to the 69 KV distribution system. At Temple Place, and the balance of the lab site (except for loads fed by transformer number 3) the flicker is estimated at 0.14%. The maximum flicker induced on the LILCO 69 KV distribution system is estimated at 0.11%.

As a practical matter the power swing is limited by the various AGS modes (see Table II) to a maximum value of 4 MW. Thus, for mixed cycle operation the induced flicker is 0.45% for the loads fed from transformer #3 and .08% for the balance of the lab site.

Phasor Diagram of Controller



V1=Line Voltage

I1 = Stator Current

Iu=Uncompensated Lag component of stator current

I2=Rotor Current

I'2=I2 referred to stator

ID=Direct component of I2

IQ=Quadrature component of I2

E2=Blocked Rotor Voltage

s=Slip

Θ =Uncompensated Power factor angle

Figure -2-

powreg1

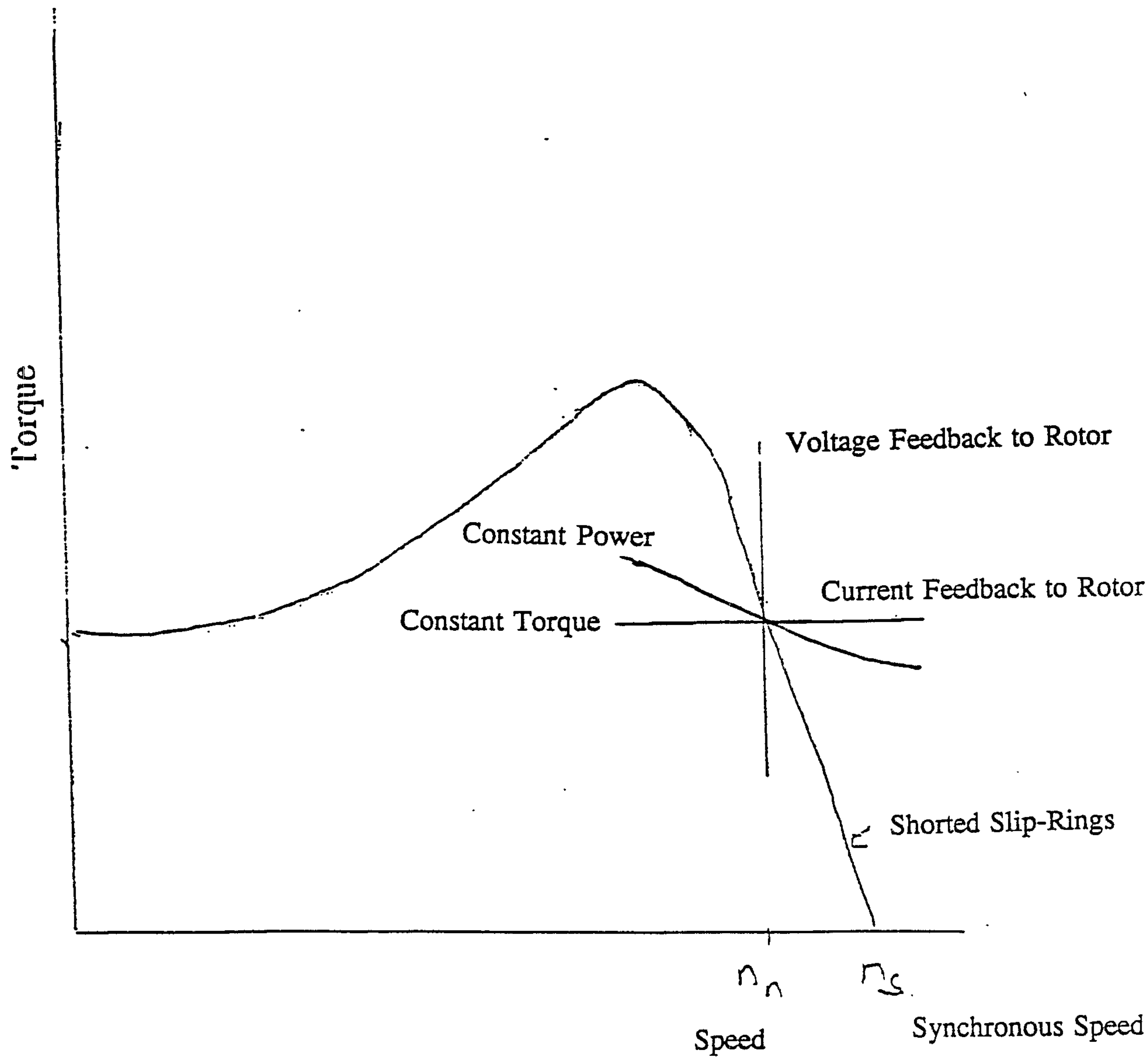
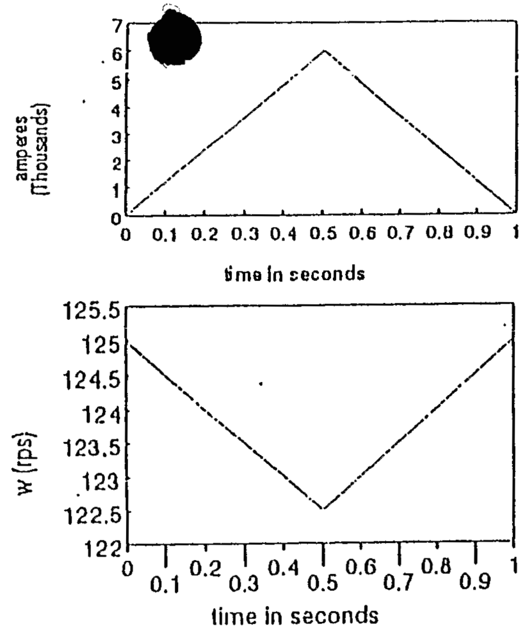


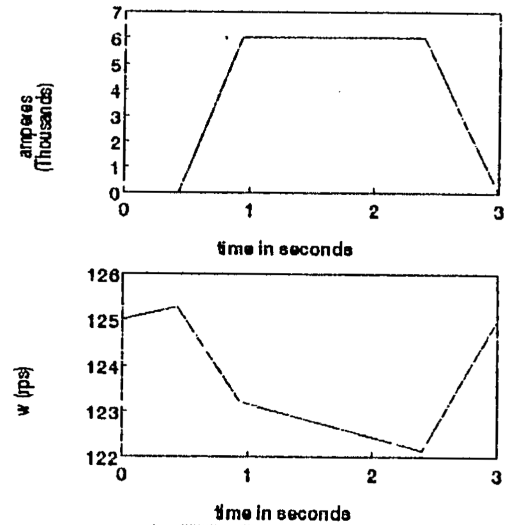
Figure 3

Torque-Speed Characteristic of Typical Wound Rotor Induction Motor With Rotor Control

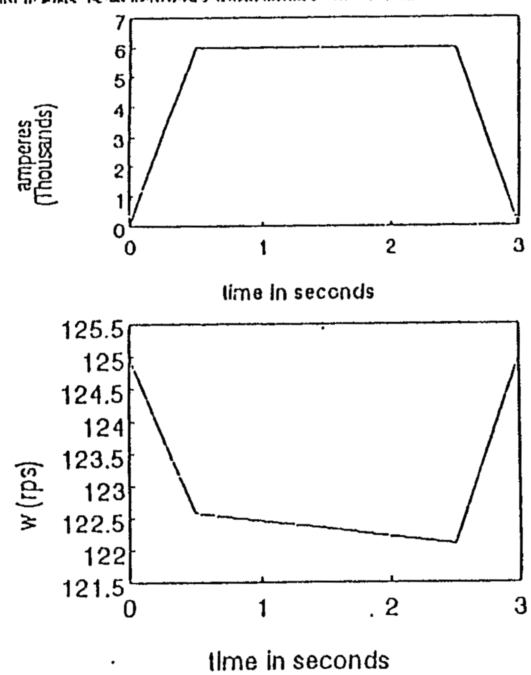


Energy Loss=
3.94 MJ
P = 3.94 MW
|delta s| =2%

SEB
front
porch

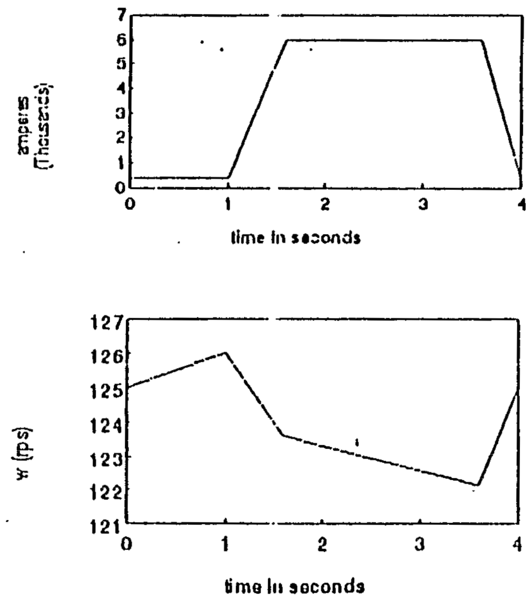


Energy Loss =
20.48 MJ
P= 6.93 MW
|delta s|= 2.60%



Energy loss =
23.74 MJ
P = 7.91 Mw
|delta s|= 2.32%

4 second
cycle



Energy loss=
24.83MJ
P=6.13 MW
|delta s|=3.13%

Figure 4

SMC Set for Common AGS Modes

T = 2 SEC

u = 10 MJ

n = 125 rad/SEC

Δn* = 1 rps

SLIP = 0.8%

MAXIMUM RESPONSE

Δn = 1.17 rps

SLIP = 0.94%

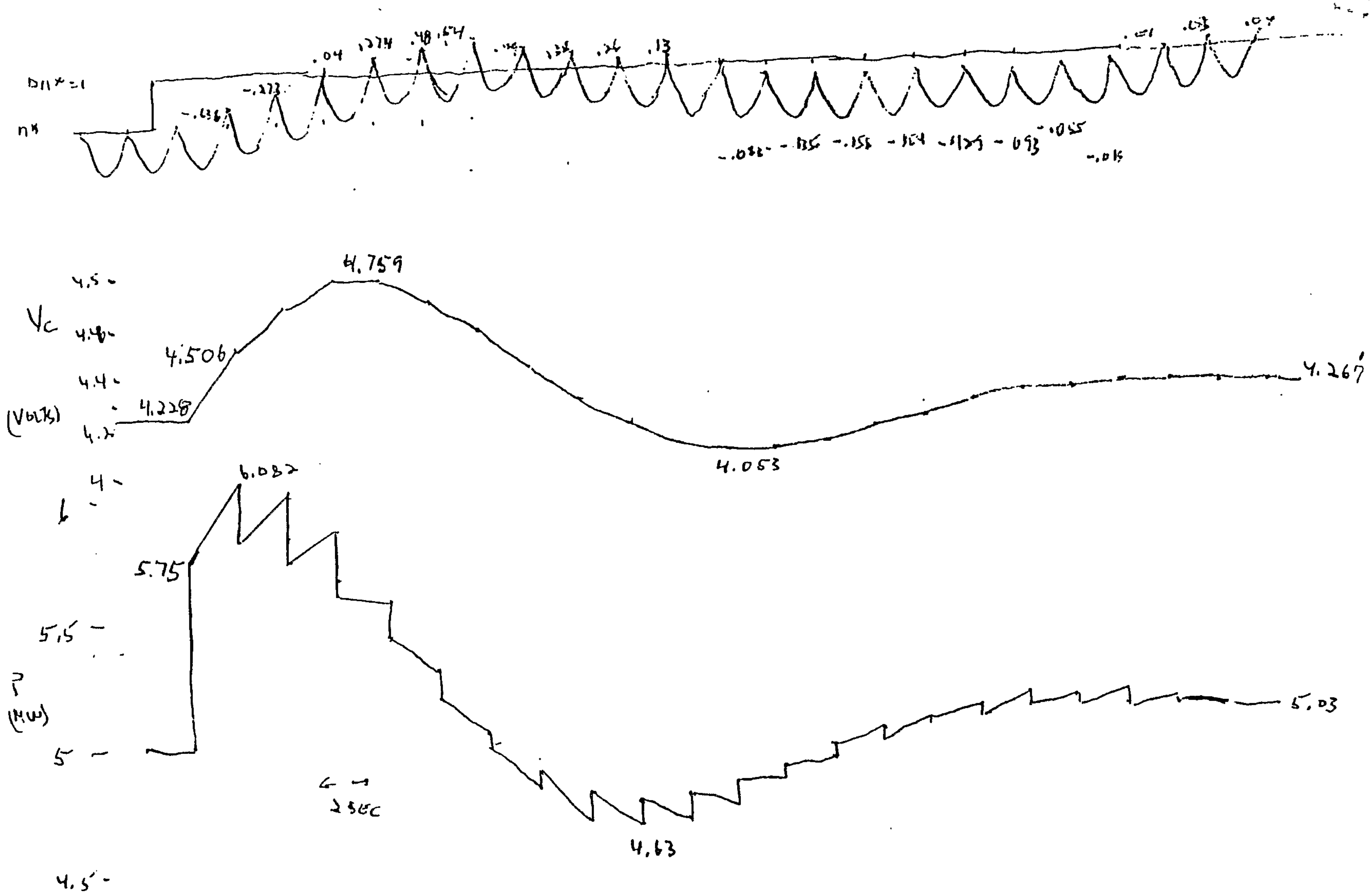


Figure 5

Transient Response of MG Set and Controller Δn* = 1 RPS

T = 2 SEC

U = 10 MJ

n = 125 rad/SEC

Δu = 2 MJ

JW = 5.026 MJ-SEC

MAXIMUM RESPONSE

Transient Δn = 1 rps

Steady State Δn = .4 rps

$|\Delta n|$ = 1.4 rps

SLIP = 1.12%

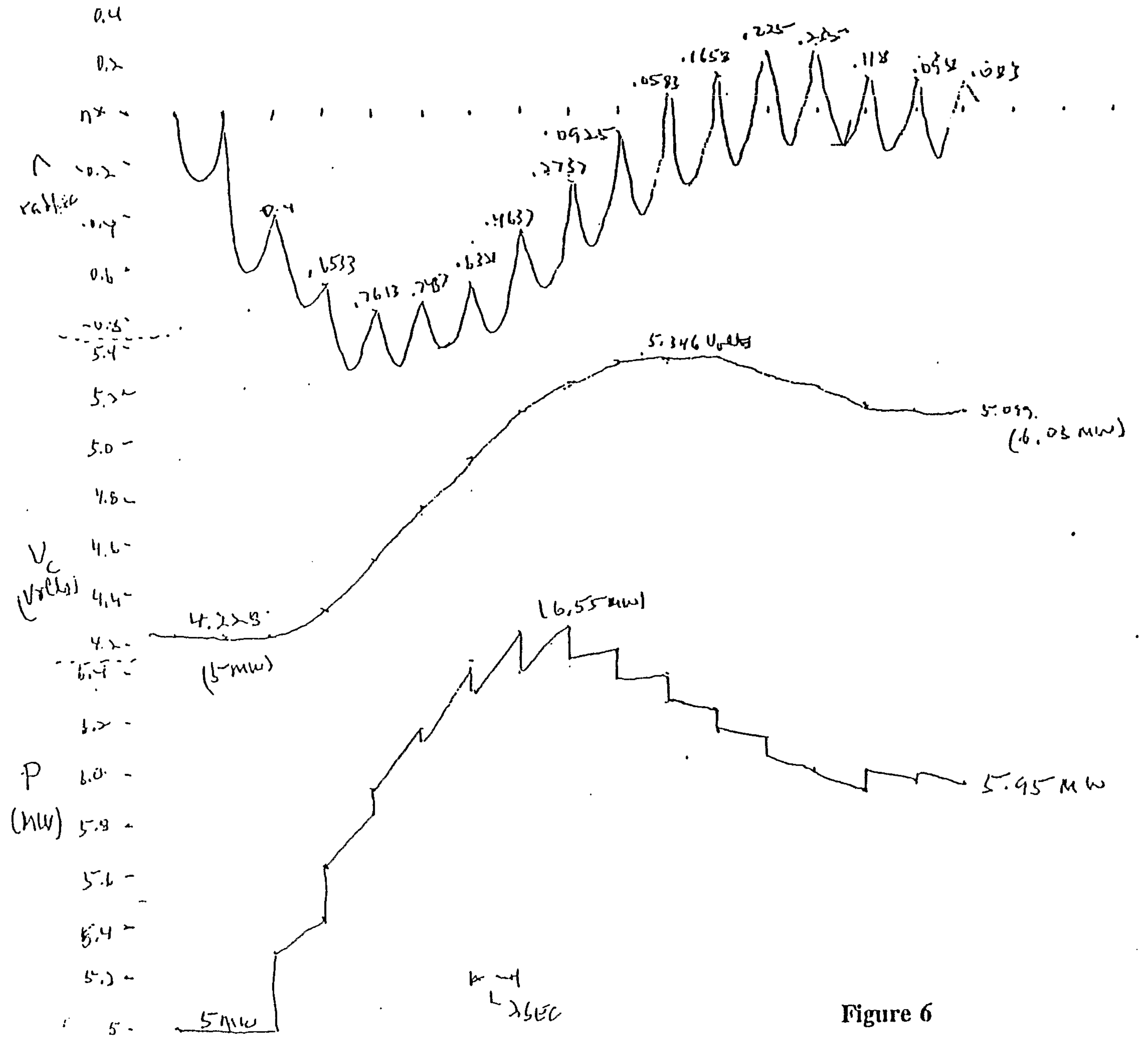
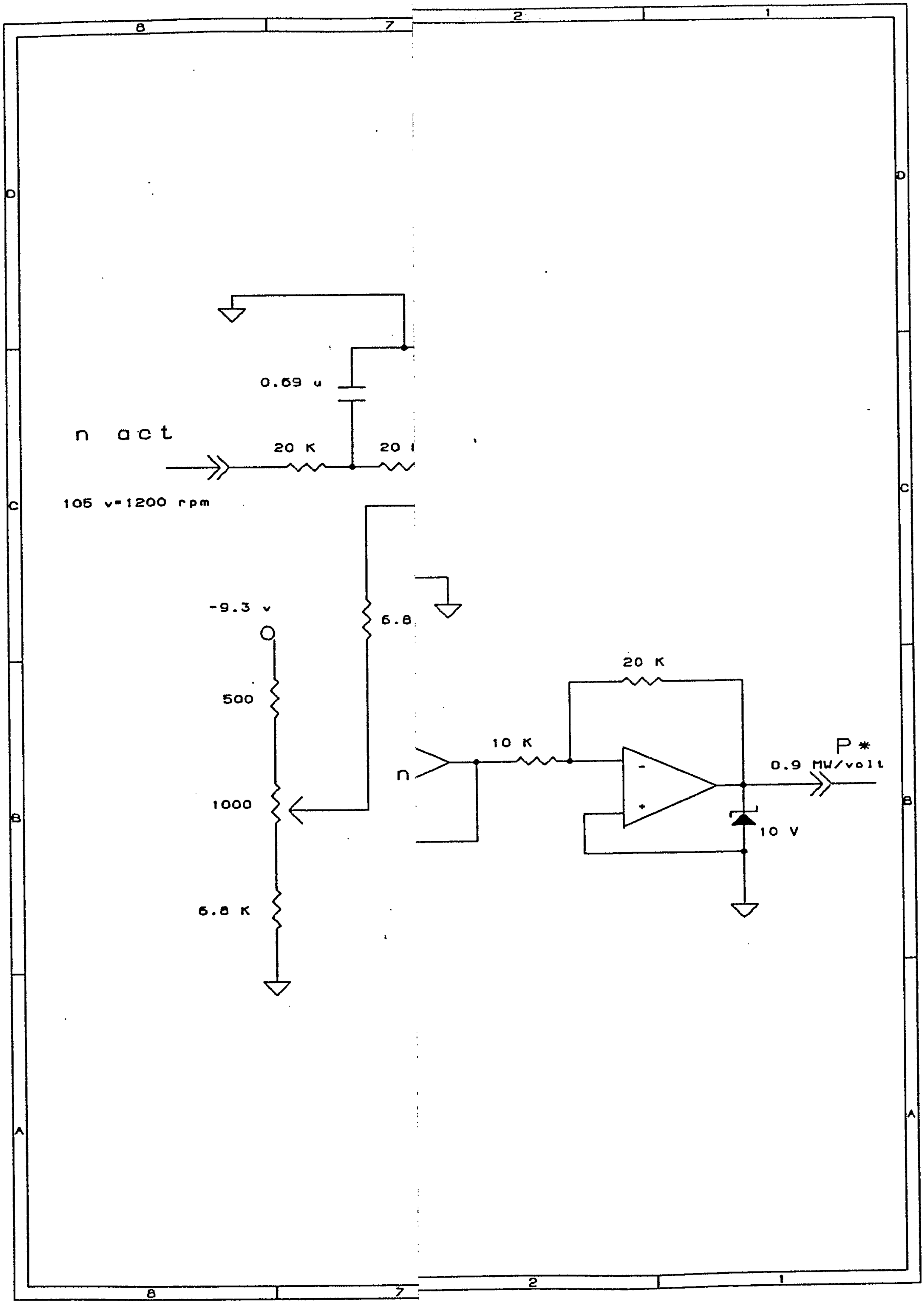


Figure 6

... Controller Δu = 2 MJ


n act
105 v=1200 rpm
0.69 u
20 K
20
-9.3 v
500
1000
6.8 K
6.8
20 K
10 K
n
P*
0.9 MW/volt
10 V

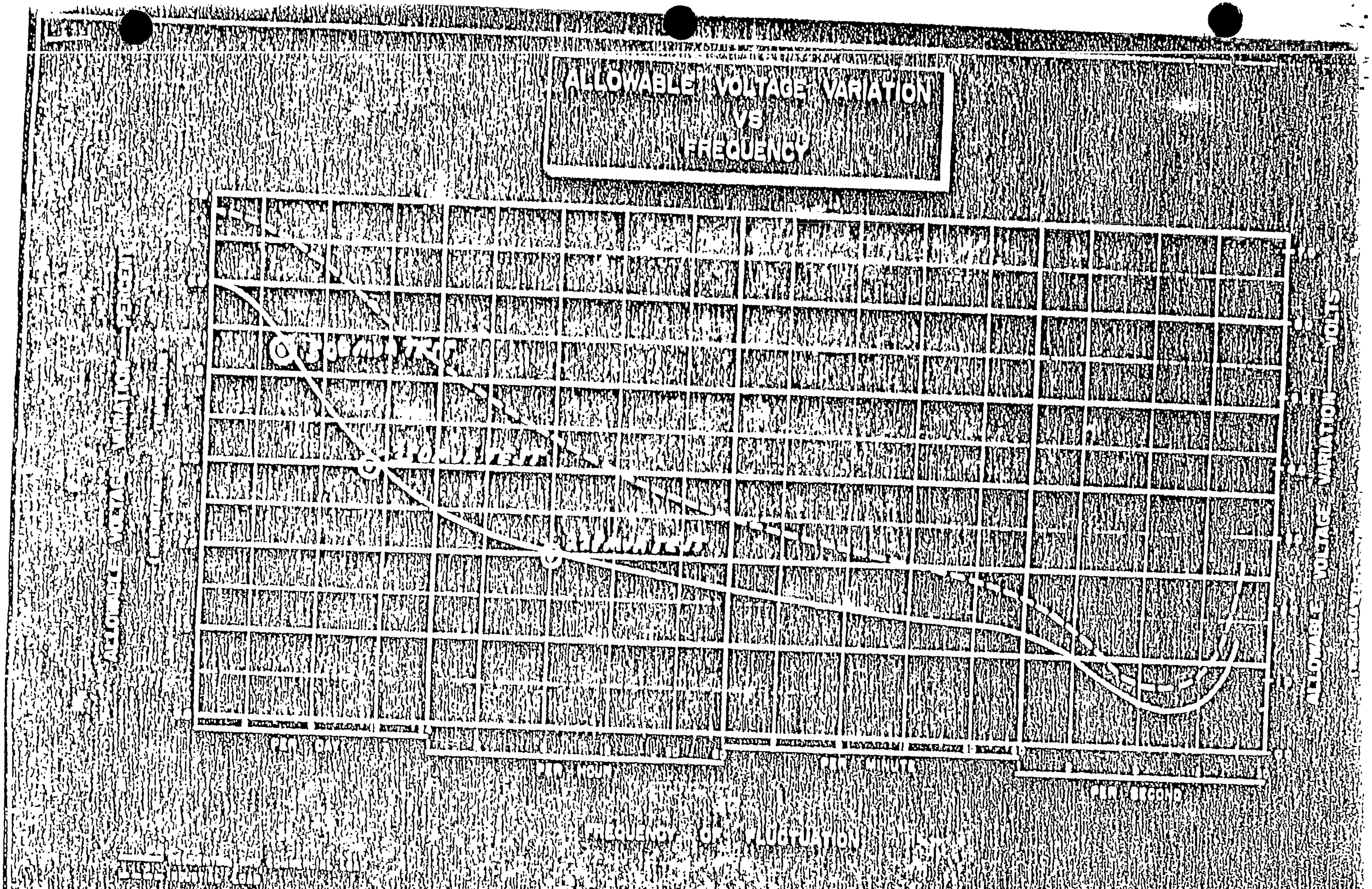


Figure 8

LILCO Flicker Curve

APPENDIX A

CALCULATIONS OF RESPONSE OF MG SET TO PERIODIC CYCLES

For the purposes of these calculations the motor and generator have been idealized, each operating at 100% efficiency. The calculations involve an energy balance of the flywheel. Each cycle is segmented into component intervals: magnet charge, flattop, discharge (or energy recovery) and front porch. The energy required for each interval is calculated and summed to yield the net energy loss per cycle, U in Table II. The net energy loss is balanced by the energy derived from the motor. The details of this calculation for the SEB cycle (with front porch) is given below.

The current waveform is given in Figure 4. The parameters involved in this calculation are summarized

I_{peak} = 6000A
L = .75H
R_{DC} = 0.26 Ohms
Reference shaft speed (ω_o) = 125 RAD/SEC
energy stored in flywheel (U_o) = 315 MJ.
Friction and windage = .85 MW.

For charging and discharging, we assume a current ramp, such that

I_{RMS} = 3464 A

I_{DC} = 3000 A

The voltage drop across the SCR's are taken as 10 volts.

Interval of magnet charging		$0.93 > t > 0.2$
Peak Energy stored in magnet		
$\frac{1}{2} LI^2$		13.5 MJ
Plus energy dissipated in charging of magnets		
ohmic loss	$(I_{RMS})^2 R_{DC} \Delta T$ $(3.464)^2$ (.26) (.73)	2.27 MJ
SCR's	$I_{DC} V_{SCR} \Delta T$ 3000 (10) (.73)	.02 MJ
	Windage and Friction	
	.85 x .73	.62 MJ
	Energy to charge magnets	16.41 MJ

Interval of Flattop		2.4 > t> .93
ohmic loss		
$(I_{peak})^2 R_{DC} \Delta T$		
$(6)^2$ (.26) (1.47)		13.75 MJ
Windage and Friction		
.85 x 1.47		1.25 MJ
Energy for Flattop		15.0 MJ
Interval of magnet discharge		3.0 >t> 2.4
Energy Recovery		
½ LI^2		13.5 MJ
Less Dissipation		
ohmic loss $(3.464)^2$ (.26) (.6)	1.87 MJ	
SCR's (3000) (10) (.6)	.02 MJ	
Windage and Friction .85 x .6	.51 MJ	
	2.4 MJ	
		-2.40 MJ
Net Energy Recovery		11.1 MJ
Interval of Front Porch		0.27 > t > 0
Windage and Friction		
.85 x .2		.17 MJ

The summations of the energy components is shown in Figure A-1.

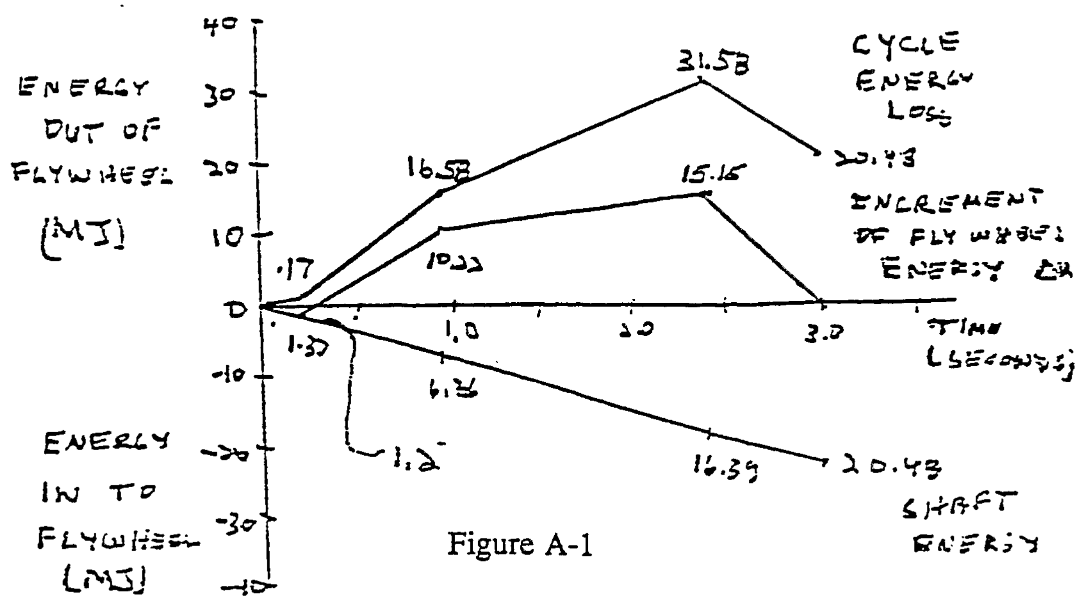


Figure A-1

The net energy loss per cycle is 20.48 MJ. Energy balance or steady-state operation requires an input of 20.48 MJ in 3 seconds or a developed shaft power of 6.83 MW.

From the increments of flywheel energy ΔU the change in shaft speed is calculated as

$$\Delta U = 2U_o \frac{\Delta\omega}{\omega_o}$$

$$\Delta U = 5.04\ \Delta\omega$$

The shaft speed is also shown in Figure 4. In terms of slip the increments of flywheel energy is calculated as:

$$\Delta U = 2U_o \Delta s$$

$$\Delta s = \frac{\Delta U}{630}$$

The maximum underspeed is calculated as $\frac{15.15}{5.04}$ or 3 rps and the maximum overspeed as $\frac{1.37}{5.04}$ or .27 rps. The maximum change in slip is $\frac{3.27}{125}$ or 2.6%.

APPENDIX B

DETAILS OF TRANSIENT RESPONSE

The speed controller or power reference loop is a sampled data system. A speed error is measured at pre-pulse and is stored as an error voltage over the full cycle time or period. Assume that the shaft speed is less than the reference speed. A positive error voltage is generated and stored. The error voltage is integrated and added to itself increasing the shaft power and shaft speed. The schematic of this loop is given in Figure 7 and the circuit parameters are given in Table III.

Being a sampled data system, the response can be calculated for each sample or AGS cycle, correcting the integrator output until the steady state shaft power balances the energy loss of the cycle as illustrated in Appendix A. The relationship between the shaft power P and required integrator voltage V_c is

$$P = 1.314 \times 0.9\ V_C \text{ MW}$$

$$= 1.183\ V_C \text{ MW}$$

For an error in speed of Δn rps, the error voltage ΔV is

$$\Delta V = .8356\ \Delta n \text{ volts.}$$

The integrator output is

$$V_C = \frac{.8356\ \Delta n}{.15}\ \frac{1}{40}\ t + V_c(0^-)$$

$$= .1393\ t\Delta n + V_c(0^-)$$

where $V_c(0^-)$ *is the output at pre-pulse*
and t is in seconds measured from pre-pulse.

Due to the integrator the power reference P* is

$$P^* = 1.183\ V_C\ MW$$

$$= .1647t\ \Delta n + 1.183\ V_C(0^-) MW.$$

For a cycle with a period of T seconds the energy transferred to the flywheel is calculated as

$$U = \int_{0}^{T} [.1647\Delta nt + 1.183\ V_C\ (0^-)]dt \quad MJ.$$

$$= .08235\Delta nT^2 + 1.183\ V_C\ (0^-)T \quad MJ.$$

Due to the proportional signal the power reference P* is

$$P^* = .9\ \Delta V \quad MW$$

$$= .752\ \Delta n \quad MW,$$

and the energy and transferred to the flywheel is calculated as

$$U = .752\ \Delta n\ T \quad MJ.$$

By linearly combining the integral and proportional controls the power reference P* is

$$P^* = (.1647\ t + .752)\ \Delta n + 1.183\ V_C\ (0^-)\ MW,$$

and the energy transferred to the flywheel in the period T is

$$U = (.08235\ T^2 + .752\ T)\ \Delta n + 1.183\ V_C\ (0^-)T \quad MJ.$$

The energy transferred to the flywheel in excess of the energy required to balance the cycle (as developed in Appendix A) provides speed correction. The excess energy ΔU increases the shaft speed by

$$\Delta n' = \frac{\Delta U}{5.04}\ rps$$

at the following pre-pulse. The speed error for the following cycle is Δn - Δn'. The procedure continues until the speed error goes to zero and the integrator voltage V_c provides a constant value of power to balance the energy flow from the flywheel. The equilibrium value of V_c is given by

$$V_c = \frac{U}{1.183T} \quad volts$$

As an illustrative example consider the first four steps in the calculation of the response due to a step in the reference speed (Δn^*) of one radian per second in the cycle depicted in Figure 5. For this example U = 10 MJ, T = 2 seconds. At the first pre-pulse the shaft speed error is 1 rps, the error voltage is .8356 volts, and the integrator output voltage V_C is 4.228 volts. Continuity is required for the integrator voltage at each pre-pulse. The response is calculated following the procedure outlined above. The calculated parameters are plotted as waveforms to a common time scale Figure B-1. Note the continuity of the integrator voltage and the jumps in shaft power at each pre-pulse.

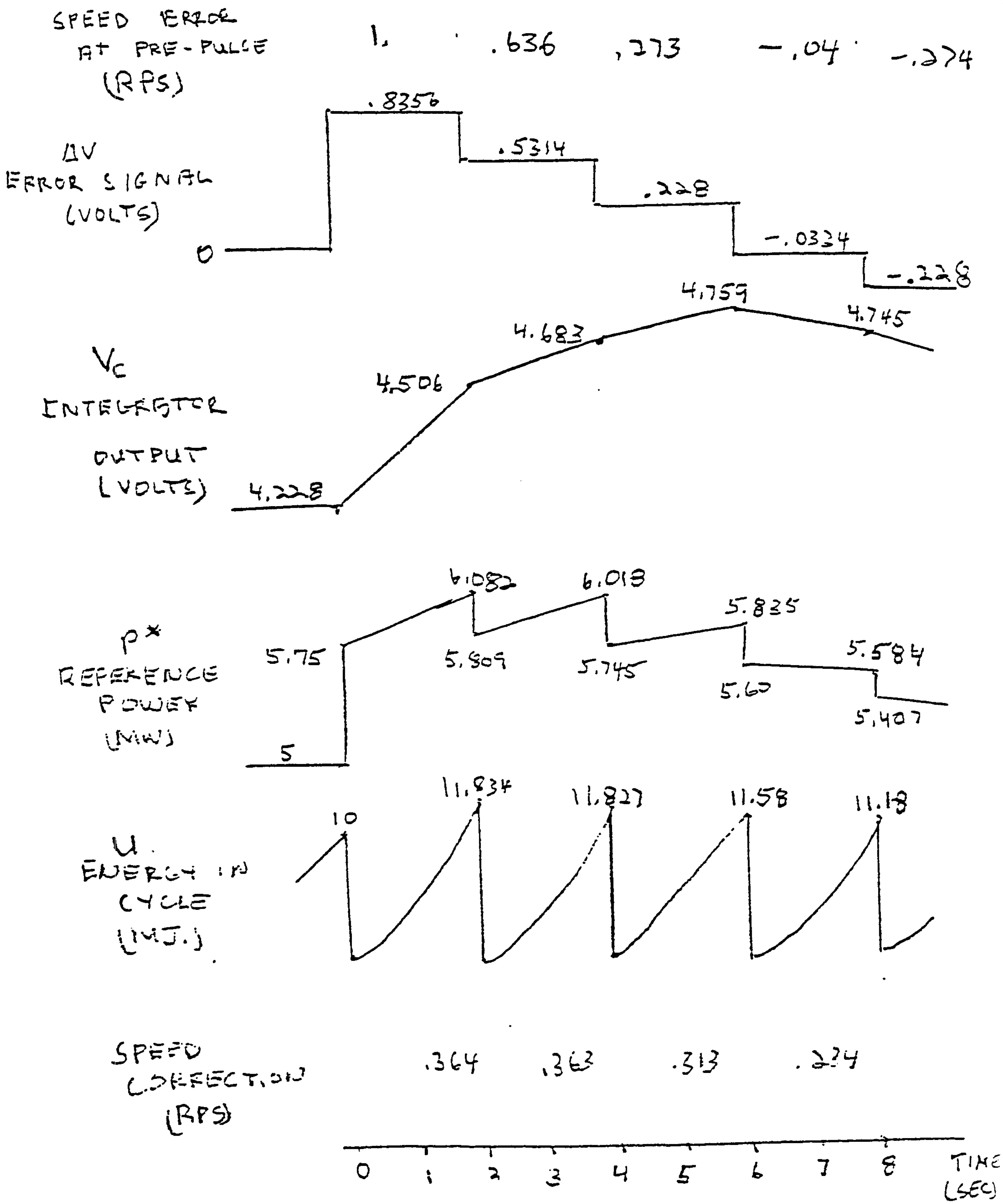


Figure B-1
Illustrative Calculation

APPENDIX C

CALCULATION OF CYCLOCONVERTER PERFORMANCE

For this analysis the induction motor is modeled (Tesla model) as a transformer with a rotating secondary. The principles employed in this analysis are discussed in Appendix D.

This calculation is based on the division of air gap power between power delivered to the shaft, power dissipated in the rotor, and power transfer between the rotor and cycloconverter. For a shaft speed that is less than the normal shaft speed (i.e. positive slip) the cycloconverter acts as a sink and absorbs power from the rotor. For a speed that is greater than the normal speed (i.e. negative slip) the cycloconverter acts as a source and delivers power to the rotor. Normal shaft speed varies with loading of the motor, and is the speed with the rotor slip rings shorted. At rated load the slip is estimated as 0.4%.

Consider that 12,000 Horsepower (8953 KW) of power is delivered to the air gap with a power factor of 0.95 lag. Refer to the phasor diagram Figure 2 and assume that the rotor EMF is equal to the line voltage (V_1) 13.8 KV. The stator current I_1 is

374.6 -j 123.15 Amperes.

$$394.3 \underline{\angle -18.2^o}.$$

The ratio of stator to blocked rotor voltage of 3.10 is also the transformation ratio between rotor and stator current.

The power regulating system corrects the stator current I_1 to unity power factor. Thus I_1 is 374.6 amperes. The required magnetizing current $I\mu$ is -j 123.15 amperes. The rotor current I_2 is given by

$$I_2 = 3.10[I\mu - I_1]$$
$$= -1162 - j382 \; Amperes$$
$$= -1223 \; \underline{\angle 18.2^o}$$

The rotor current is independent of the value of slip.

The flywheel is free wheeling, responding to the power requirements of the generator, and determines the motor slip. To a first approximation the power regulating system holds I_2 at a constant value.

The relationship between the induced rotor voltage SE_2, rotor current I_2, and cycloconverter voltage V_2, is illustrated in the rotor equivalent circuit, Figure C-1.

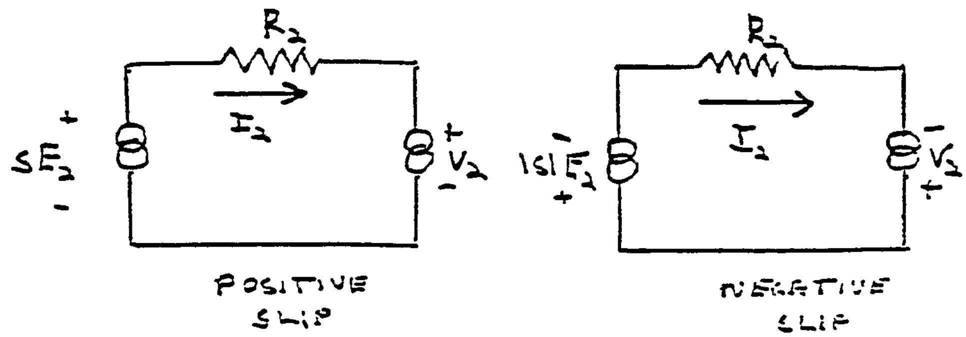


Figure C-1

E_2 is the blocked rotor voltage per phase 2569 volts. R_2 is the rotor winding resistance to neutral 5.6×10^{-3} ohms.

For positive slip

$$V_2 = SE_2 - I_2R_2$$

For negative slip

$$V_2 = SE_2 + I_2R_2$$

For a slip limit of $\pm$ 4%

$$SE_2 = 102.8 \text{ volts.}$$

V_2 is calculated from the phasor diagram, Figure C-2.

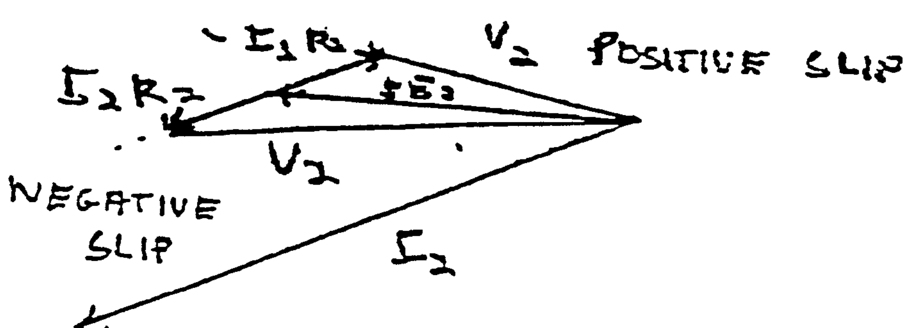


Figure C-2

Thus for positive slip

$$V_2 = 96.3 \angle -1.3^o$$

and for negative slip

$$V_2 = 109.35 \angle 1.1^o$$

In both cases

$$I_2 = 1223 \angle +18.2^o$$

The power factor angle is (18.2 + 1.3)° for positive slip and (18.2 - 1.1)° for negative slip. For positive slip the cycloconverter acts as a sink and absorbs 3x96.3x1223 cos 19.5°=333 KW of power. For negative slip the cycloconverter acts as a source and delivers 3x109.35x1223 cos 171°=383 KW of power.

In both cases the ohmic loss in the rotor is $3 \times (1223)^2(5.6 \times 10^{-3}\Omega) = 25$ KW. Thus, for positive slip the rotor absorbs (333 + 25) = 358 KW of power from the rotating field. For negative slip the rotor delivers (383 - 25) = 358 KW of power to the rotating field.

In both cases the reactive power is calculated as

3 x 96.3 x 1223 sin 19.5° = 118 KVAR, or

3 x 109.35 x 1223 sin 17.1° = 118 KVAR.

The maximum cycloconverter terminal voltage is 109.35 volts and maximum current is 1223 Amperes.

APPENDIX D

ANALYSIS OF DOUBLE-FED INDUCTION MOTOR

The following principles are employed in analyzing the double-fed wound rotor induction motor.

1. Principles involving circuit terminal parameters:

   A. Voltage transformation, ratio of rotor to stator voltages is

$$\frac{V_2}{V_1} = as$$

   B. Current transformation, ratio of rotor to stator currents is

$$\frac{I_2}{I_1} = \frac{1}{a}$$

$$\text{where } a = \frac{\text{blocked rotor voltage}}{\text{stator voltage}}$$

$$s = slip = \frac{\omega_o - \omega}{\omega_o}$$

ω_o = *synchronous rotor rotational frequency*
ω = *rotor rotational frequency*

2. Principles involving power flow

   If P_1 is stator power delivered to air gap,
   P_2 is power delivered to shaft from air gap, and
   P_{ROTOR} is power transferred to rotor from air gap, then

$$P_1 = T\omega_o$$
$$P_2 = T\omega = P_1 (1 - s)$$
$$P_{ROTOR} = T (\omega_o - \omega) = sP_1$$
where T = torque developed at shaft

Power flow is illustrated in Figure D-1.

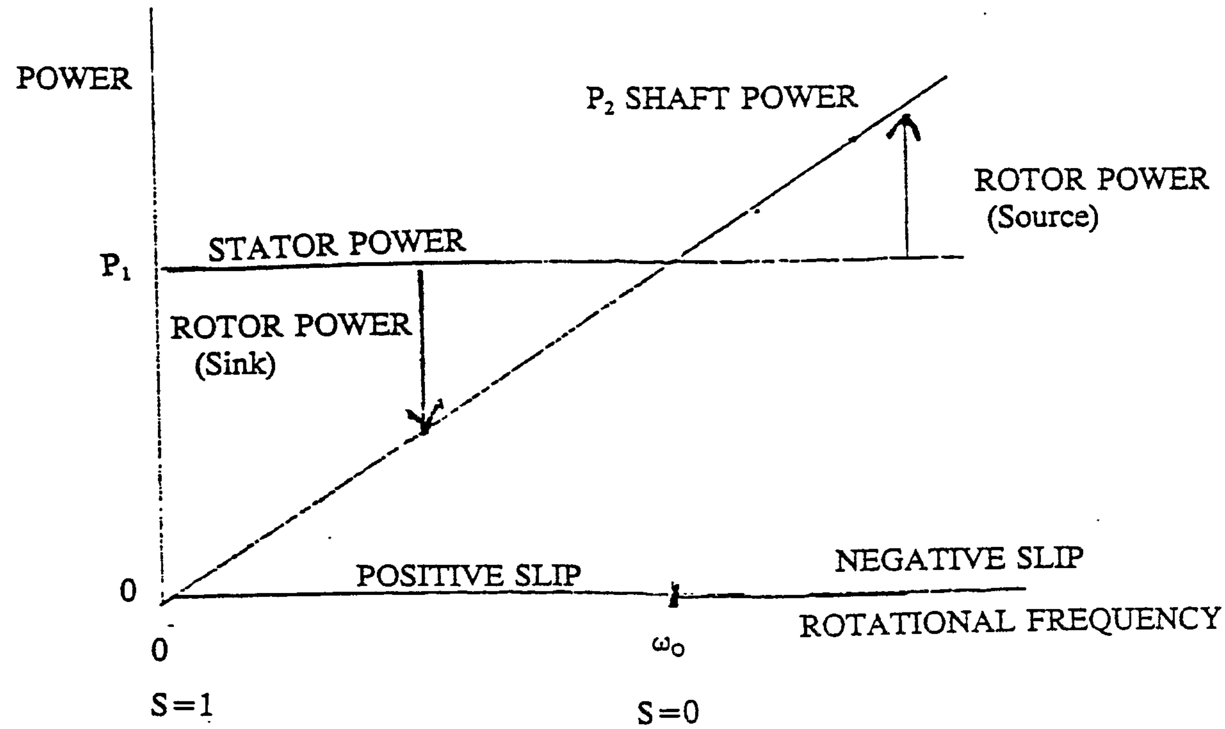


Figure D-1

Power Flow

The transformation ratio for real power flow also holds for reactive power flow between rotor and stator. For both cases

$$\frac{P_{STATOR}}{P_{ROTOR}} = \frac{1}{s}$$

The impedance transformation between rotor and stator is

$$\frac{Z_{STATOR}}{R_{ROTOR}} = \frac{1}{a^2 s}$$

With blocked rotor (s = 1), the network properties of the motor reduce to the properties of a linear passive two port network.