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EVALUATION OF INDUCTION MOTOR PERFORMANCE USING AN ELECTRONIC POWER FACTOR CONTROLLER

Final Report

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A JOINT PROJECT FOR EVALUATION OF INDUCTION MOTORS WITH ELECTRONIC CONTROLS

Submitted By

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June 21, 1978

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National Aeronautics and Space Administration

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I. INTRODUCTION

The purpose of this study was to evaluate the concept of reducing the losses in an induction motor by electronically controlling the time interval between the zero crossing of the applied voltage and the zero crossing of the armature current. The first part of the study was to experimentally study the effect reducing the applied sinusoidal voltages below the rated value will have on power losses and power factor. Next the reduction in power losses using an electronic controller designed and built by the Marshall Space Flight Center was measured and those results compared to that obtained with sinusoidal voltages.

A third part of the work involved some modifications to the Marshall Space Flight Center designed controller. In addition a manually controlled electronic device which will not require that the motor be wye connected and the neutral available was designed and operated.

A fourth part is a brief look at the energy savings possible.

II. EXPERIMENTAL DATA

Four three-phase induction motors and one single-phase induction motor were tested. The 5 hp and 3 hp motors built by Louis Allis are of comparatively recent design. The 3 hp polyphase motor built by Wagner and the 1 hp polyphase unit built by General Electric are old motors reflecting the conservative design methods of that day; both motors ran cool under full-load. The 1.5 hp single-phase unit built by Century is also a rather old motor. Figures 1-34 and Tables 1-5 give the results of these tests.

The procedure was to first test the motors with rated applied voltage, varying the torque from full load to no load. Next the torque was held constant and the voltage reduced until the motor almost stalled. Third as the torque was reduced from full load to no load a variac was adjusted to maintain consistent power factor. The same test was made using an electronic device designed at Auburn University and manually adjusted to maintain a fixed time interval between the voltage and current zero crossings. Last, all the polyphase units were tested using the electronic controller designed at Marshall Space Flight Center. It was not used with the single-phase unit because of the voltage rating.

The curves of input power versus torque, one with a constant supply voltage and one with the electronic controller active, were conducted in a manner to minimize changes in voltage and torque

settings for the two conditions. First the torque and supply voltages were set with the electronic controller active and measurements taken. Then with no adjustments, the controller was shorted with a three-phase switch, and the measurements retaken. All measurements were taken on the supply side so that losses in the controller are included.

The data is presented in percentage form since primary interest was on relative magnitudes. For nonsinusoidal voltages and currents the power factor is computed as the ratio of real power to apparent power.

The data correlates fairly well. Some differences result from using different types of instruments. Also some tests were run with an ambient temperature in the sixties (°F) and some with an ambient temperature in the eighties. All the polyphase motors exhibited some unbalance. The torque read out was digital with a minimum increment of one inch-pound. The data in the tables was taken using standard General Electric ammeters, voltmeters and wattmeters. The power in each phase was measured.

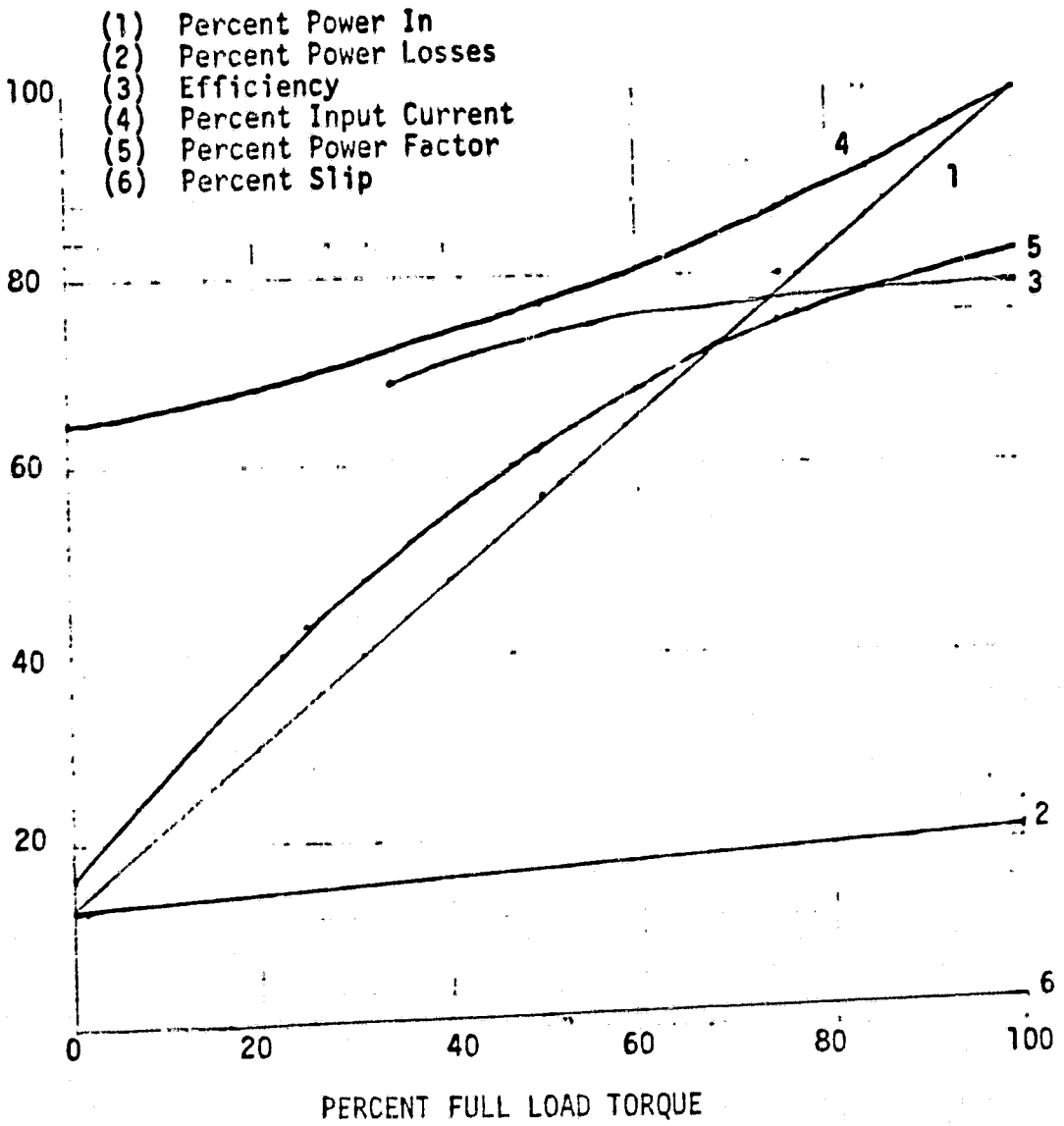

Figure 1. Rated Voltage Test

5 HP, 3¢, 208-220/440 V
3445 RPM
Pacer (Louis Allis)

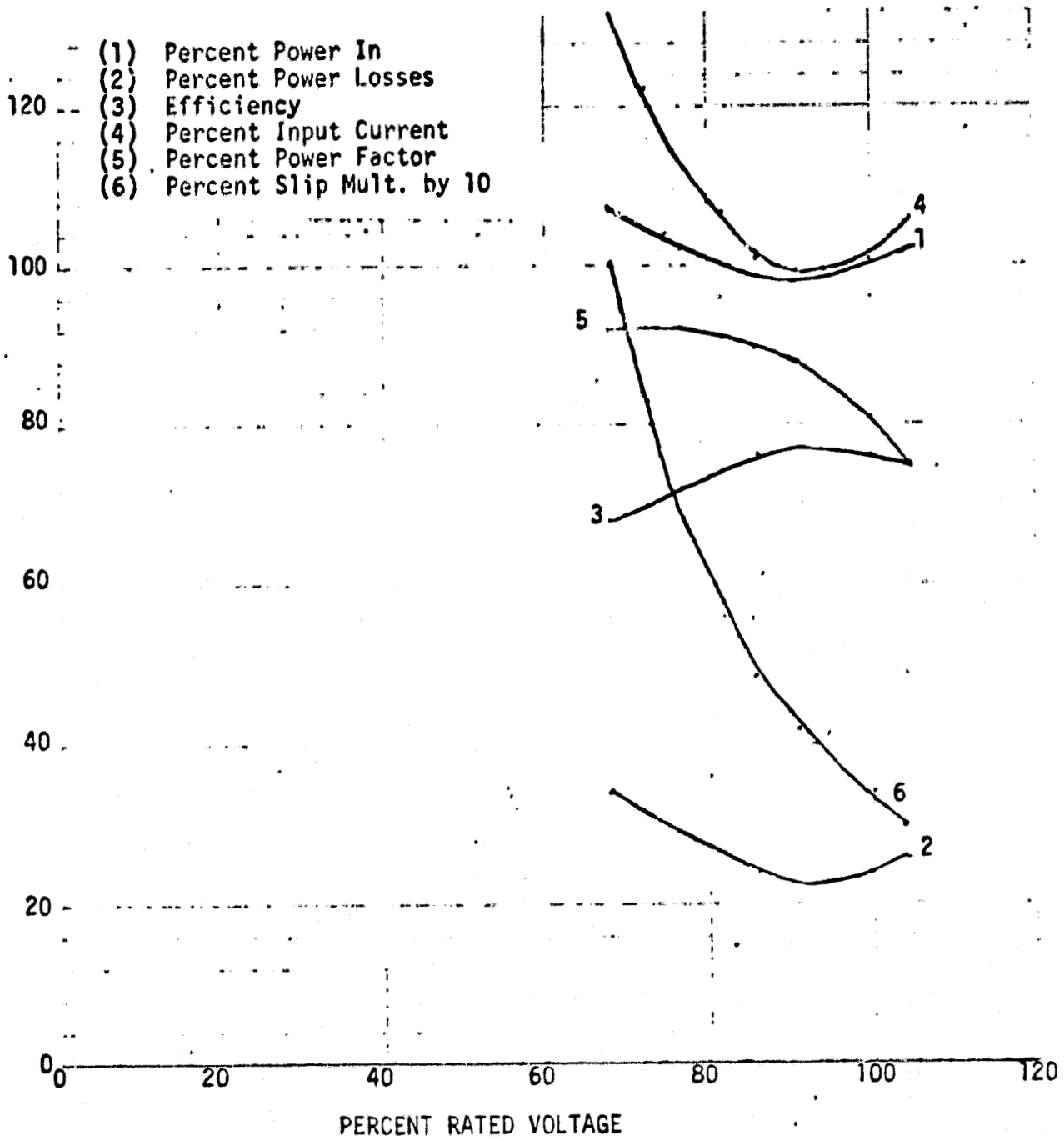

Figure 2. Constant Voltage Test: 100% Torque
5 HP 3ϕ Pacer
208-220/440 V
3445 RPM

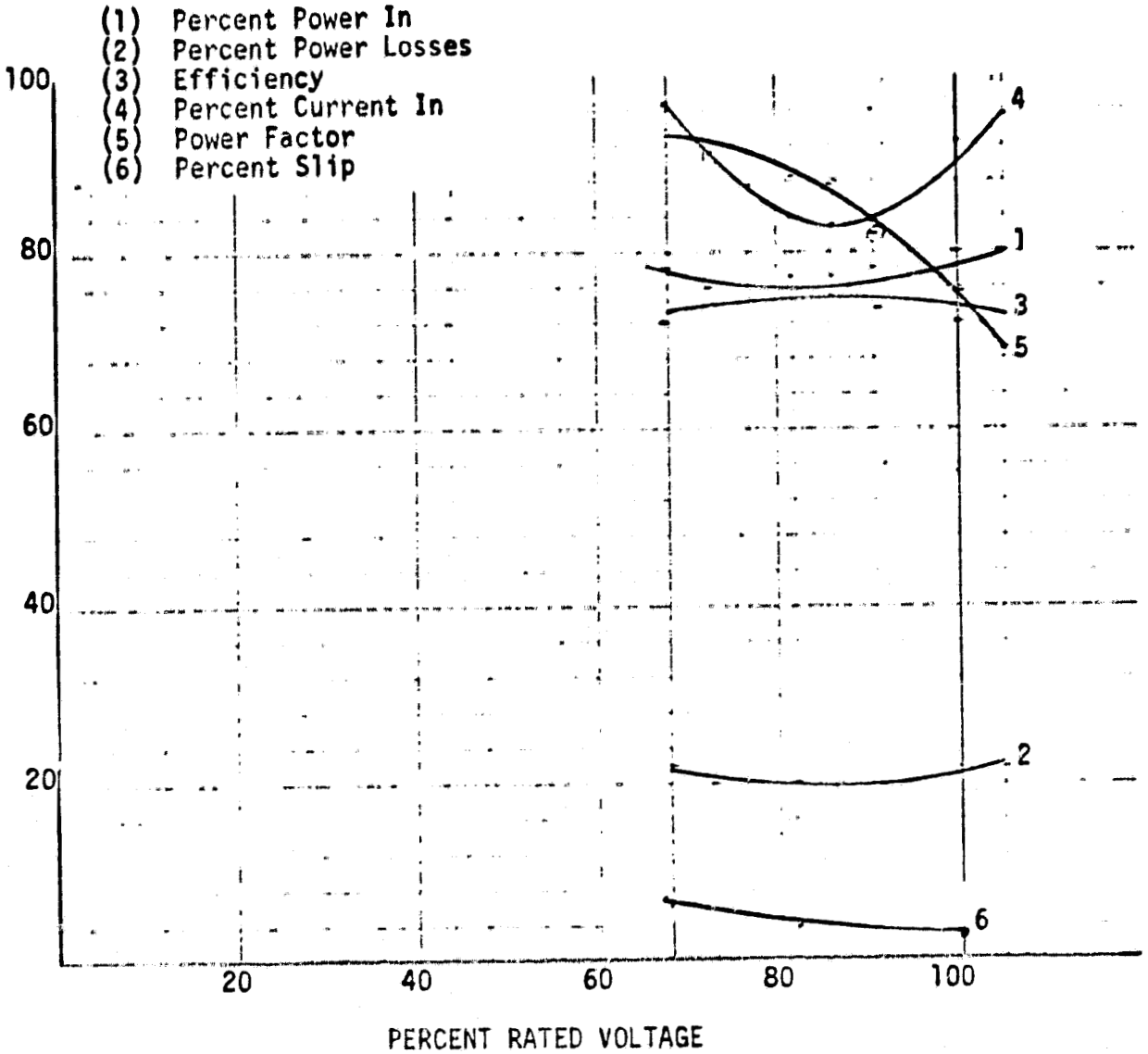

Figure 3. Constant Torque Test: 75% Torque
5 HP 3ϕ Pacer
208-220/440 V
3445 RPM

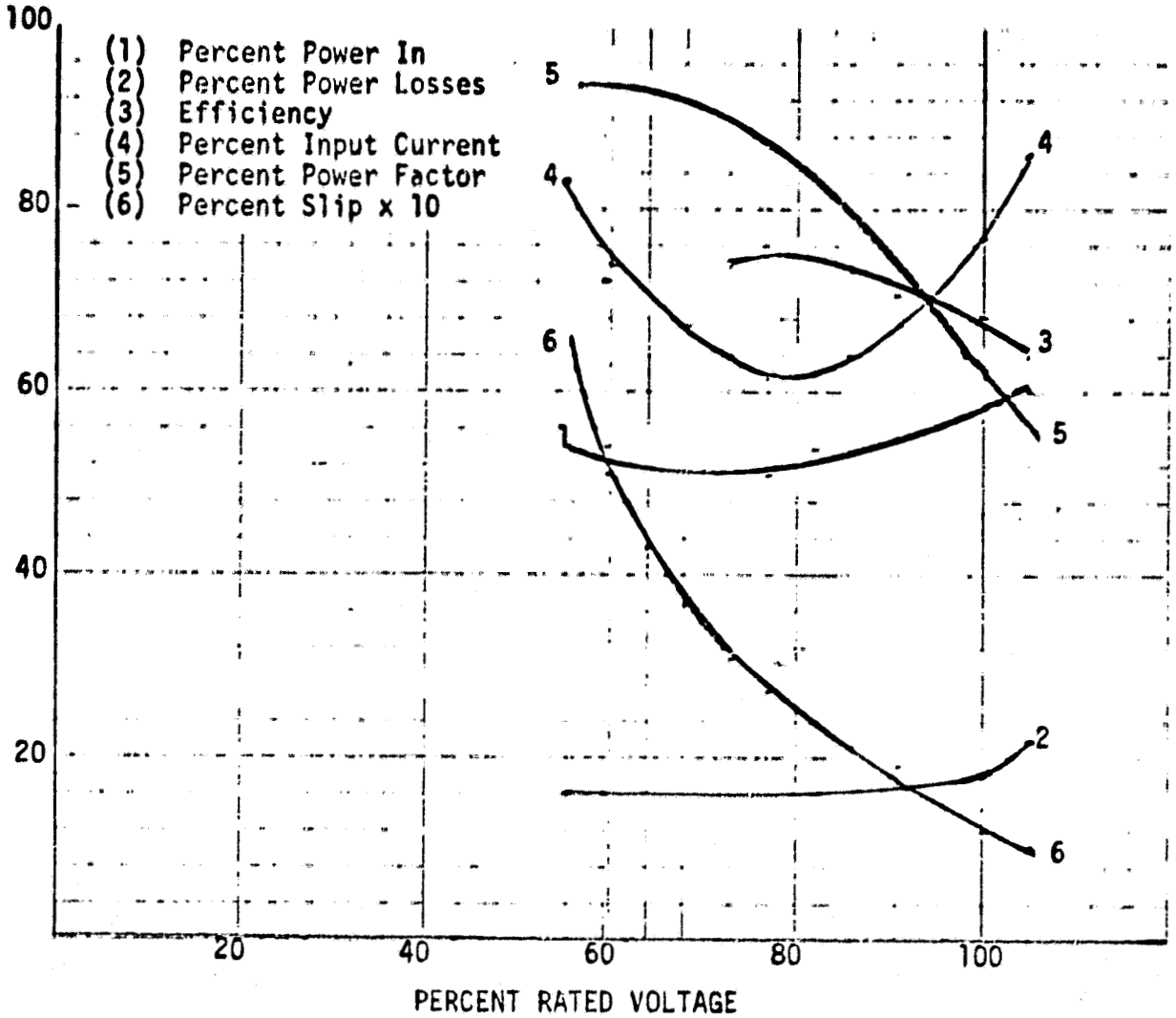

Figure 4. Constant Torque Test: 50% Torque

5 HP 3¢ Pacer
208-220/440 V
3445 RPM

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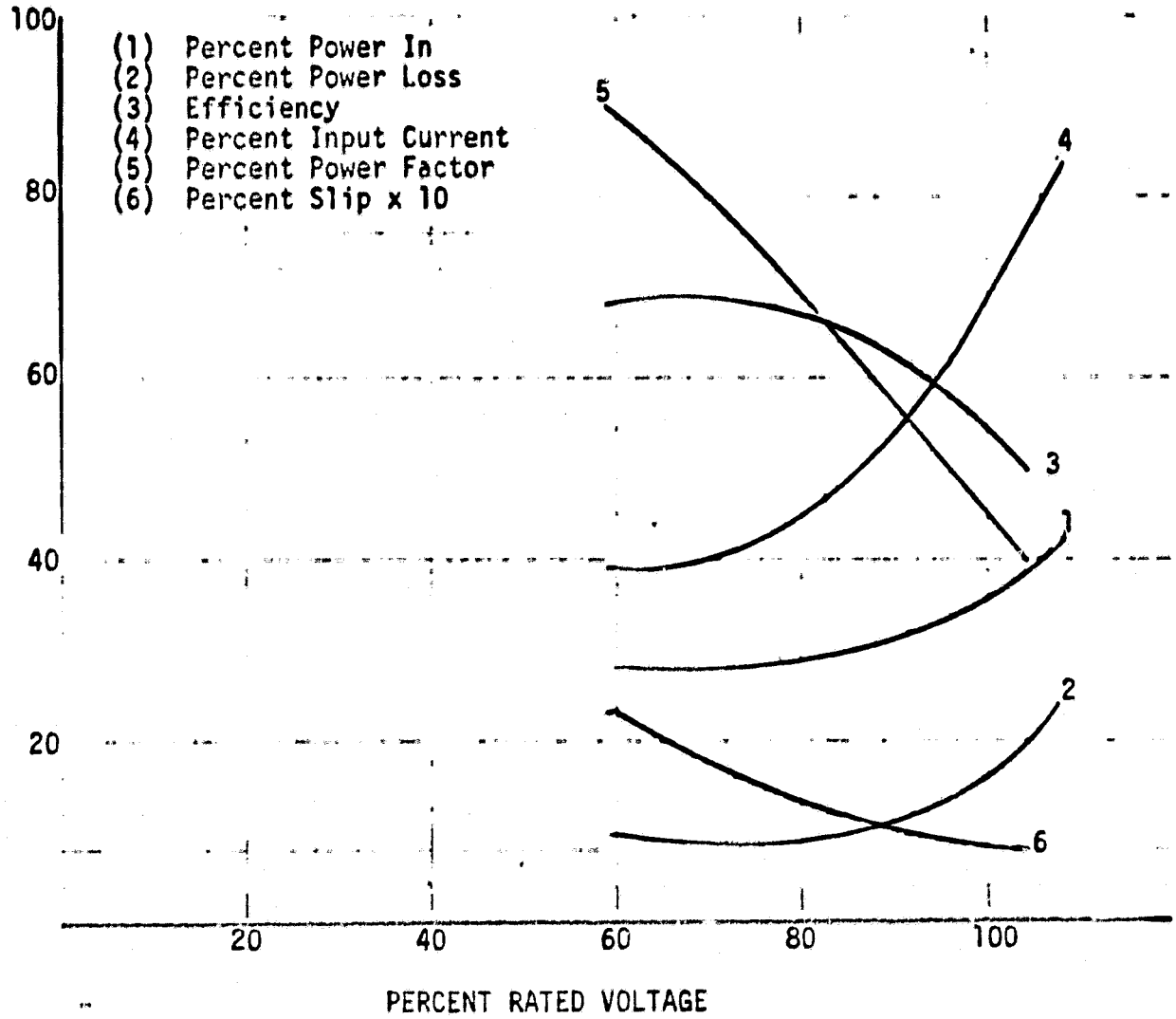

Figure 5. Constant Torque Test: 25% Torque
5 HP 3ϕ Pacer
208-220/440 V
3445 RPM

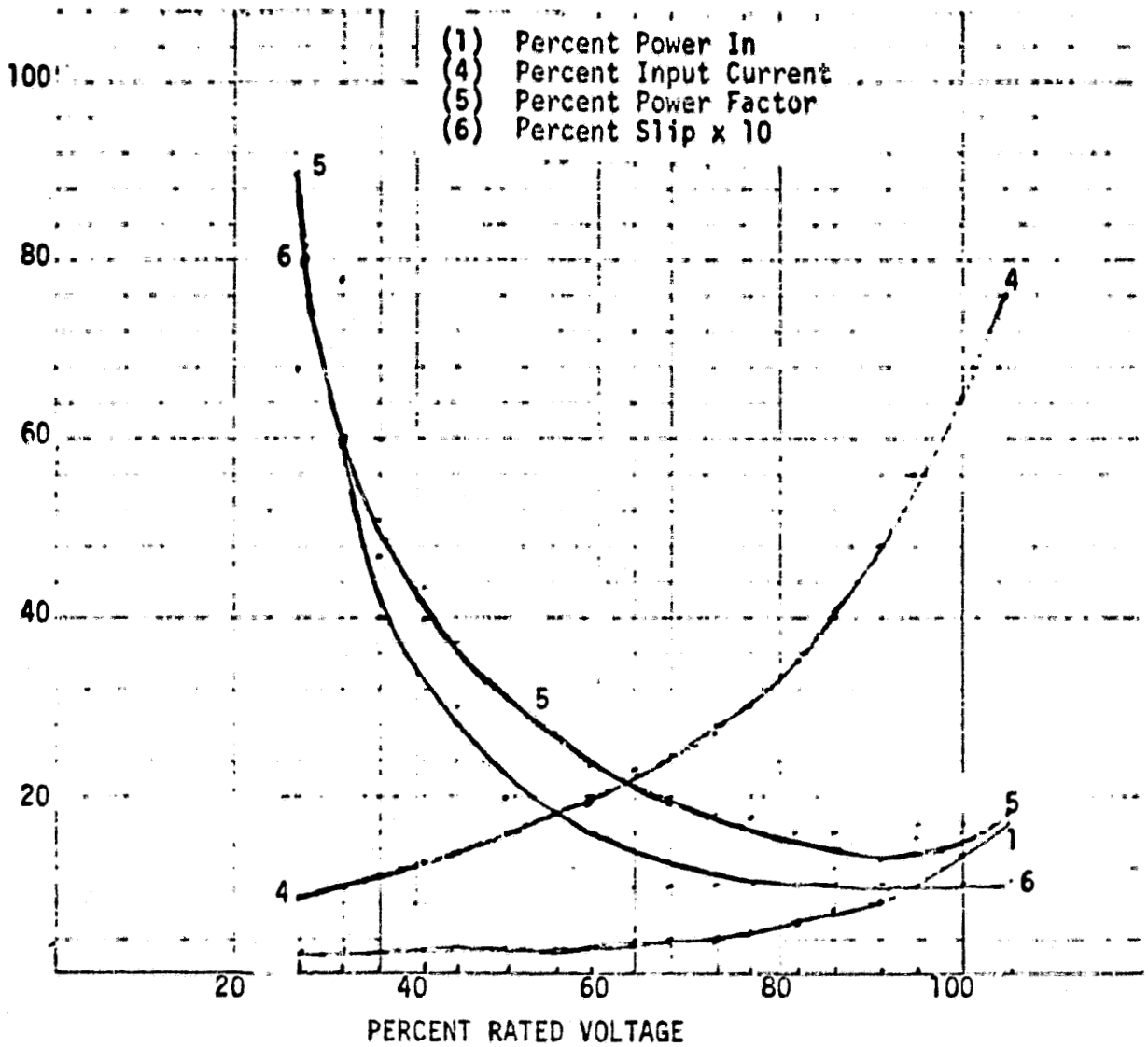

Figure 6. Constant Torque Test: No Load
5 HP 3ϕ Pacer
208-220/440 V
3445 RPM

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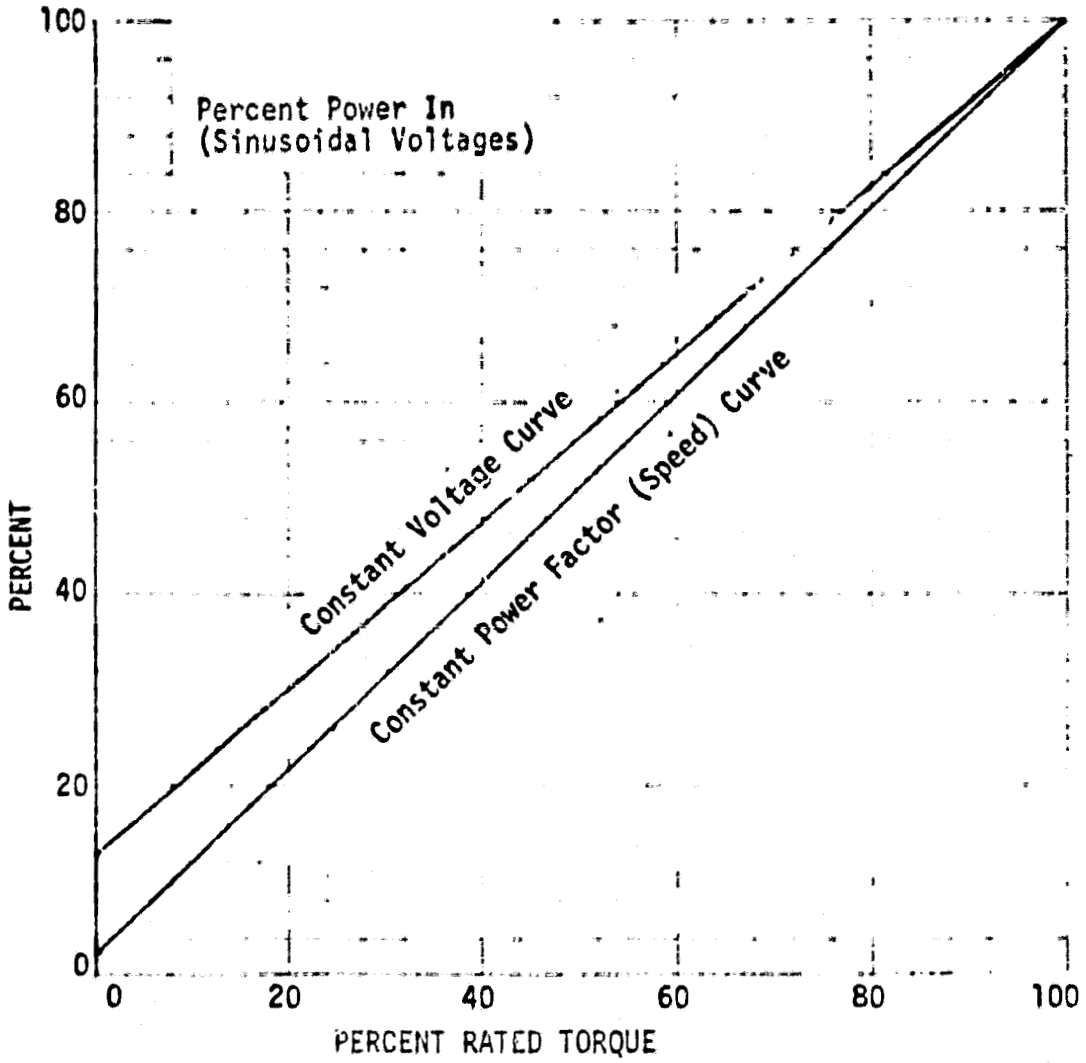

Figure 7. Constant Voltage/Constant Power Factor Test
5 HP 3ϕ 208-220/440
3445 RPM
Pacer

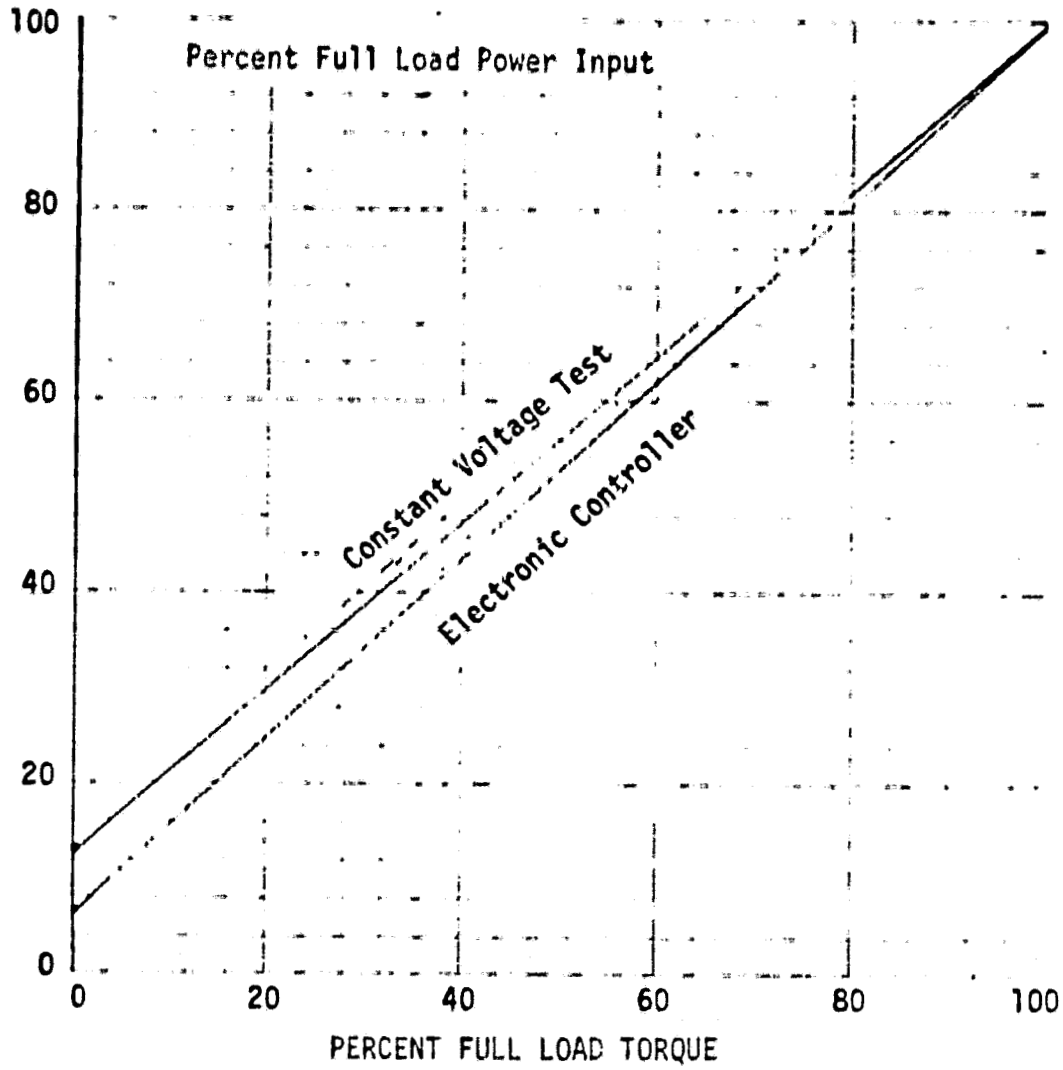

Figure 8. Constant Voltage/Electronic Controller Test.
5 HP 3¢ 220 V
3445 RPM
Pacer

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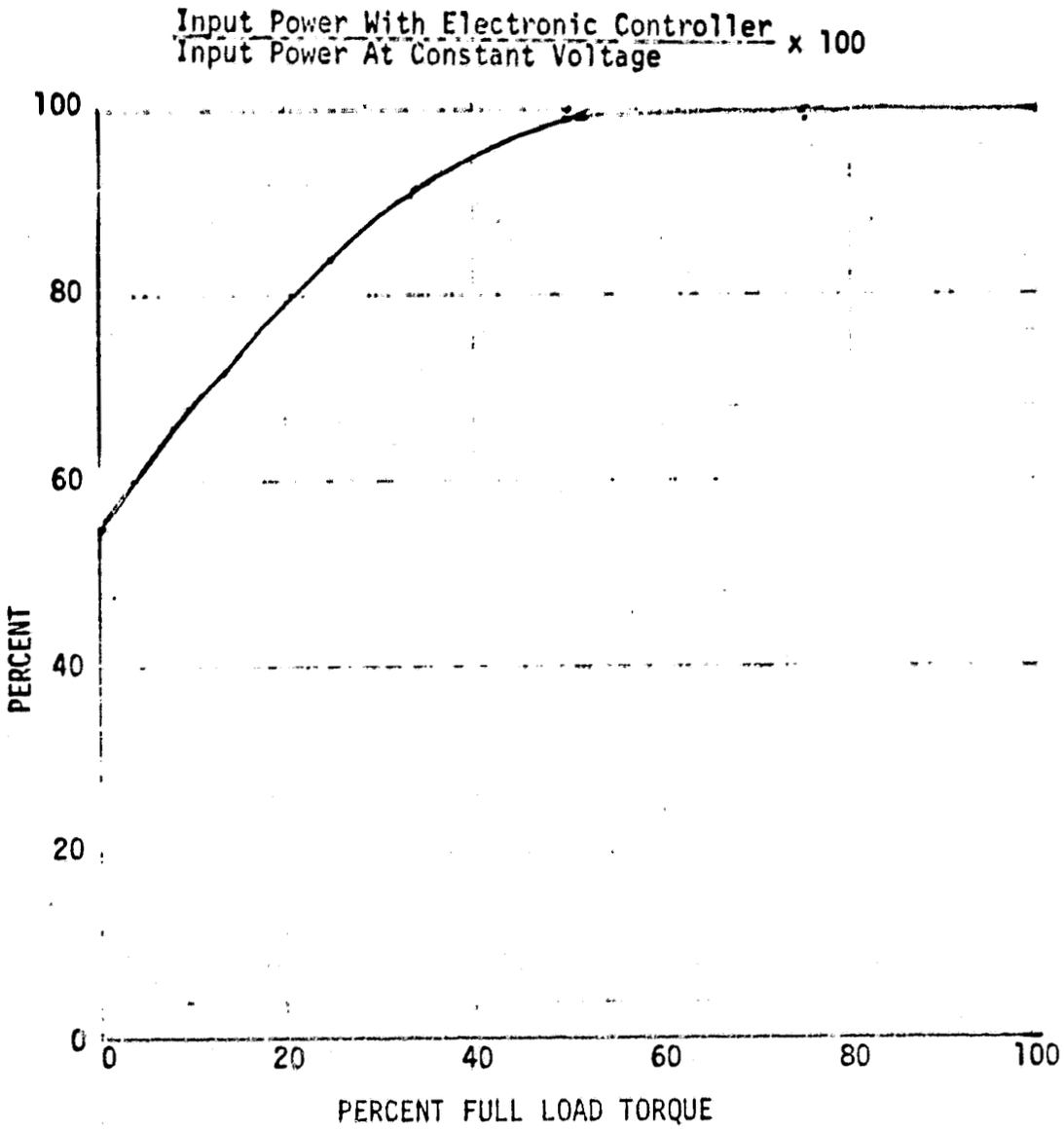

Figure 9. Input Power Reduction with Electronic Controller
5 HP 3ϕ 220 V
3445 RPM
Pacer (Louis Allis)

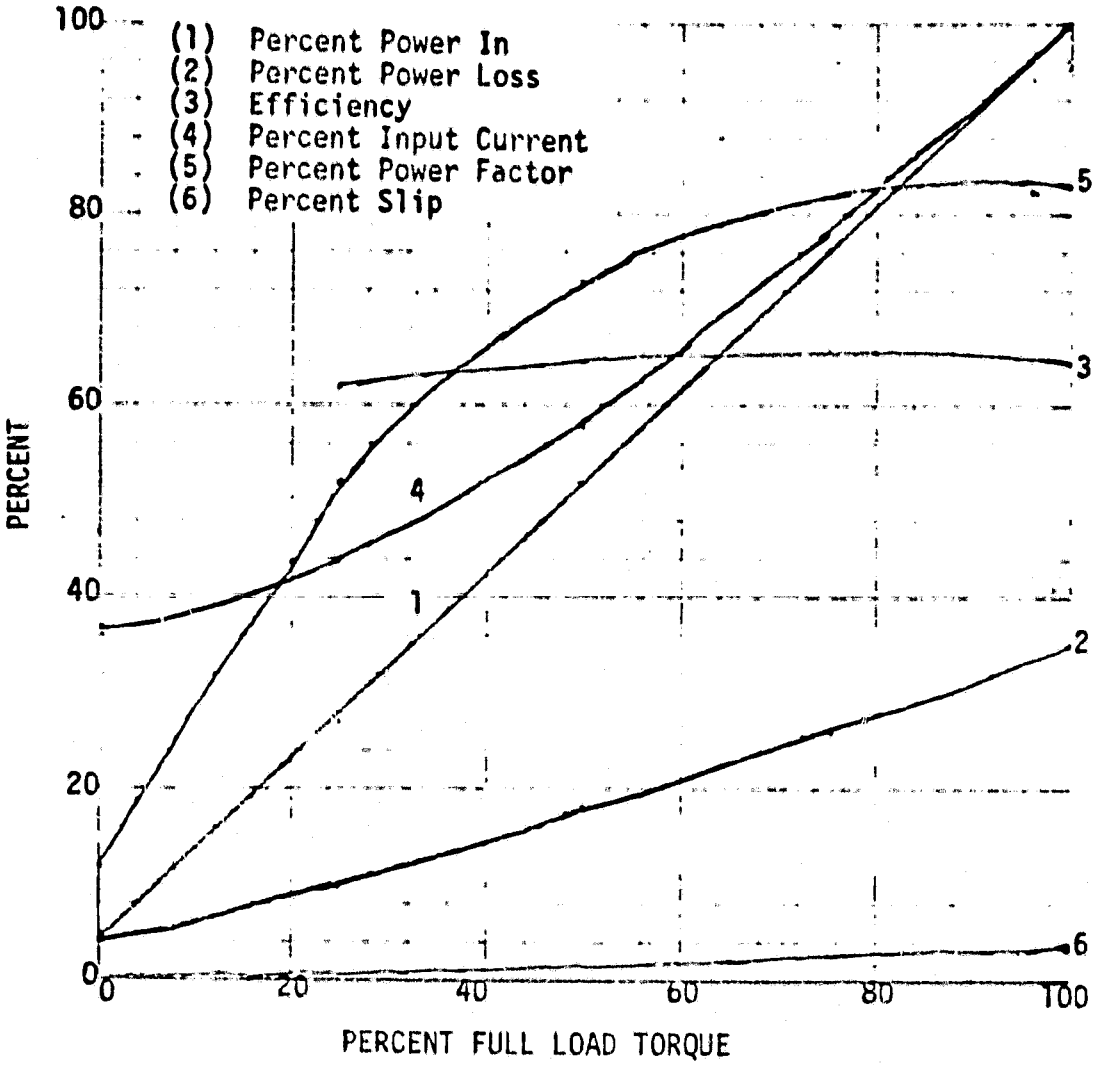

Figure 10. Rated Voltage Test
3 HP 3ϕ 220 V
1750 RPM
Wagner

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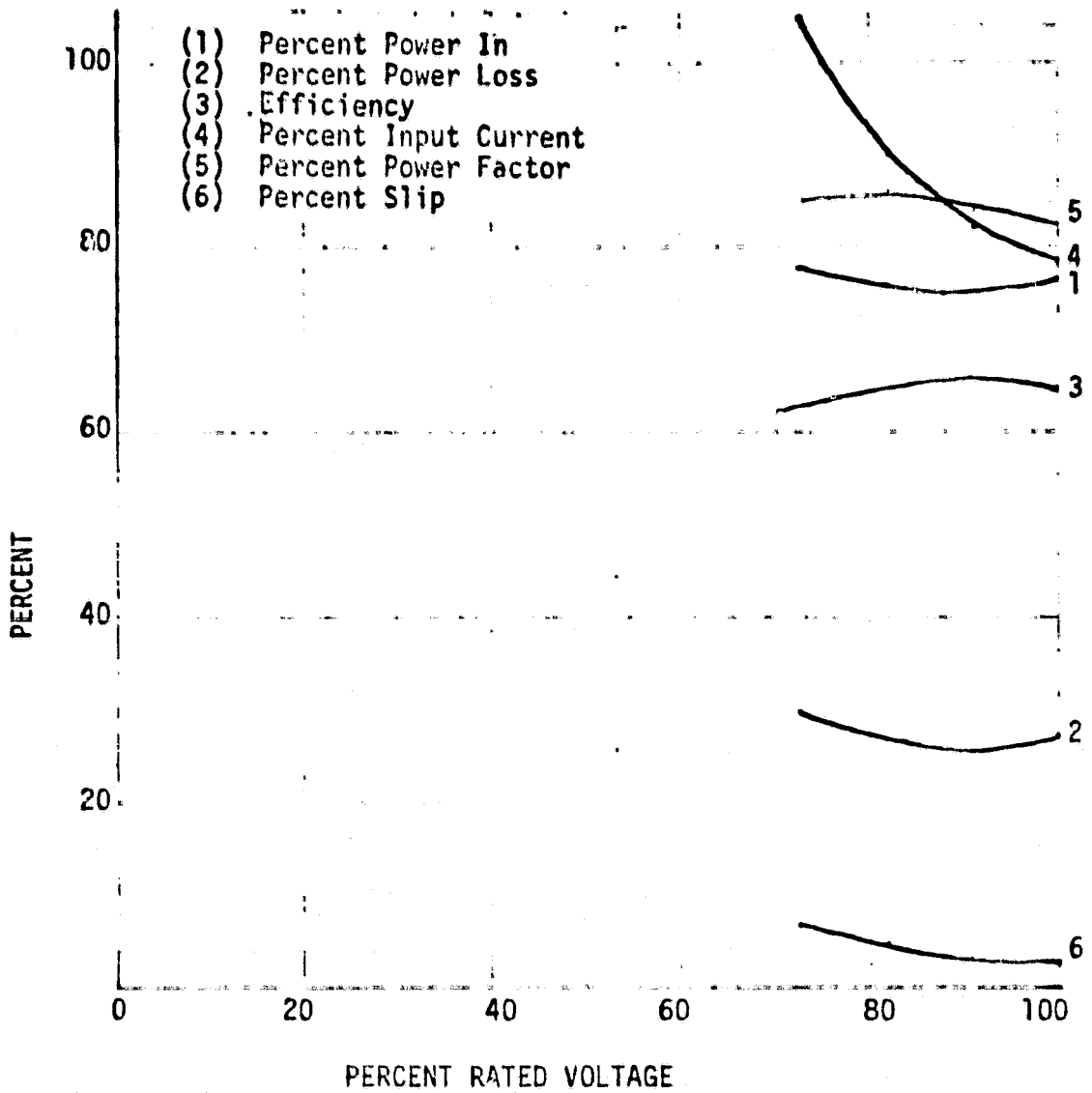

Figure 11. Constant Torque Test: 100% Torque
3 HP 3φ 220 V
1750 RPM
Wagner

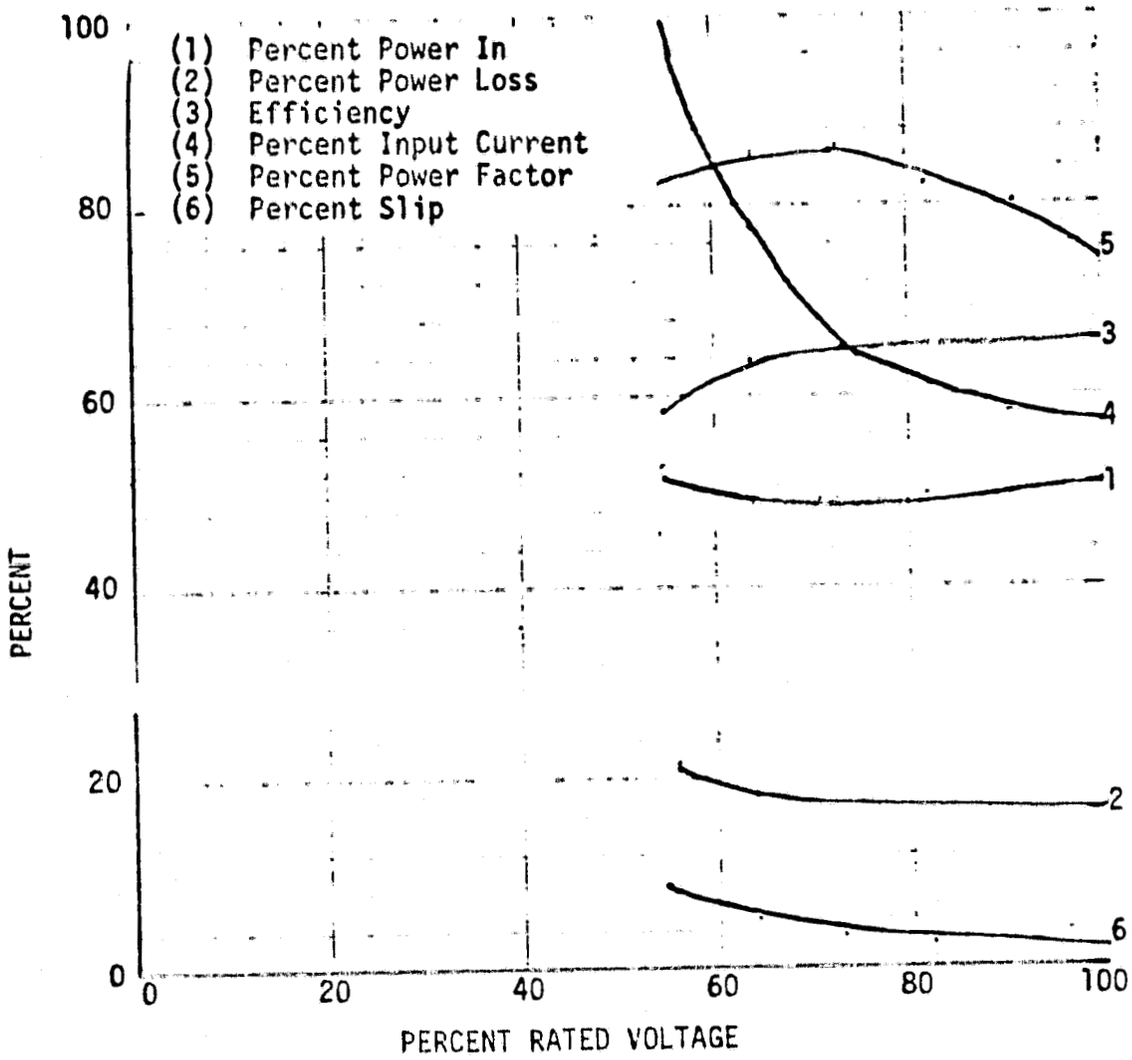

Figure 12. Constant Torque Test: 50% Torque
3 HP 3ϕ 220 V
1750 RPM
Wagner

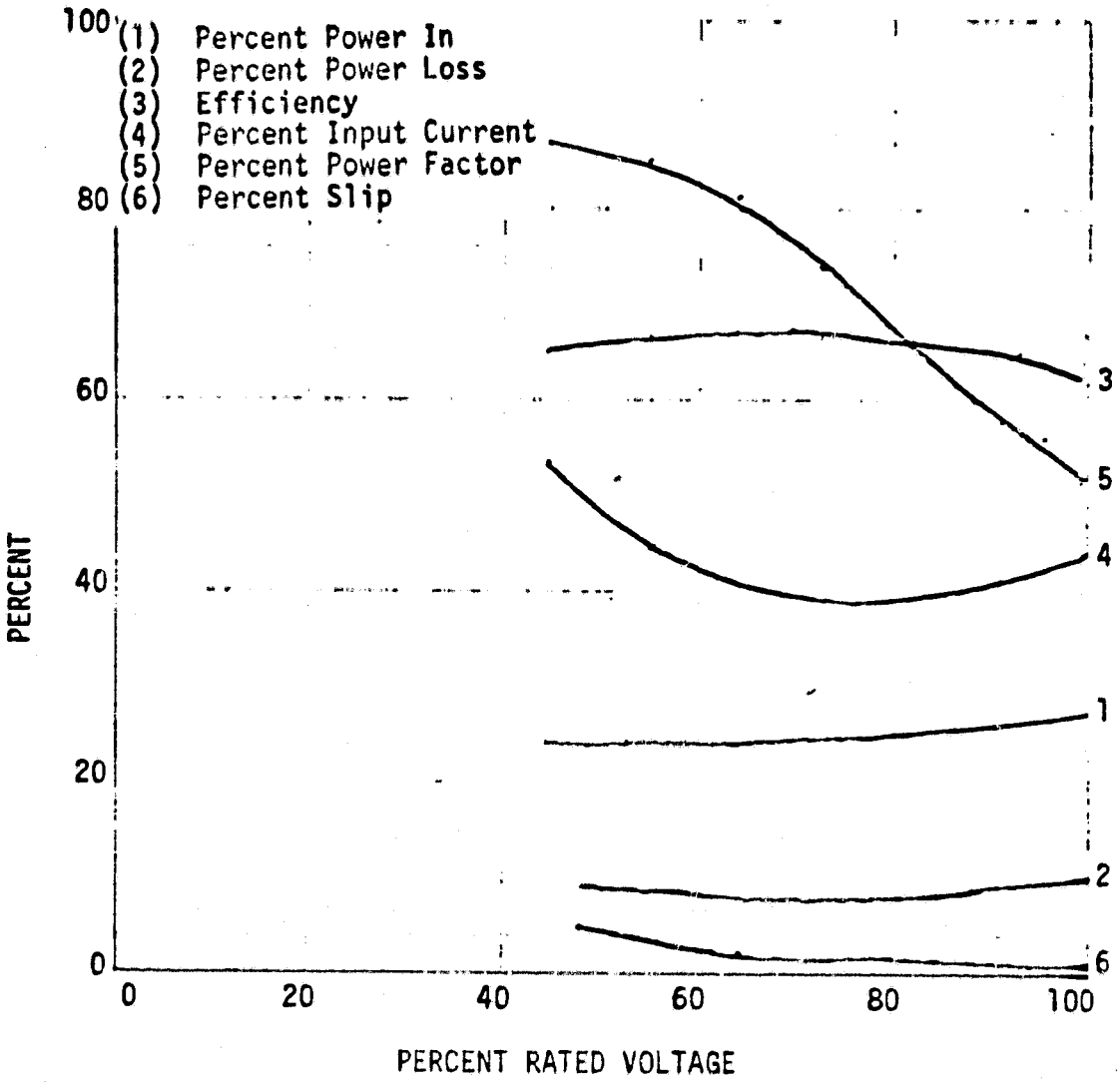

Figure 13. Constant Torque Test: 25% Torque
3 HP 3Φ 220 V
1750 RPM
Wagner

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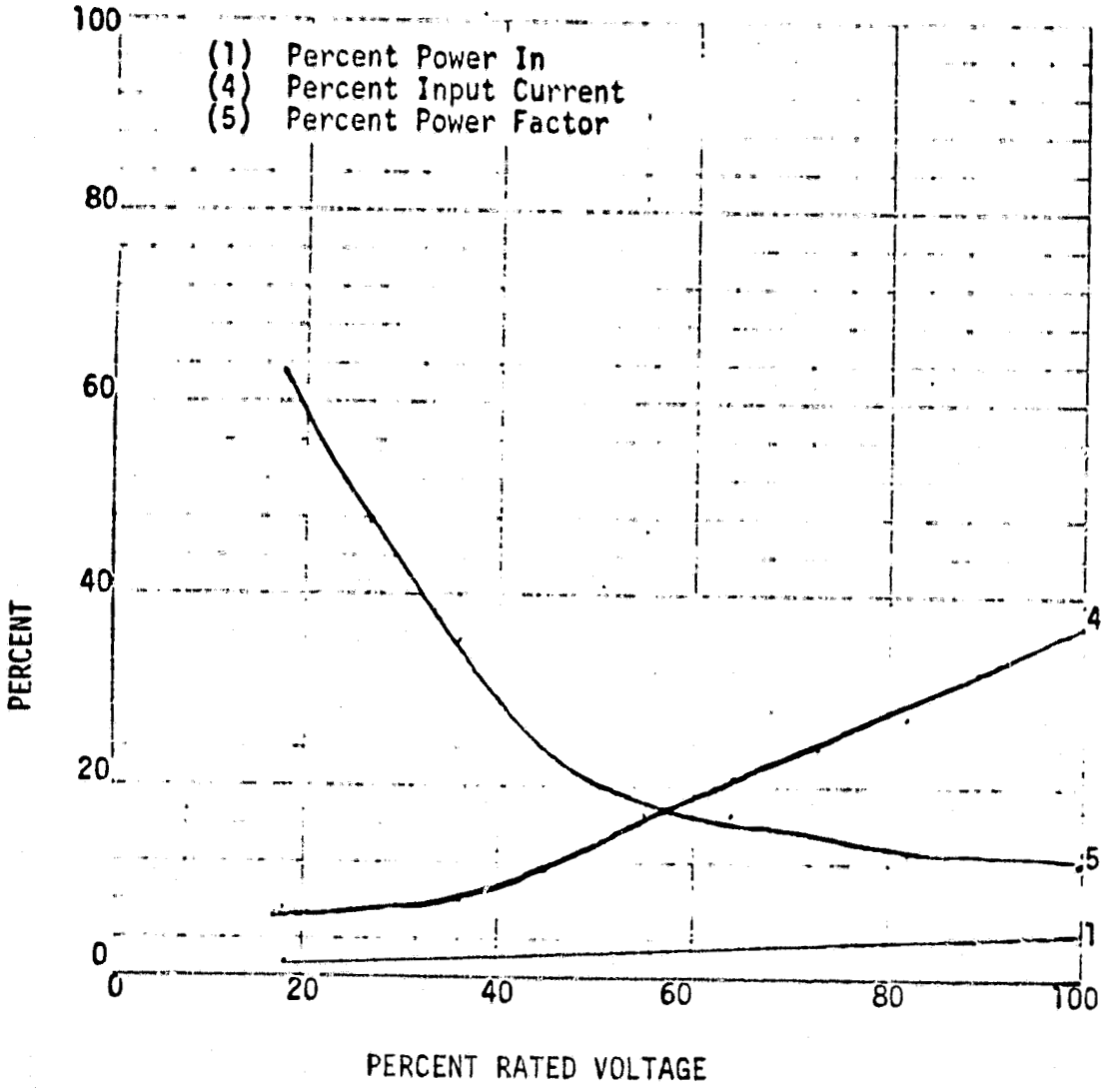

Figure 14. Constant Torque Test: No Load
3 HP 3ϕ 220 V
1750 RPM
Wagner

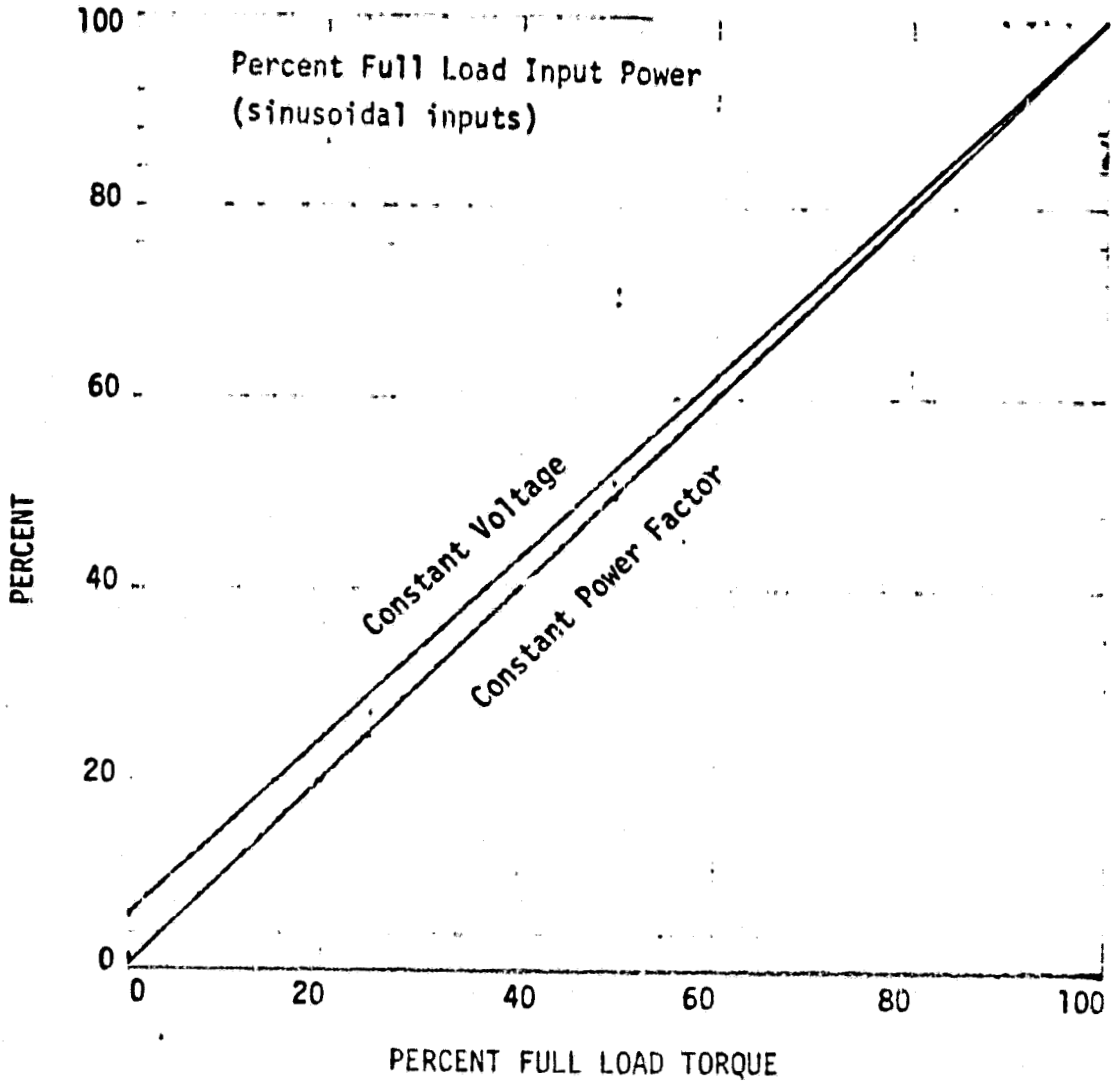

Figure 15. Constant Voltage/Constant Power Factor Test
3 HP 3ϕ 220 V
1750 RPM
Wagner

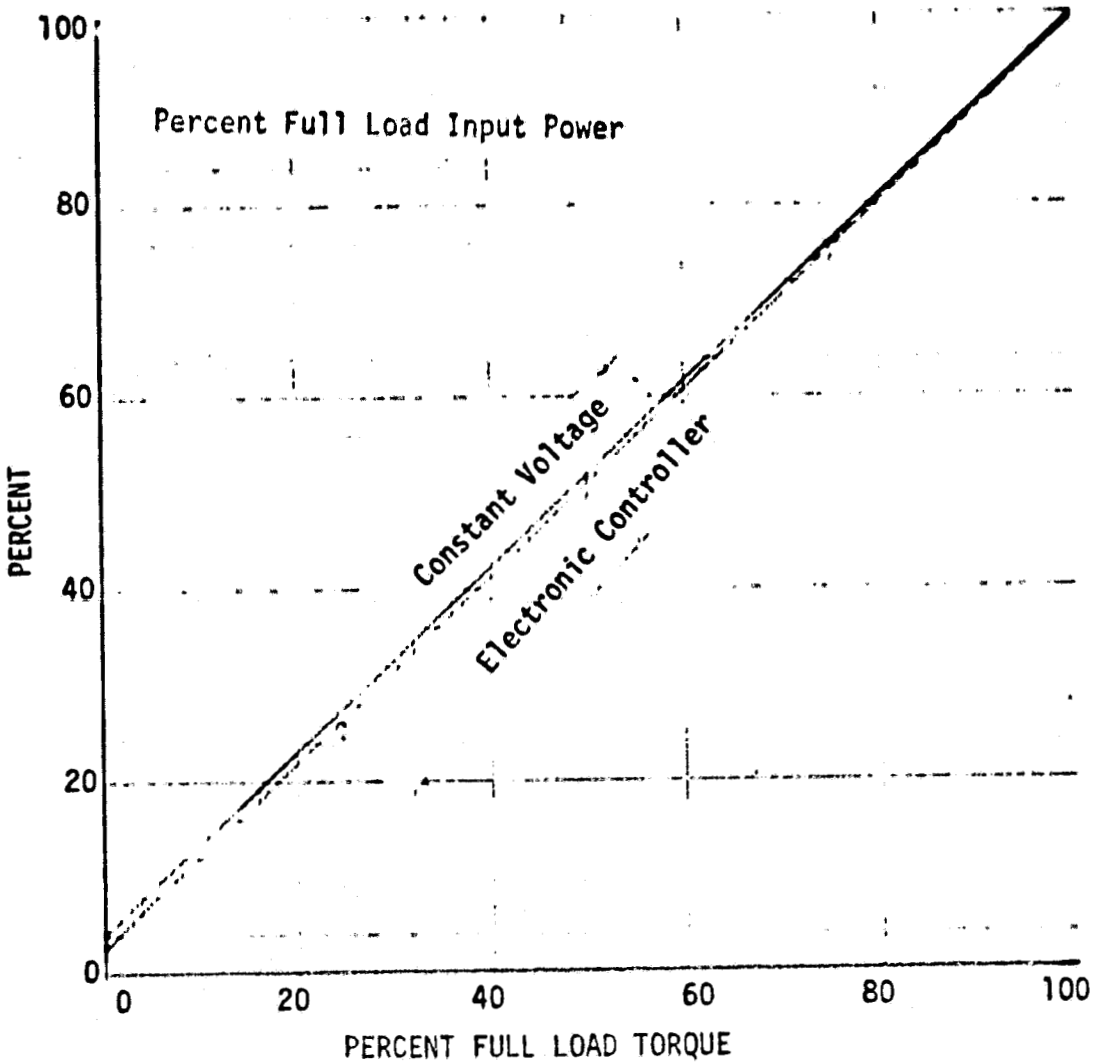

Figure 16. Constant Voltage/Electronic Controller Test
3 HP 3ϕ 220 V
1750 RPM
Wagner Induction Motor

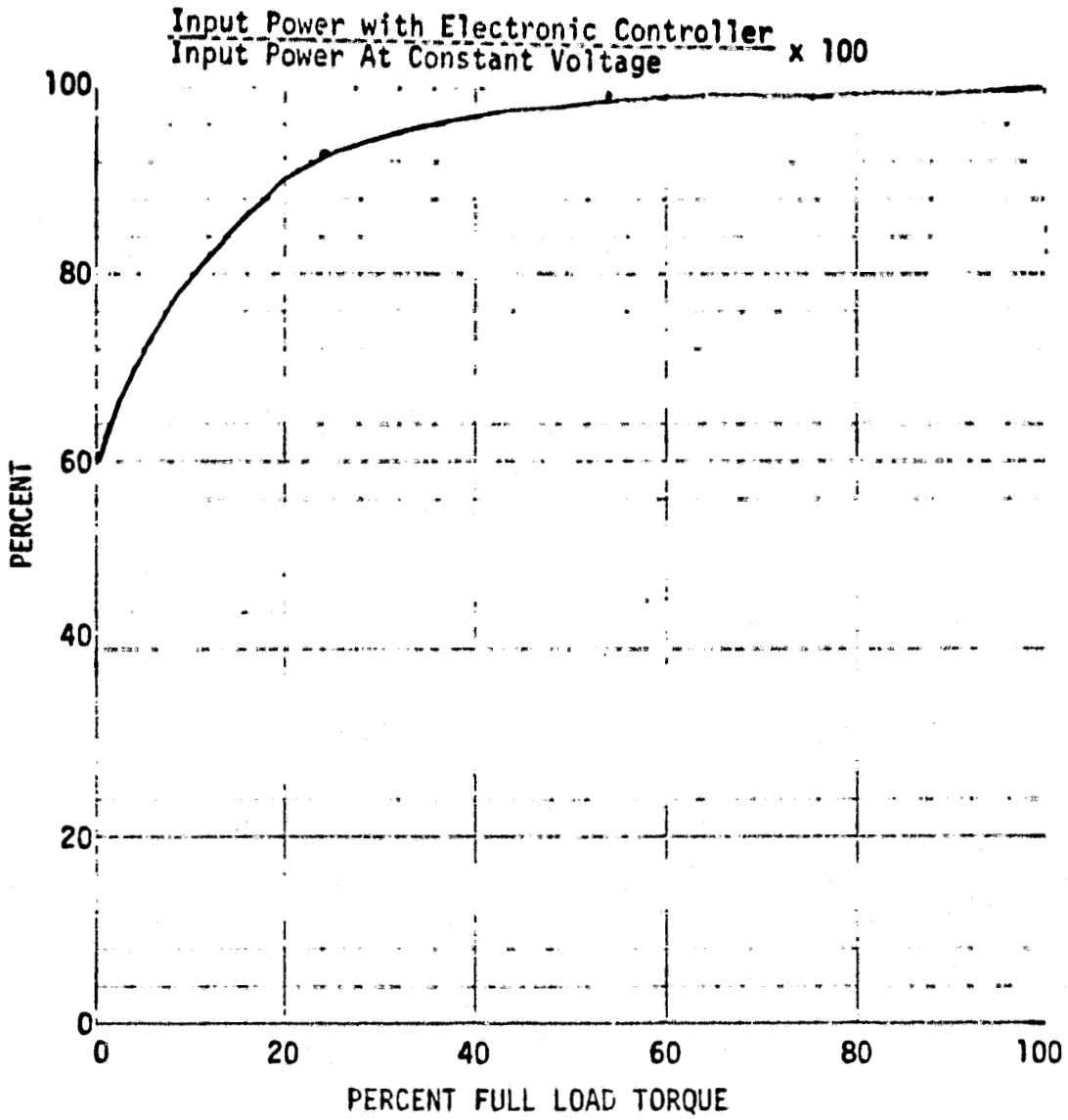

Figure 17. Input Power Reduction with Electronic Controller

3 HP 3ϕ 220 V
1750 RPM
Wagner Induction Motor

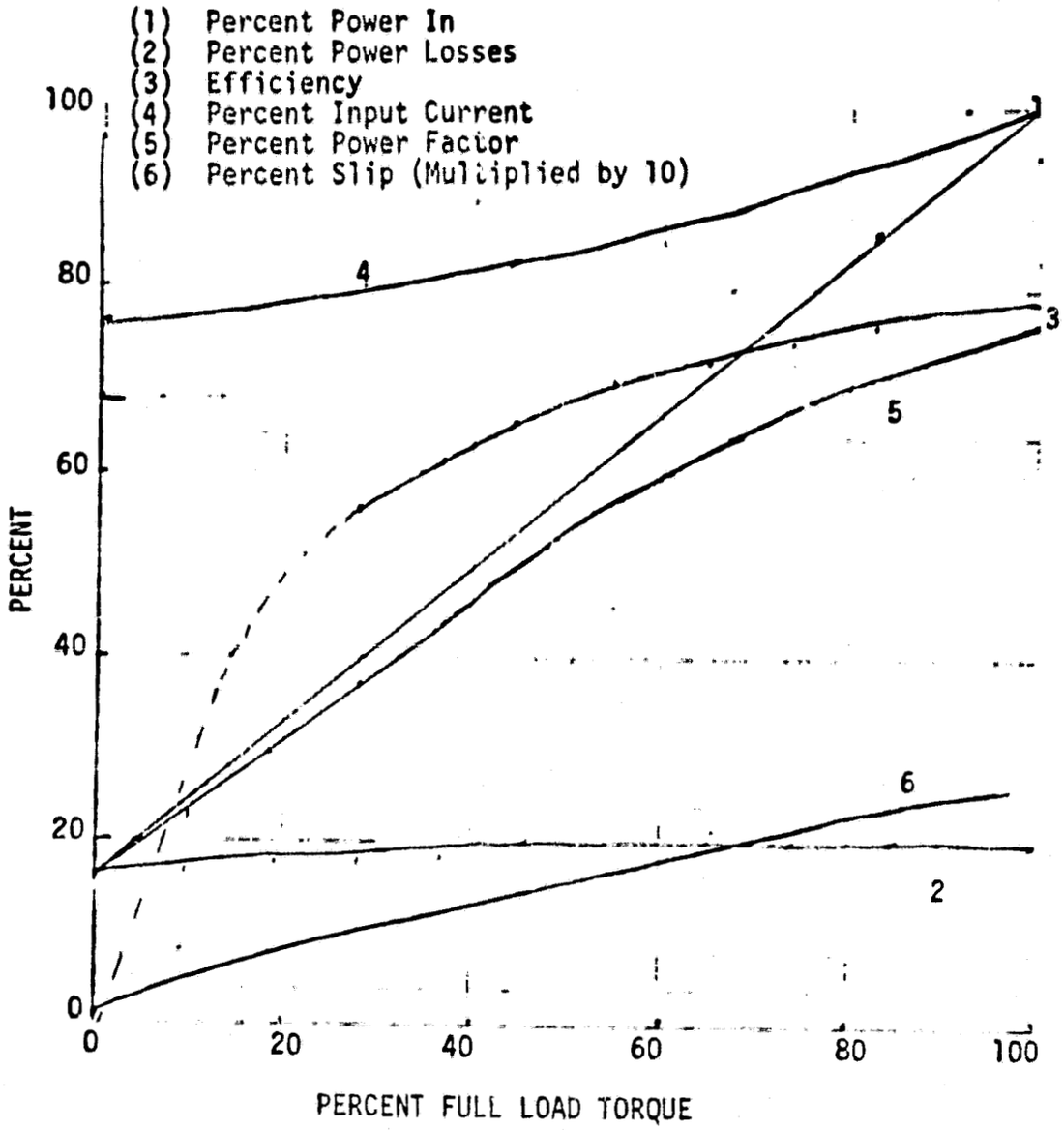

Figure 18. Rated Voltage Test
3 HP 220 V 3¢
1750 RPM
Pacer (Louis Allis)

T(F.L) = 108 in - lb
I(F.L) = 11.6A
P_{IN}(F.L.) = 2829 watts

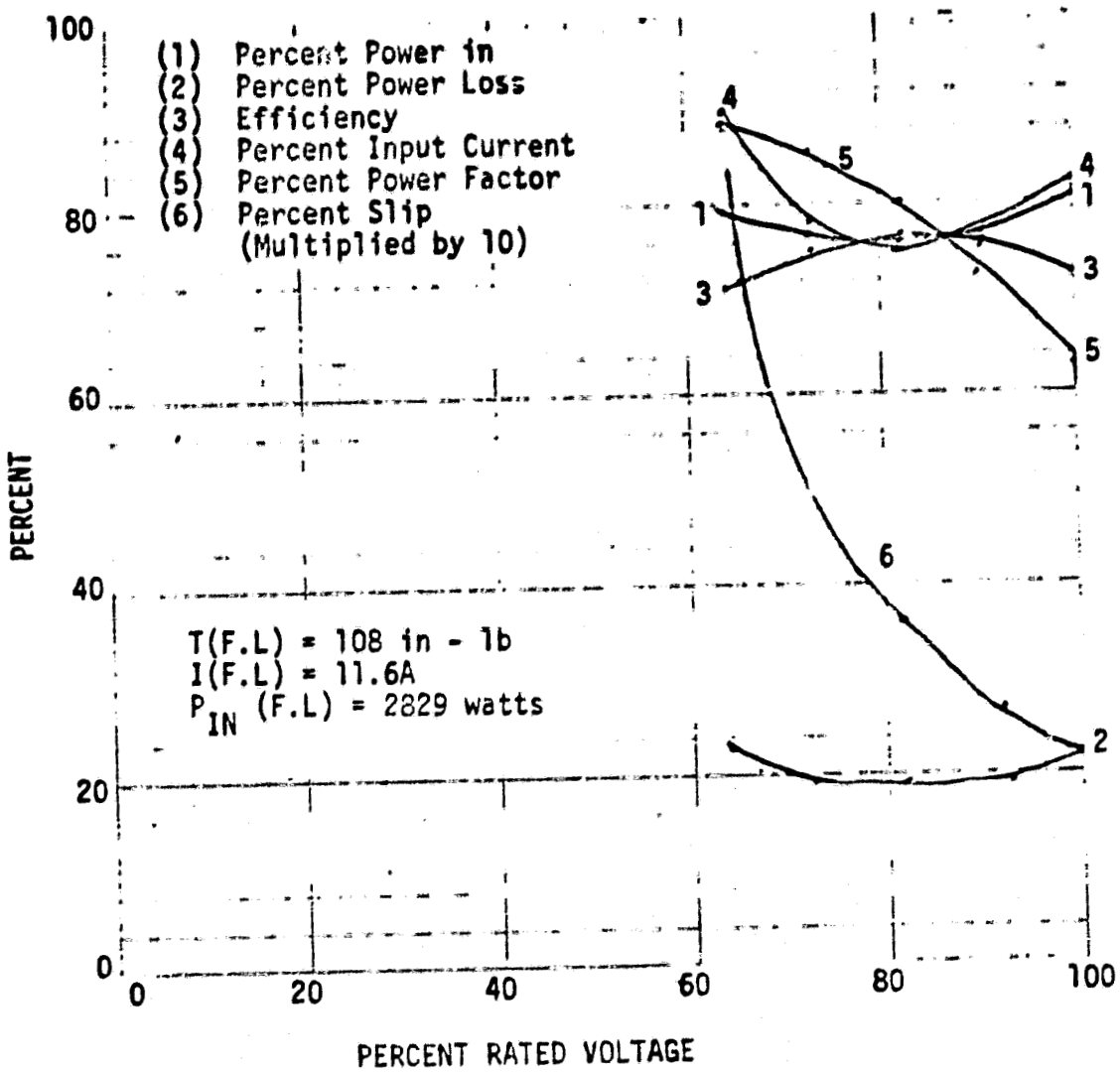

Figure 19. Constant Torque Test: 74% Torque
3 HP 220 V 3ϕ
1750 RPM
Pacer

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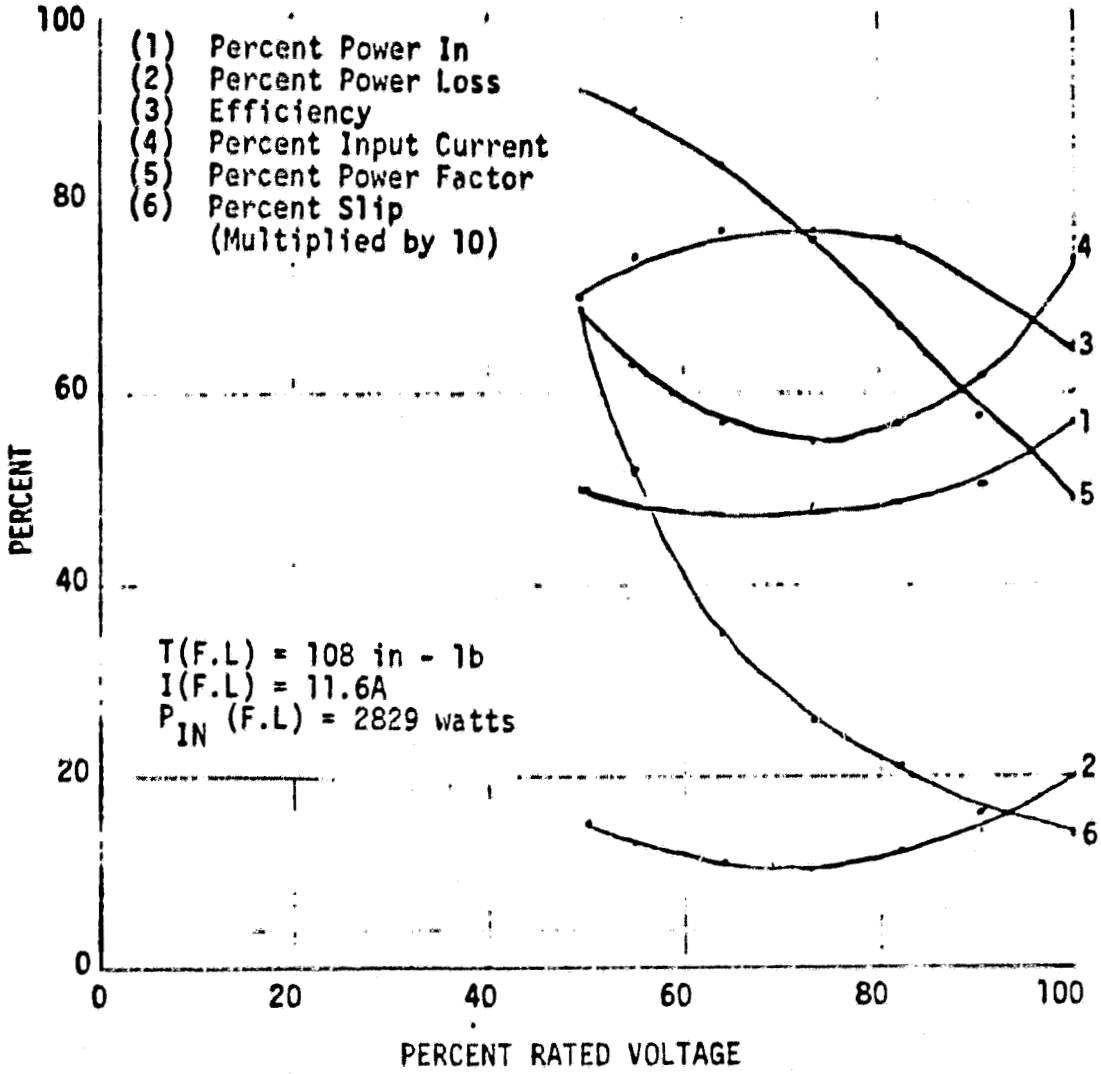

Figure 20. Constant Torque Test: 46% Torque

3 HP 220 V 3ϕ
1750 RPM
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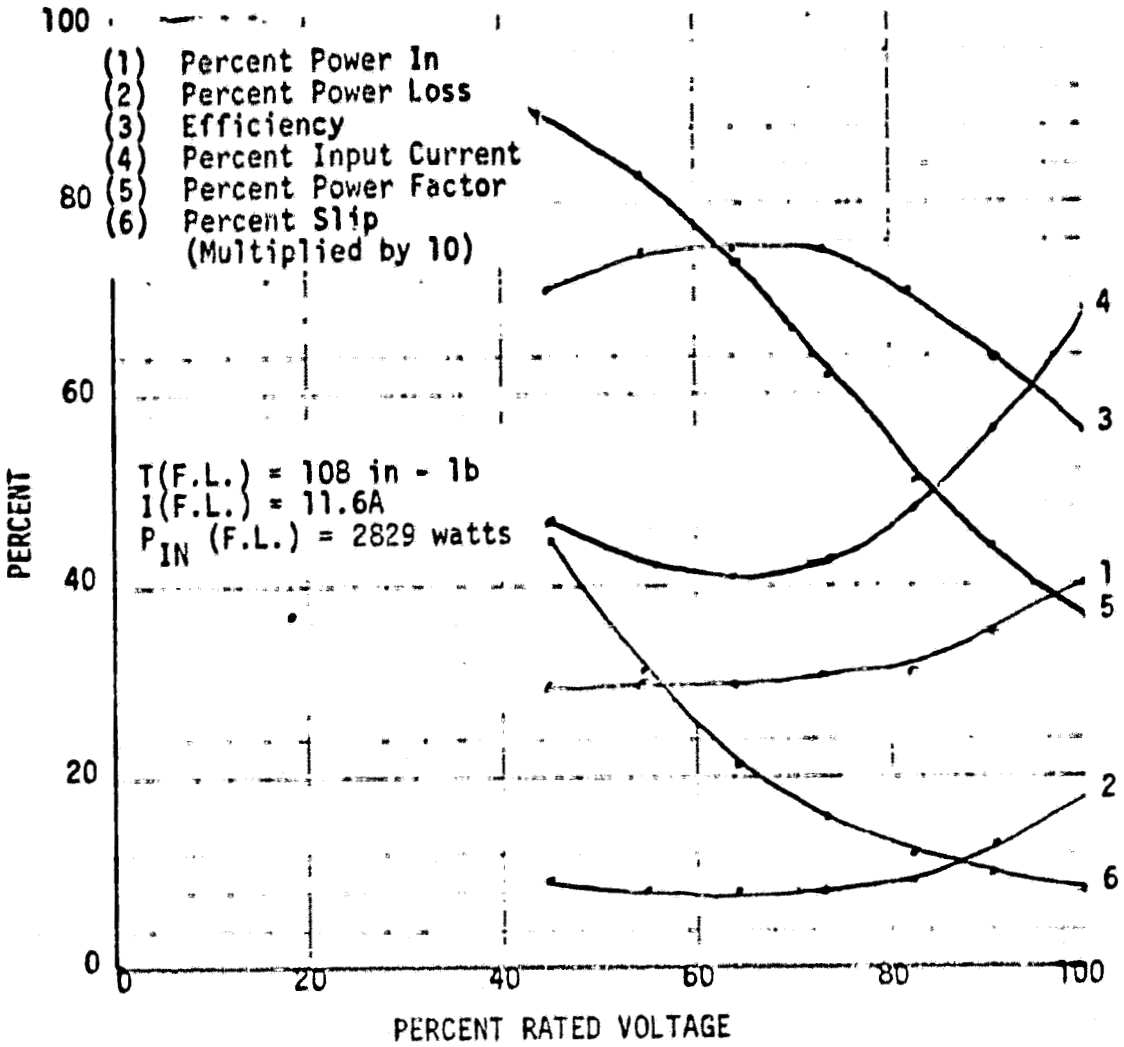

Figure 21. Constant Torque Test: 28% Torque
3 HP 220 V 3ϕ
1750 RPM
Pacer

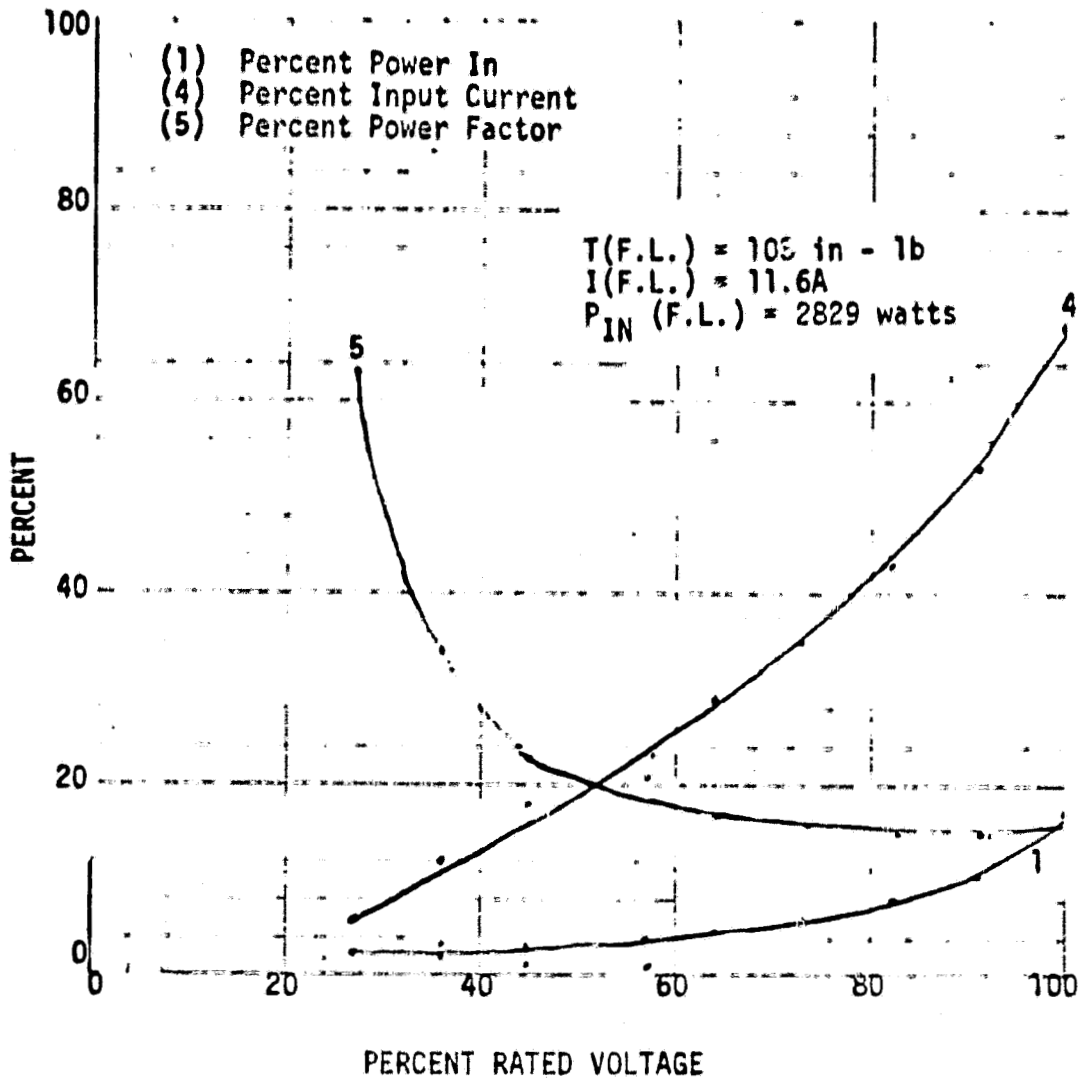

Figure 22. Constant Torque Test: No Load
3 HP 220 V 3φ
1750 RPM
Pacer

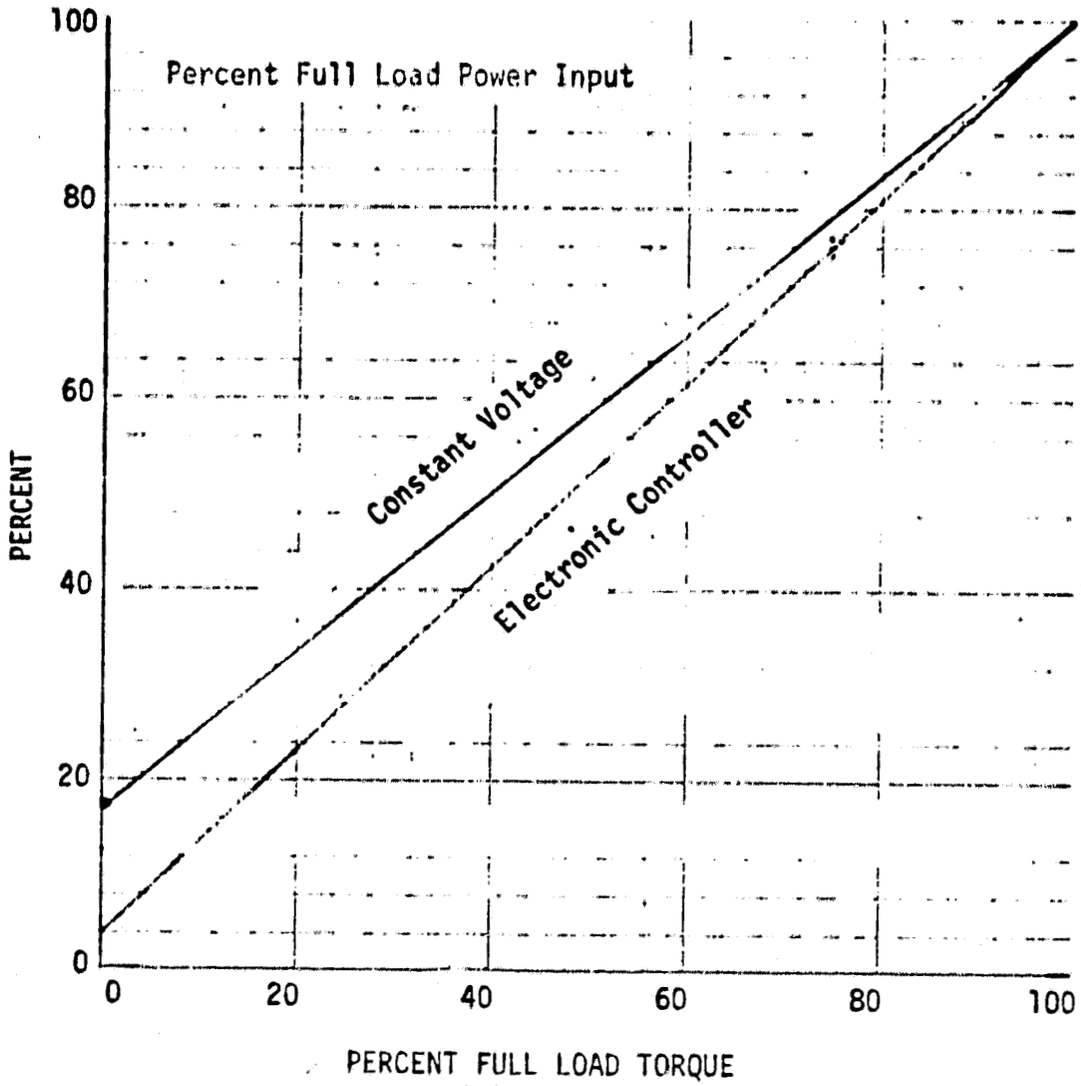

Figure 23. Constant Voltage/Electronic Controller Test
3 HP 3ϕ 220 V
1750 RPM
Pacer (Louis Allis)

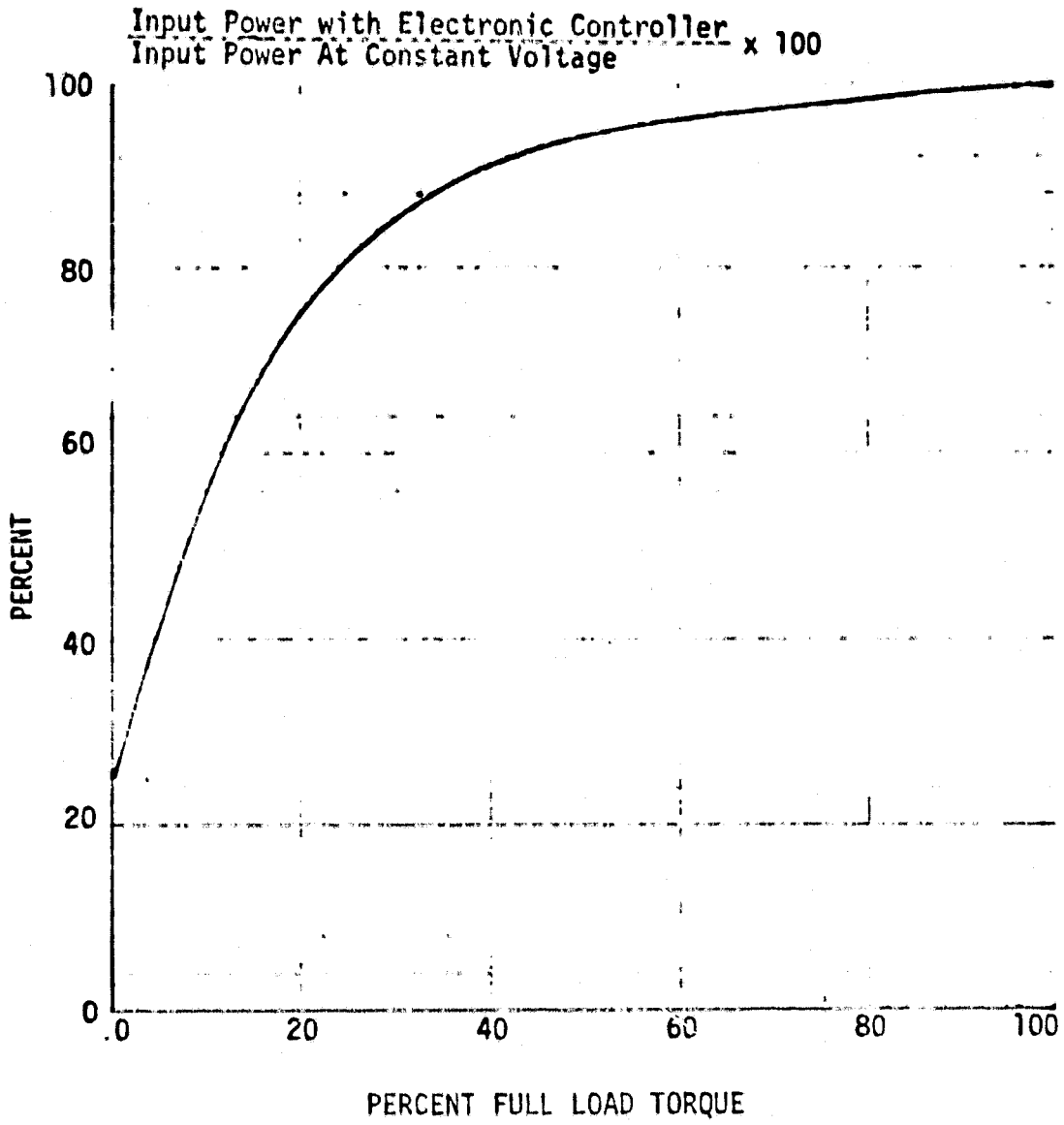

Figure 24. Input Power Reduction with Electronic Controller
3 HP 3φ 220 V
1750 RPM
Pacer (Louis Allis)

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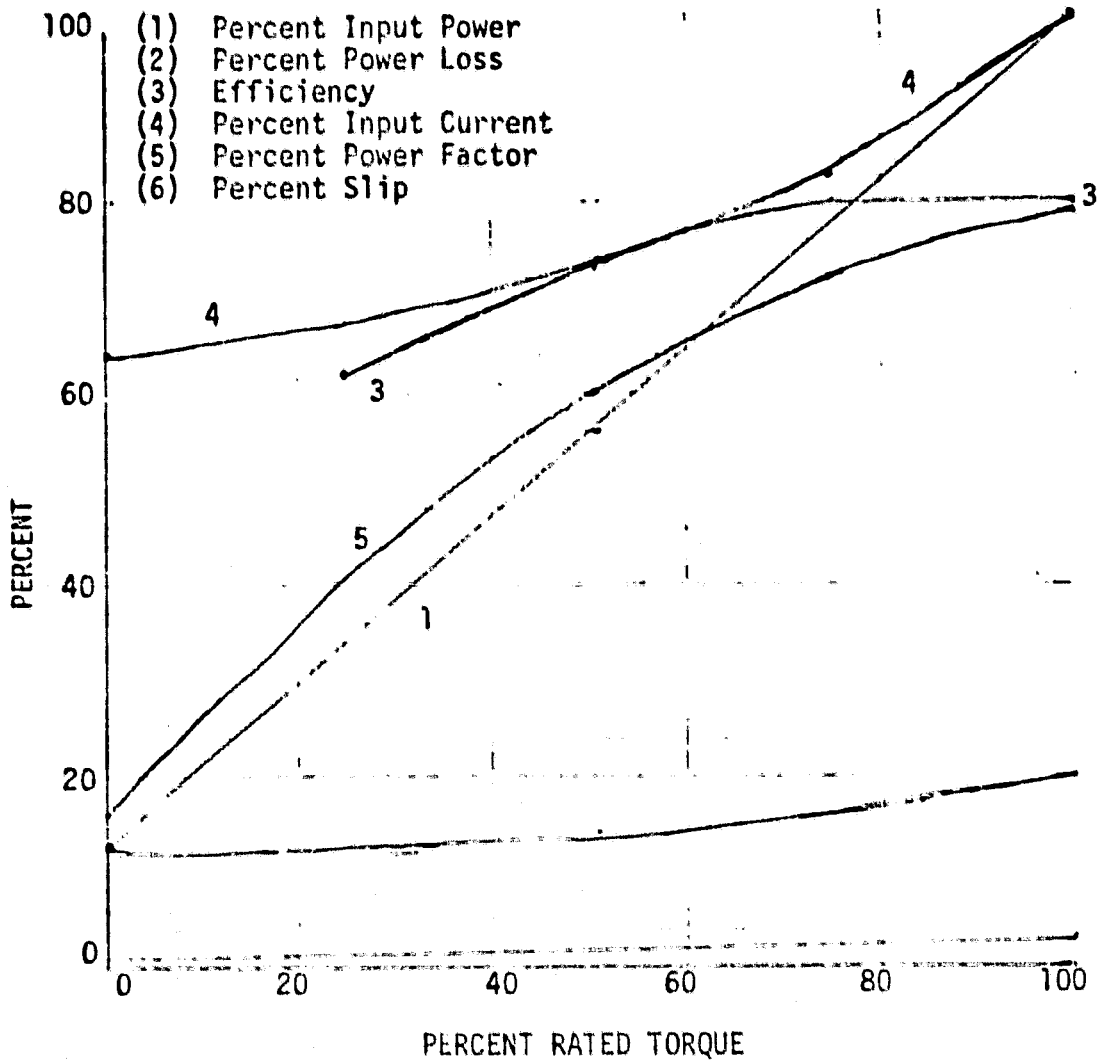

Figure 25. Rated Voltage Test
1 HP,3¢,220/440 V
3.4 A,1140 RPM
General Electric

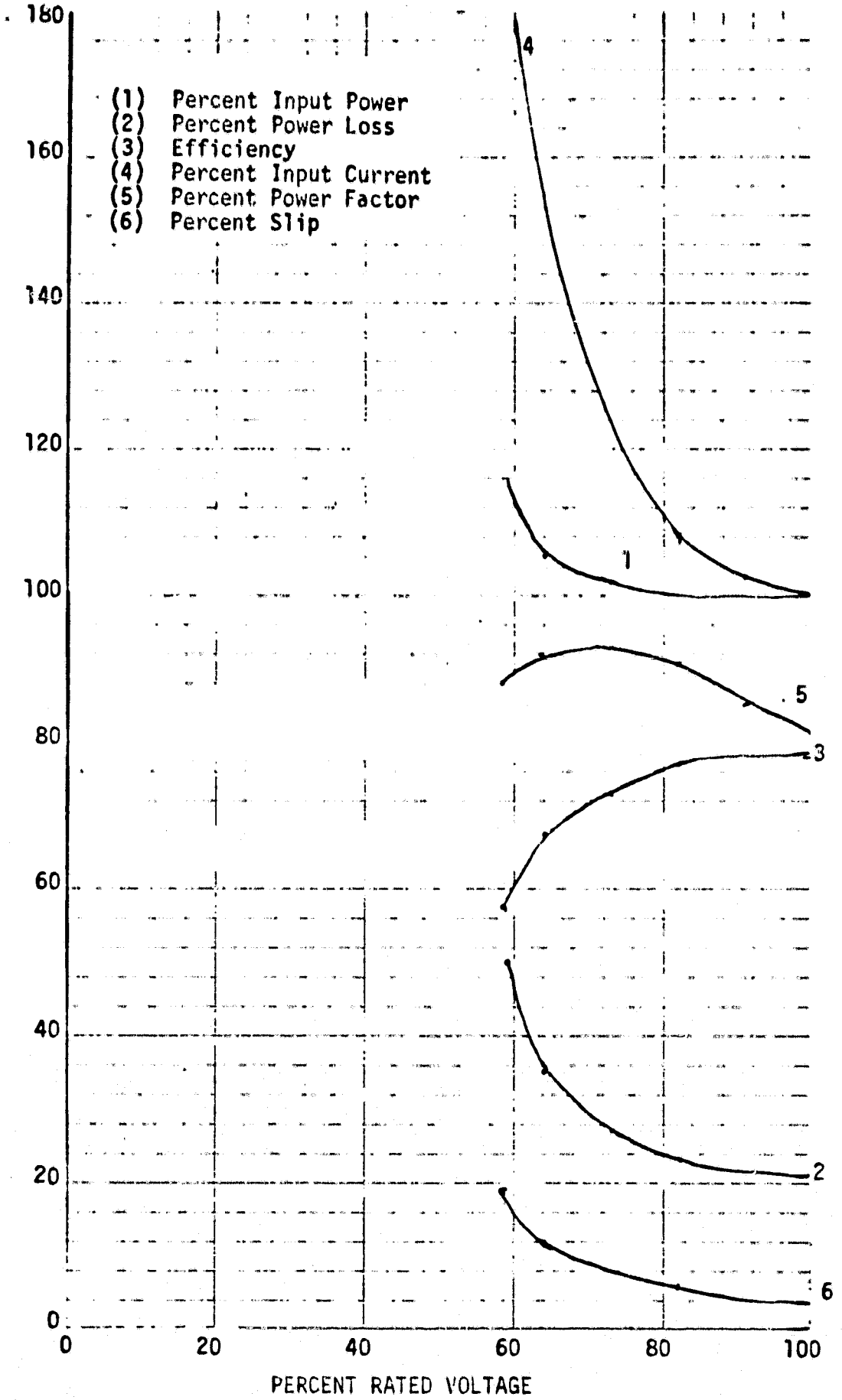

Figure 26. Constant Torque Test: Torque = 100%
1 HP, 3φ, 220/440 volt
3.4A, 1745 RPM
GENERAL ELECTRIC

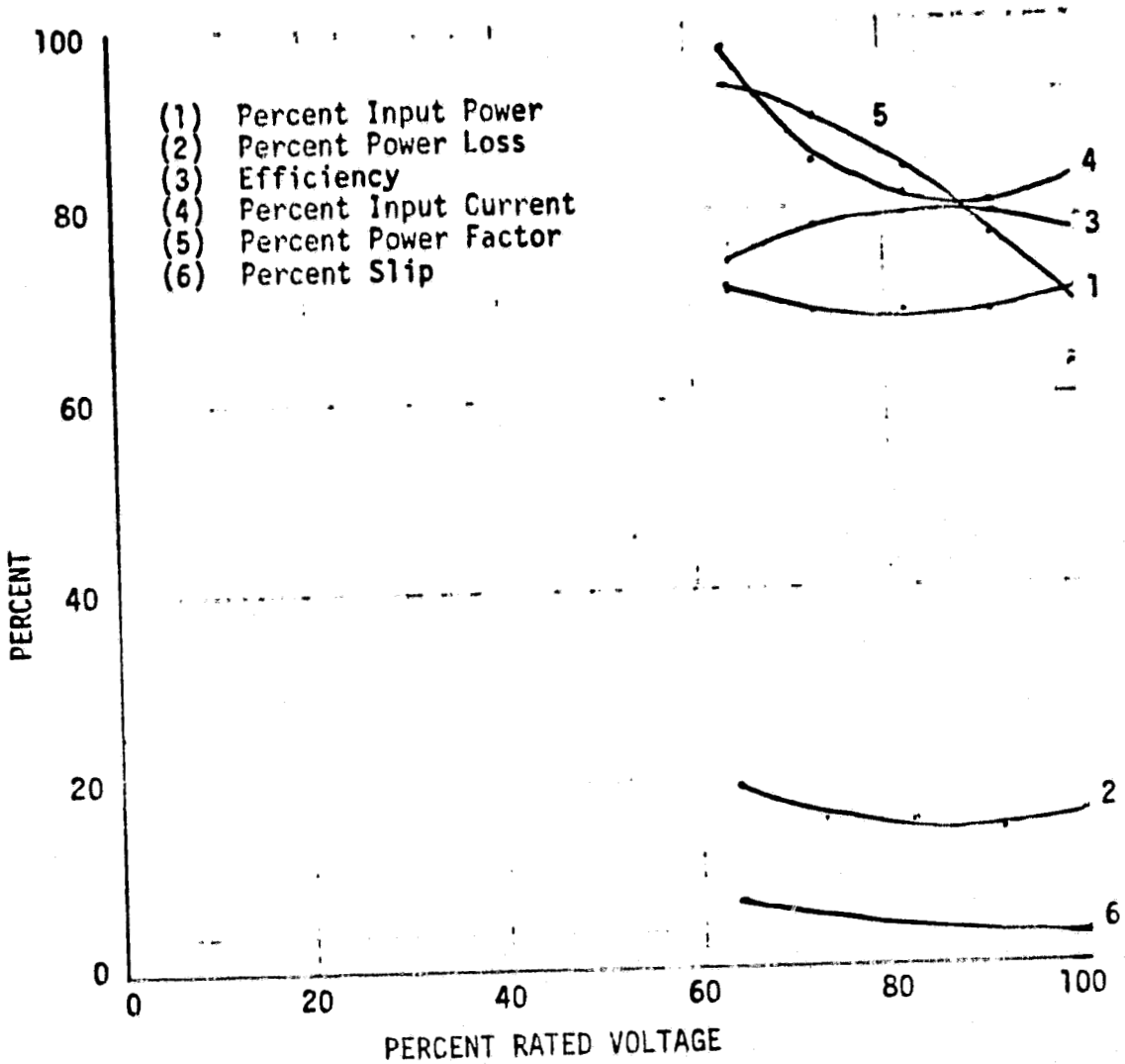

Figure 27. Constant Torque Test: Torque = 69%
1 HP, 3¢, 220/440 volt
3.4A, 1140 RPM
GENERAL ELECTRIC

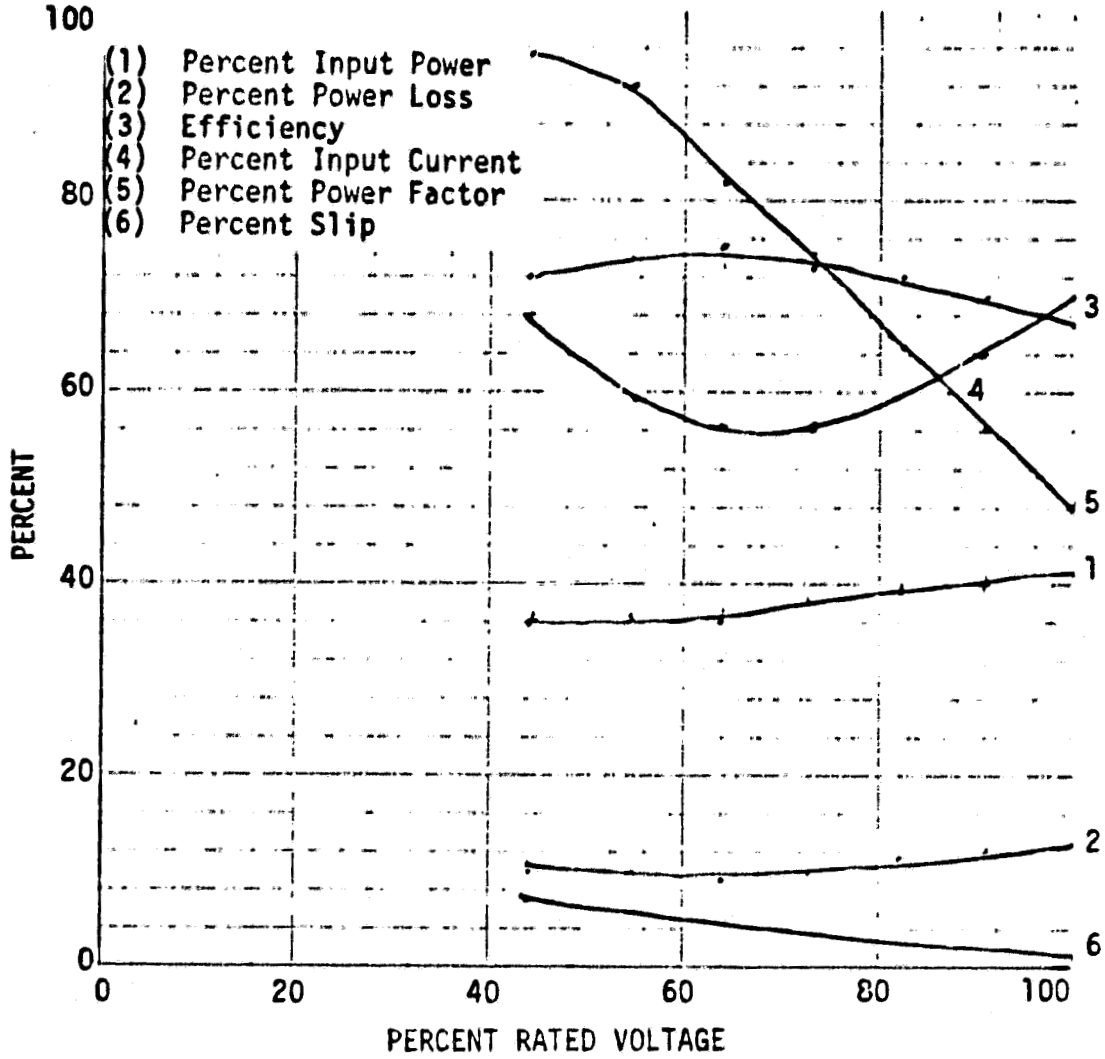

Figure 28. Constant Torque Test: Torque = 35%
1 HP, 3ϕ, 220/440 volt
3.4A, 1140 RPM
GENERAL ELECTRIC

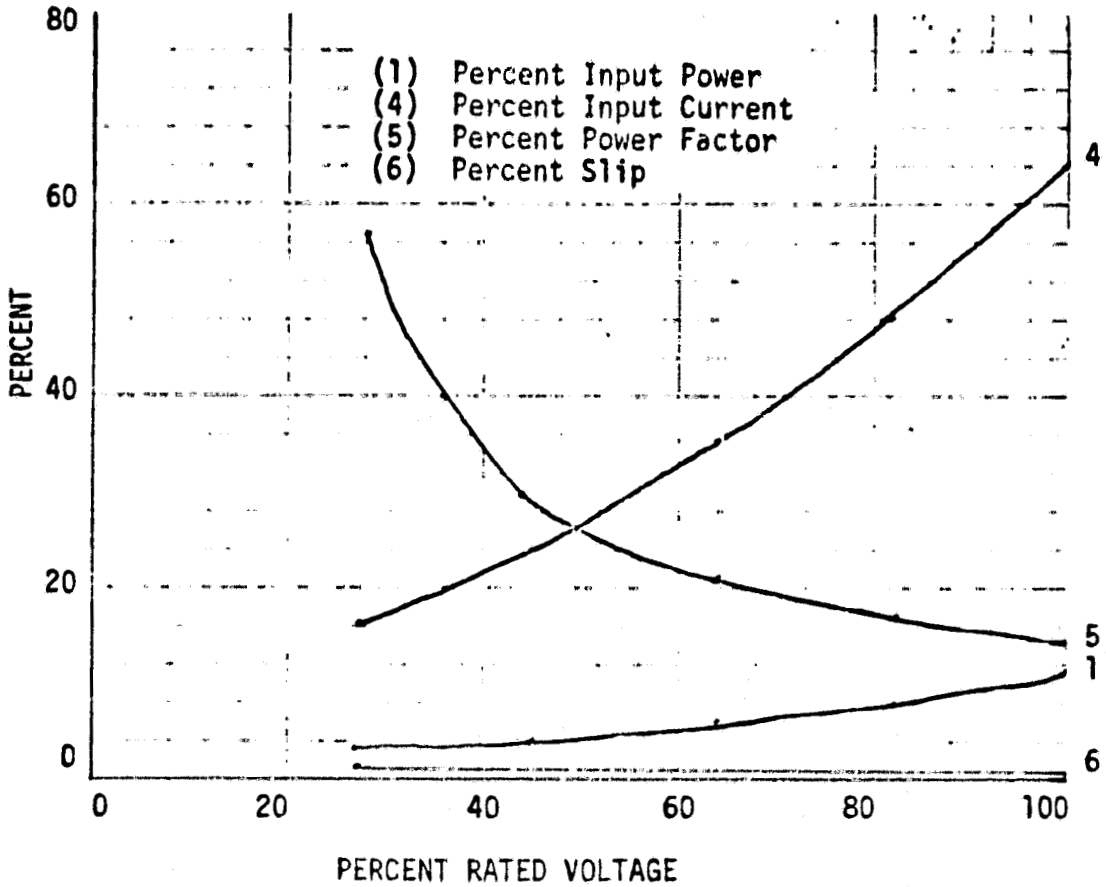

Figure 29. Constant Torque Test: No Load
1 HP, 3¢, 220/440 volt
3.4A, 1140 RPM
GENERAL ELECTRIC

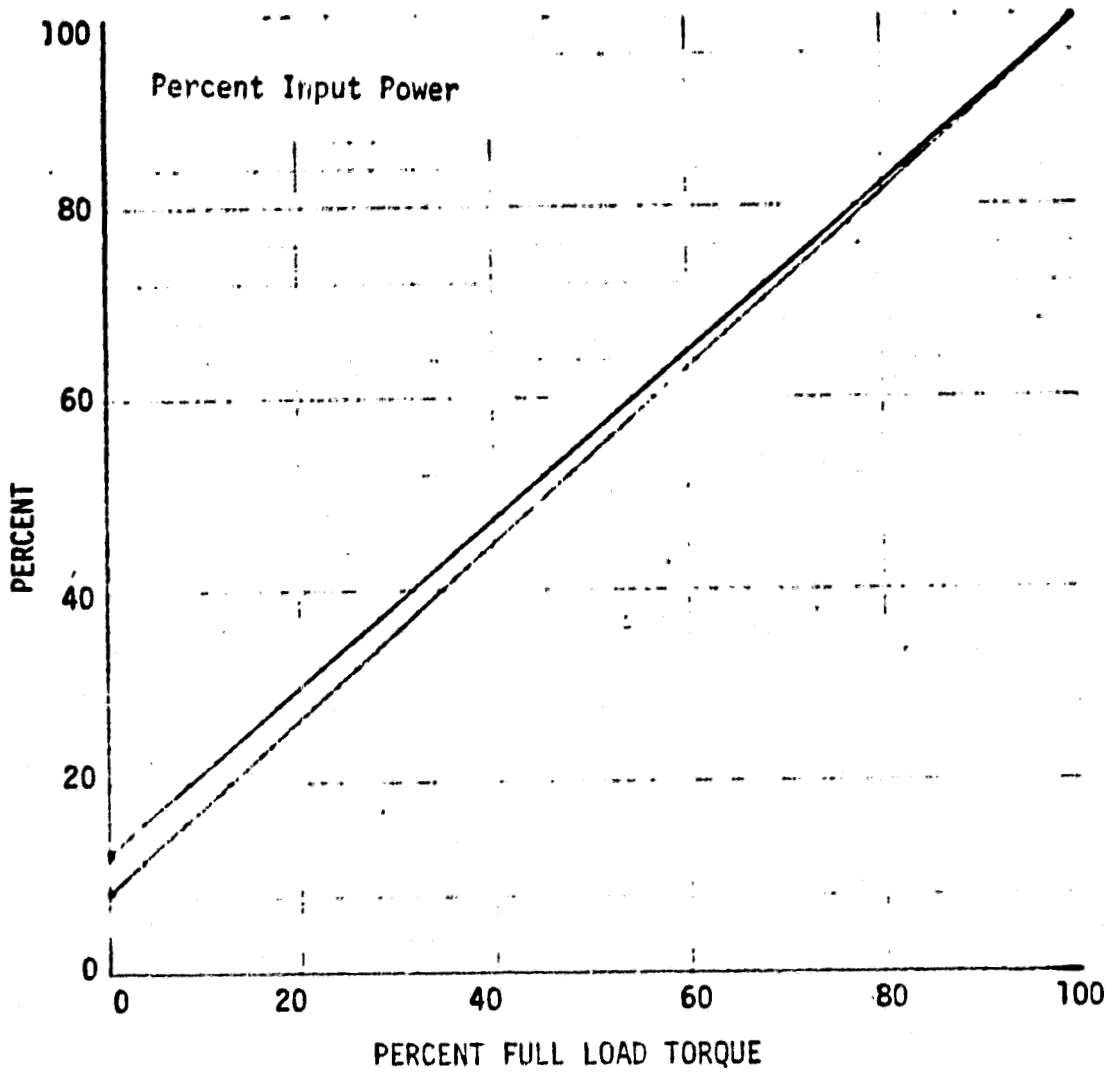

Figure 30. Constant Voltage/Electronic Controller Test
1 HP, 220 V, 3Φ
1140 RPM
GENERAL ELECTRIC

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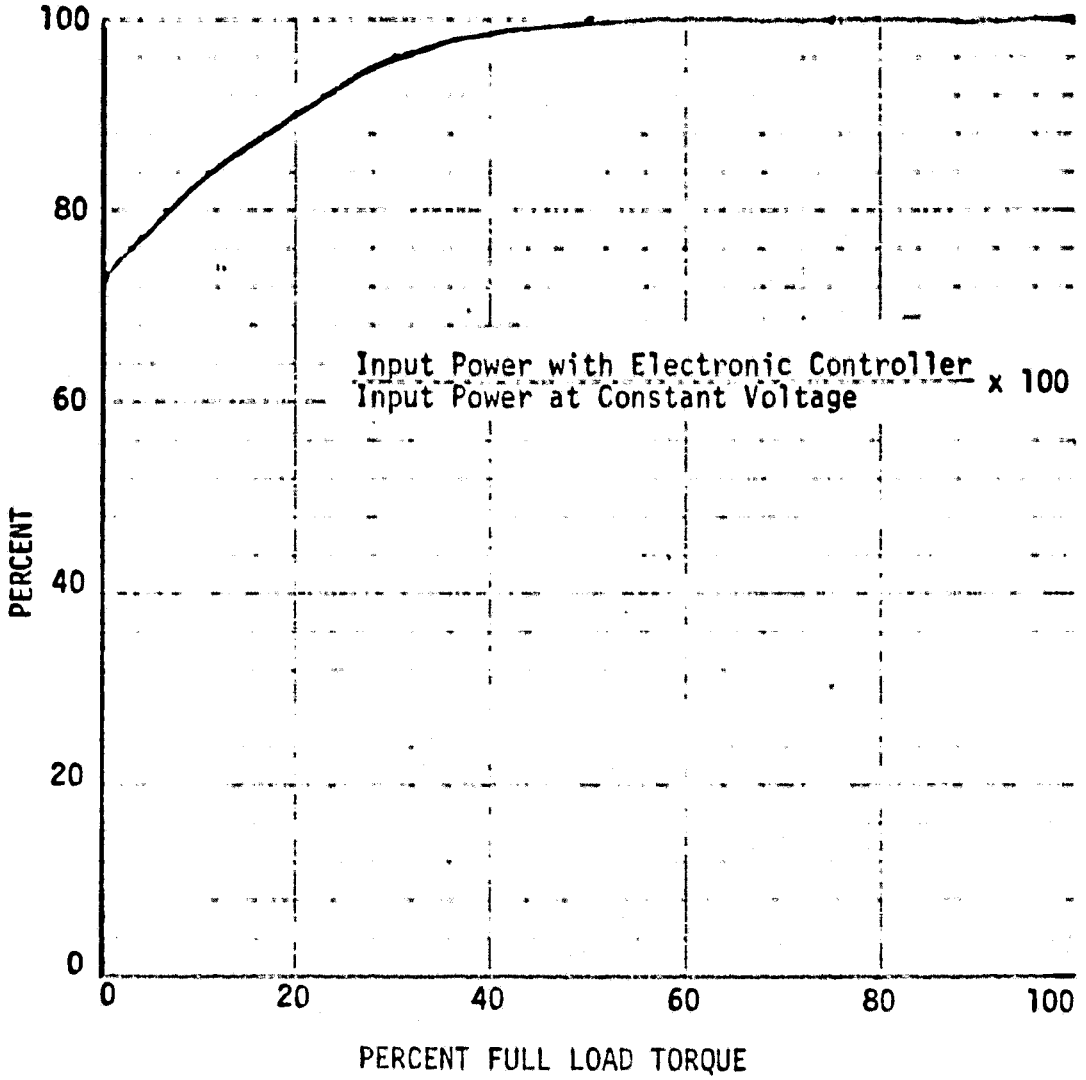


Figure 31. Input Power Reduction with Electronic Controller
1 HP, 3ϕ, 220 v
1140 RPM
GENERAL ELECTRIC

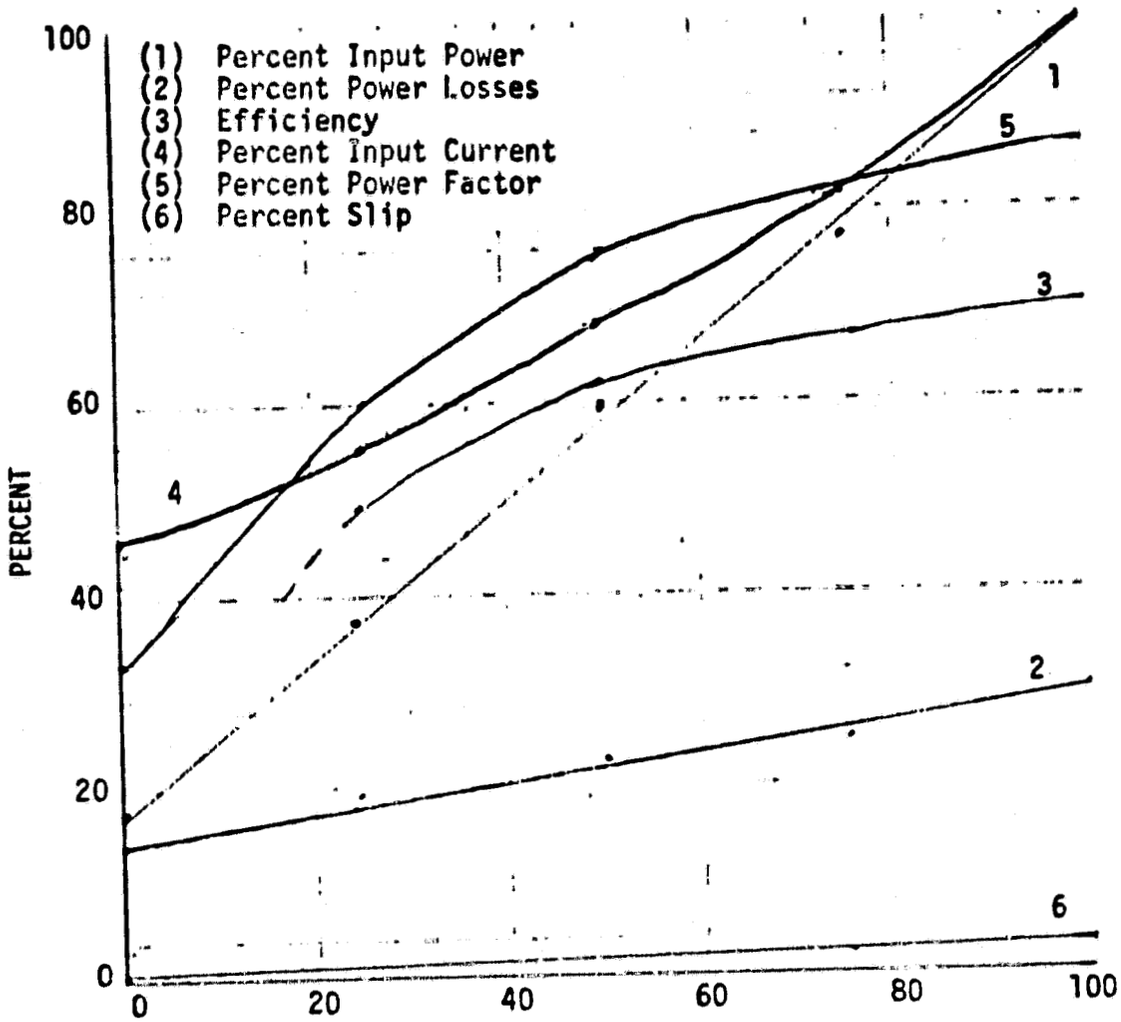


Figure 32. Constant Voltage Test
1.5 HP, 220 v, 1Φ
8A, 3450 RPM
CENTURY

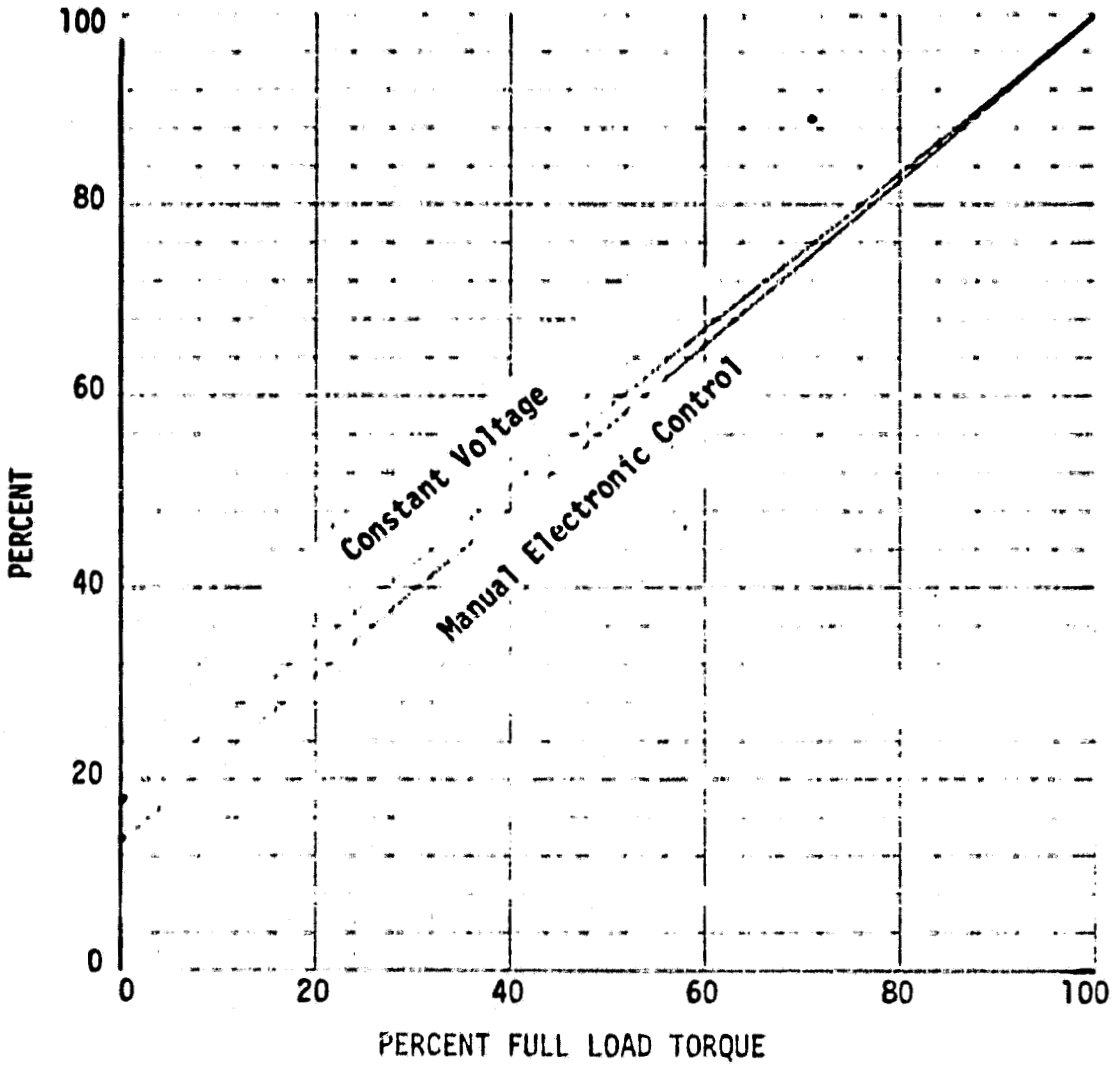


Figure 33. Constant Voltage/Manual Electronic Controller Test
1.5 HP, 220 v, 1φ
8A, 3450 RPM
CENTURY

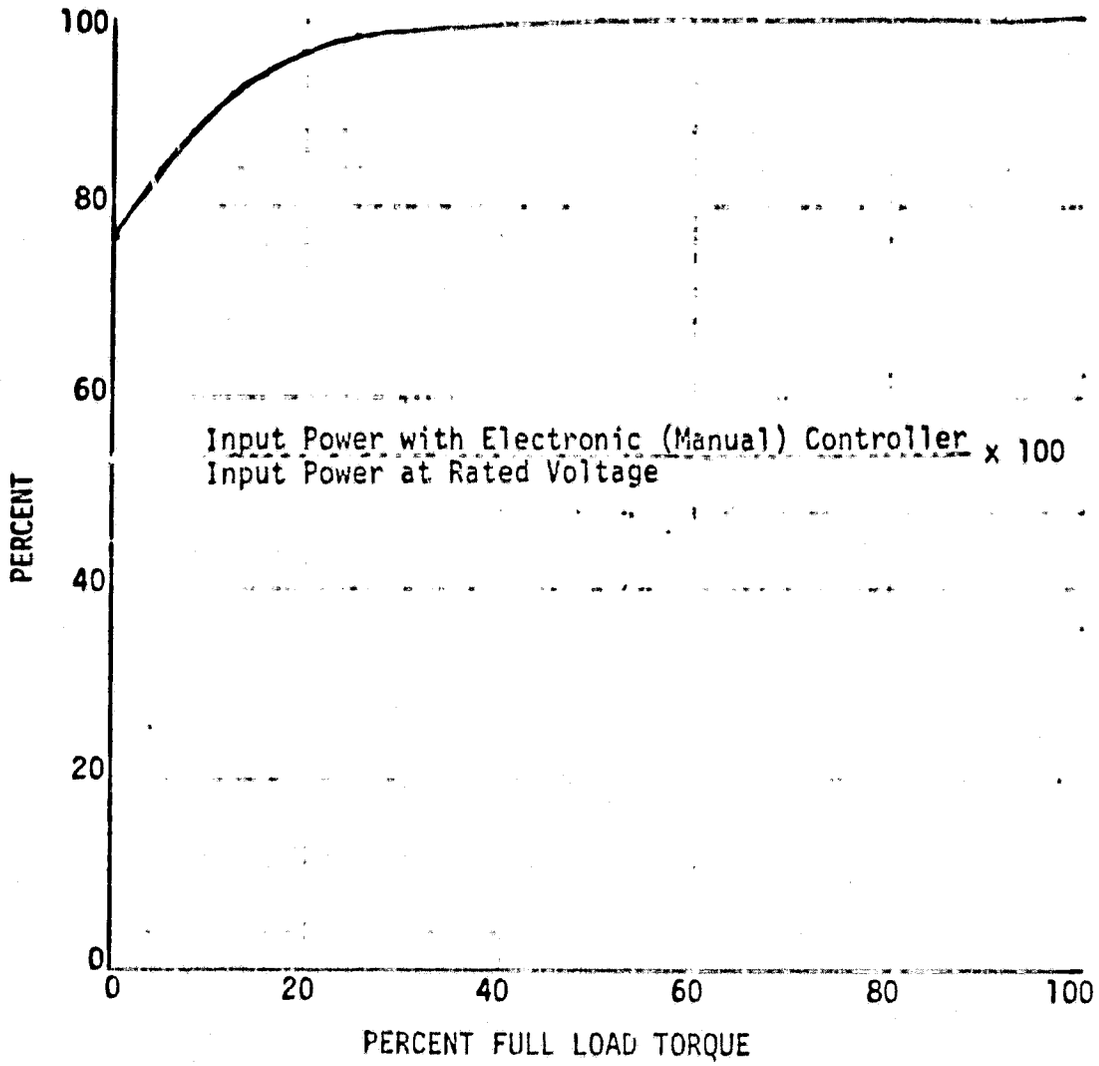


Figure 34. Input Power Reduction with Manual Electronic Controller
1.5 HP, 1φ, 220 v
3450 RPM
CENTURY

Table 1. Electronic Controller/Constant Voltage Test Data

Electronic Controller	Line Voltage (volts)	Line Current (amps)	Input Power (watts)	Torque (in-lb)	Speed (RPM)
Active Shorted	220	19.2	6486	123	3410
Active Shorted*		15 15	4746 4794	92 92	3459 3470
Active Shorted		11.6 12.0	3288 3306	62 62	3503 3517
Active Shorted		11.6 9.9	1752 1902	31 31	3546 3560
Active Shorted		5.76 9.42	324 594	0 0	3596 3596

*Base Data

5 hp, 3ϕ, 220 watt, 3445 RPM, PACER

(Louis Allis) induction motor

Table 2. Electronic Controller/Constant Voltage Test Data

Electronic Controller	Line Voltage (volts)	Line Currents (amps)	Input Power (watts)	Torque (in-lb)	Speed (RPM)
Active	220	10.9	3552	108	1724
Shorted*		10.7	3534	107	1728
Active		8.49	2670	81	1745
Shorted		8.46	2652	81	1748
Active		6.09	1782	54	1764
Shorted		6.09	1800	54	1767
Active		4.35	876	27	1782
Shorted		4.38	930	27	1784
Active		3.03	90	0	1798
Shorted		3.75	132	0	1799

*Base Data

3 hp, 220/440 volt, 3ϕ, 1750 RPM,

Wagner induction motor

Table 3. Electronic Controller/Constant Voltage Test Data

Electronic Controller	Line Voltage (volts)	Line Current (amps)	Input Power (watts)	Torque (in-lb)	Speed (RPM)
Active		10.2	2826	109	1744
Shorted*		10.1	2922	109	1746
Active		8.61	1962	73	1758
Shorted		8.91	2076	73	1764
Active		7.59	1122	36	1770
Shorted		7.80	1278	36	1782
Active		3.9	132	0	1798
Shorted		7.71	516	0	1798

*Base Data

3 hp, 3ϕ, 220 volt, 1750 RPM PACER

(Louis Allis), induction motor

Table 4. Electronic Controller/Constant Voltage Test Data

Electronic Controller	Line Voltage (volts)	Line Current (amps)	Input Power (watts)	Torque (in-lb)	Speed (RPM)
Active	220	3.19	939	55	1156
Shorted*		3.19	939	55	1156
Active		2.97	843	49	1159
Shorted		2.96	843	49	1162
Active		2.47	609	34	1174
Shorted		2.51	617	34	1173
Active		2.03	356	18	1182
Shorted		2.12	367	18	1186
Active		1.55	83	0	1197
Shorted		1.97	113	0	1198

*Base Data

1 hp, 220 volt, 3ϕ, 1140 RPM, General

Electric induction motor

Table 5. Manual Electronic Controller/Constant Voltage Test Data

Manual Electronic Control	Line Voltage (volts)	Line Current (amps)	Input Power (watts)	Torque (in-lb)	Speed (RPM)
Active	220	8.3	1584	27	3463
Shorted*		8.28	1576	27	3465
Active		6.86	1232	20	3496
Shorted		6.78	1224	20	3501
Active		5.54	896	14	3526
Shorted		5.46	896	14	3533
Active		4.36	564	7	3554
Shorted		4.42	576	7	3562
Active		3.16	220	0	3581
Shorted		3.86	284	0	3581

*Base Data

1.5 hp, 1ϕ, 220 volt, 3450 RPM,

Century induction motor

III. ELECTRONIC CONTROLLER MODIFICATIONS

The Electronic Controller furnished by NASA for tests at Auburn was modified to eliminate misfiring of the triacs. The modifications also eliminated the necessity of rebalancing the phase currents each time the three phase unit was used. The controller can now be supplied by any 3ϕ, 208 volts, 4 wire voltage supply without worrying about phase sequence or order of terminal connections.

The misfiring was due to the firing pulses from one half cycle extending into the beginning of the next half cycle. When the current went to zero before the firing pulses ended, the conditions for firing the triac were satisfied and the triac fired.

The circuit that generates the firing pulses for the triac uses a ramp that is reset by a pulse. The reset pulse is generated from the zero crossing of the ac line to neutral voltage and should turn the firing pulses off at the zero voltage crossing. Due to phase shifts and time delays in the circuits that are used to generate the reset pulse and the ramp, the firing pulses were not turning off until some time after the zero voltage crossing.

In the three phase controller the phase that contained the sensing circuit was as stated in the above paragraph. The method of grounding effectively added a small percent of the A phase voltage to the B and C phase voltages before the zero crossing points were detected. This caused time shifts in the zero crossing of both voltages, one advanced in time and the other delayed. The time delay of the C phase was so that the firing pulses extended 12 degrees into the next half cycle as shown

in Figure 34. This was the worst phase and therefore it was the one that was misfiring.

Two changes were made in order to eliminate the misfiring. The changes are shown in Figure 35 and are:

1) Capacitors were added to time advance the zero crossing in each phase to compensate for the time delays already in the circuits.

2) The grounding was changed so that all three phase voltages were referenced to the neutral of the system.

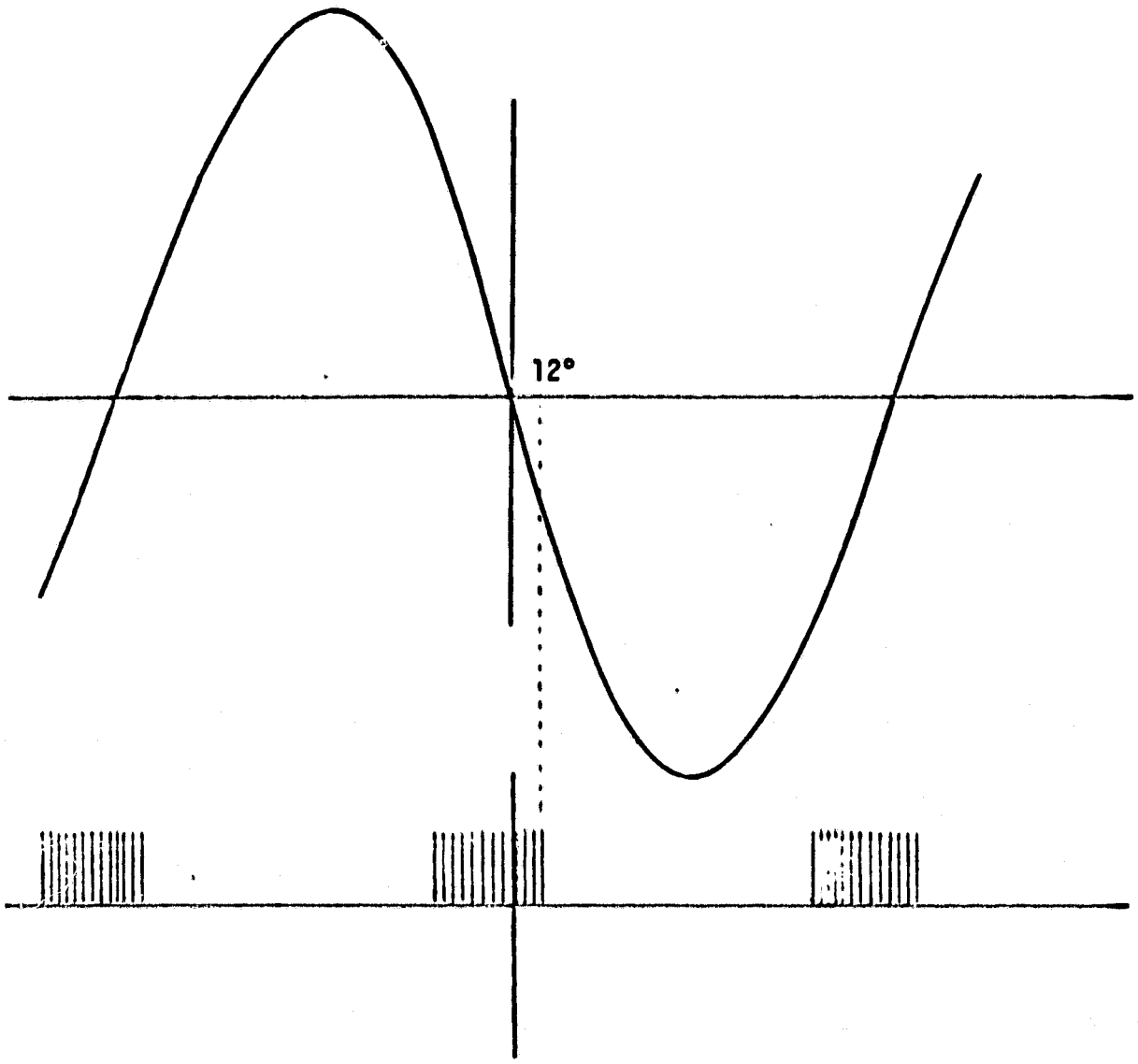


Figure 34

Firing pulses referenced to line to neutral voltage in the worst phase of the 3 phase controller

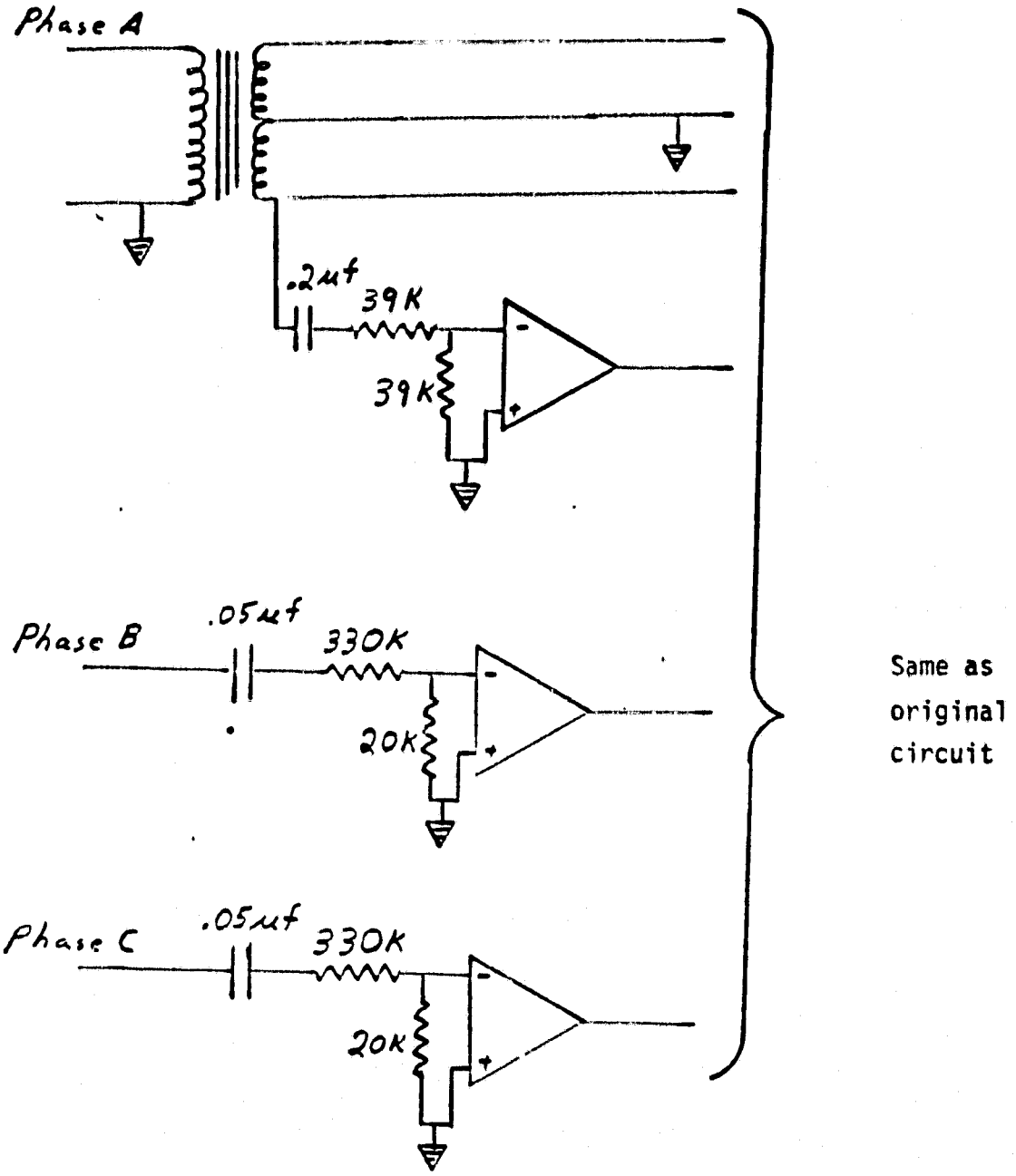


Figure 35. Circuit modifications to elimiate Triac misfiring
Series capacitors added and ground changed.

IV. DESIGN OF CONTROLLER APPLICABLE TO MOTORS WITH INACCESSIBLE NEUTRAL

A pulse generator has been designed at Auburn to be used in the study of three-phase ac voltage controllers. The unit is designed for full-wave operation on either 3-wire or 4-wire systems using either six thyristors (SCR) or three triacs. A pulse is generated that is synchronized to the sixty cycle power line with the leading edge and trailing edge separately controlled. This pulse is then time delayed to produce six identical pulses that are one sixth of a cycle apart. The six pulses are then optically coupled into six current-limited gate drivers.

This type of design has been chosen because of its versatility. The six firing circuits are electrically isolated so that they can be connected safely to thyristors anywhere in the circuit. The leading edge control is used to vary the conducting angle. The trailing edge control is used to investigate the necessity of keeping some thyristors on where others are being gated on and off. In three-phase, 3-wire systems, it is necessary that at least two thyristors are on at all times. The timing of the trailing edge of the gating pulse controls this condition.

The controller has been constructed and is now operational. The unit has been operated only with a purely resistive load. Time has not permitted an investigation of the controller to control motors.

V. ENERGY SAVINGS USING THE ELECTRONIC CONTROLLER

The electronic controller will produce significant savings in input power when the motor is operating under lightly loaded conditions. An equation that is useful in computing the energy that might be saved over a period of one year by using the electronic controller is:

$$\text{KWH savings/year} = (T_{NL}\Delta P_{NL} + T_{PL}\Delta P_{PL})\frac{(T_{OP})}{10^5}$$

where T_{NL} = operating time at no load in percent of total operating time per year

ΔP_{NL} = power savings at no load in watts = input power with rated voltages - input power with the electronic controller

T_{PL} = operating time at partial load in percent of total operating time per year

ΔP_{PL} = power savings at partial load in watts = input power with rated voltage - input power with the electronic controller

T_{OP} = total operating time of motor per year in hours

For example, suppose the 5 hp motors were operated eight hours/day, five days a week and that for 60% of the time it operated at no load and the remainder at full load. Using data from Table 1

$$\text{KWH savings/year} = \frac{(60)(270)(8)(5)(52)}{10^5} = 337 \text{ KWH}$$

VI. RESULTS AND RECOMMENDATIONS

The data shows that under lightly loaded conditions the electronic controller can significantly reduce the power losses of an induction motor. At no load this ranged from 20% to 74% on the motors tested. It should be a valuable technique for reducing the energy consumption of induction motors which operate for significant periods of time at no load or light loads.

In the process of testing the motors it was observed that at about one-third load a resonant condition occurred; this had been observed previously at Marshall Space Fight Center. This occurred with both the manually controlled unit and the feedback control unit. The cause of this is not known and needs further study. Although noticeable, in no case was the resonant condition such as to cause the motor to stall.

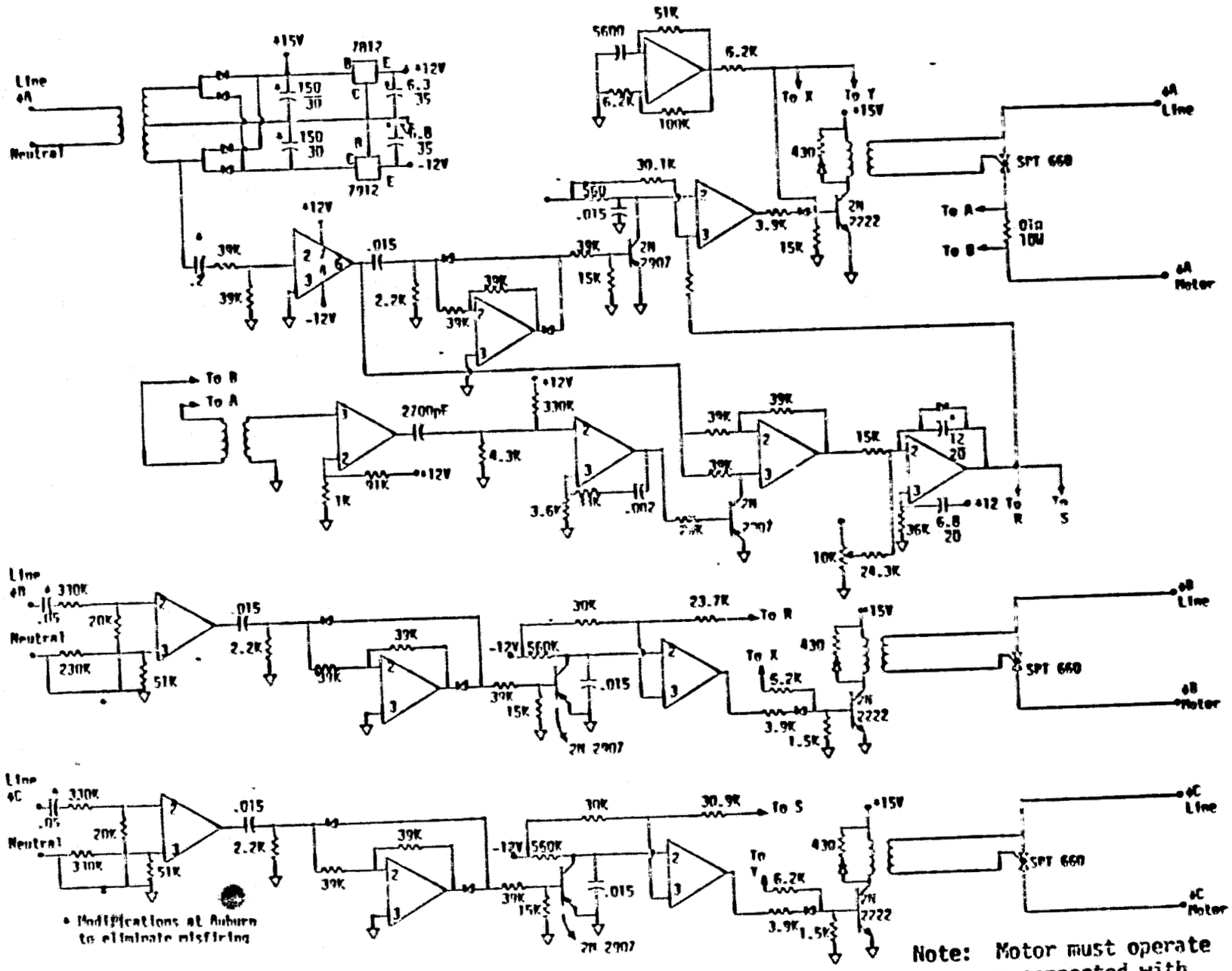
The concept of the electronic controller has spawned other ideas. For example, a motor that operates either loaded or unloaded might be improved by an electronic device that simply switches in-and-out a bucking transformer.

Additional work is needed to evaluate the design of the unit which does not require access to a neutral. More field testing in an actual industrial application, such as that at the textile mill in Alabama, would provide valuable information on possible savings in energy.

A detailed study of the operation of the electronic controller as a feedback control system is needed to evaluate the effect changes in circuit parameters will have in the operation. Possibly changes can be made to reduce or eliminate the resonance. Its application to much larger motors needs to be studied. The response to step changes in load should be investigated.

VII. Circuit Diagram of Motor Controller

Designed by Frank J. Nola for NASA



Note: Motor must operate y connected with neutral (4-wire) in in order for this controller to function.

ELECTRONIC POWER FACTOR CONTROLLER
Designed by Frank J. Nola for NASA

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