PRELIMINARY DRAFT

LABORATORY TESTING

OF

CIRCUIT RIDER UNITS 480V

April 2002

1. Introduction

Increasing electric energy costs have encouraged users in all levels of the power system (industrial, commercial and residential) to consider energy saving measures, with the goal of reducing their electricity bill. Considering that approximately 65% of the electric energy generated in the U.S. is consumed (or "processed") by electric motors, related energy savings opportunities have a substantial impact and market. Users of electric motors have long realized the benefits of various types of motor input power "conditioning" devices, to reduce their electric energy consumption and costs. These devices can save energy by means such as power factor improvement, or providing a more efficient method of matching motor output with the actual load, and can range from relatively inexpensive power factor correction capacitor configurations, to elaborate control devices (or adjustable speed drives) that can cost more than the motor they are controlling.

The purpose of this laboratory testing was to determine the effect of applying a Circuit Rider device to the input of an induction motor, by characterizing the motor input parameters, before and after the device was applied.

2. The Motor Systems Resource Facility (MSRF) Test Platform

The tests conducted in this study have taken place in the Motor Systems Resource Facility (MSRF); a laboratory in the Electrical and Computer Engineering Department A schematic of the laboratory power system is given in Fig. 1. For the range of induction motor tests required in this project (30hp and 100hp) the larger test bed rated up to 300hp was used. Fig. 2 shows a photograph of the 480V Circuit Rider unit installed at the terminals of the 100hp motor in the MSRF.

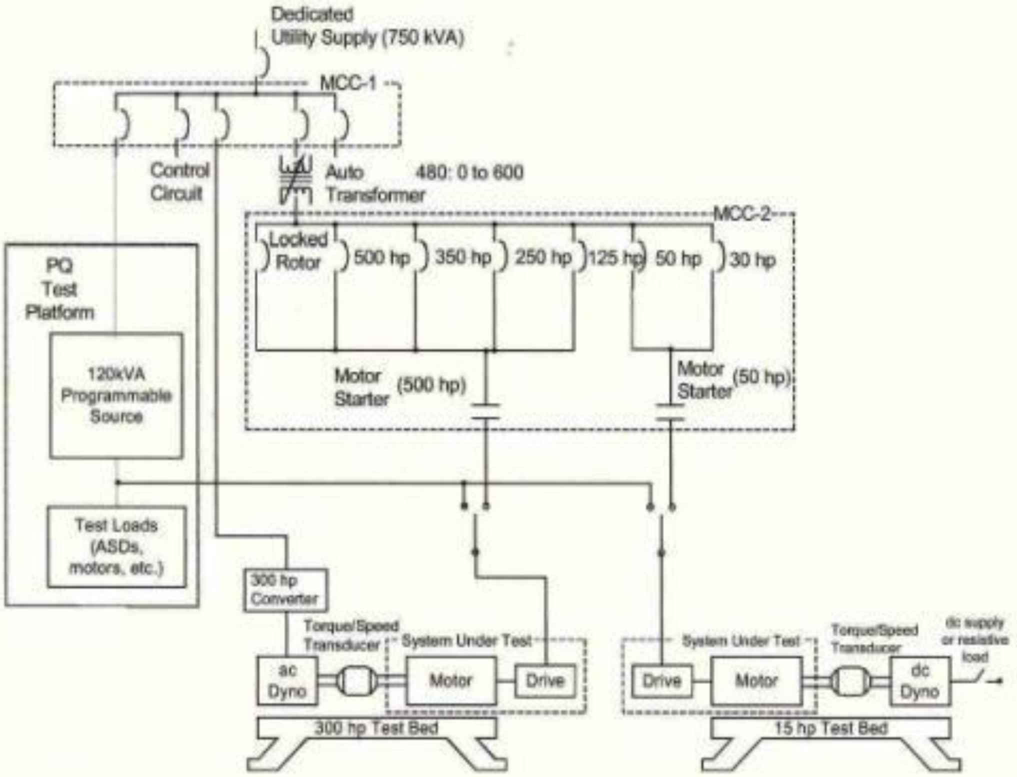


Fig. 1 Schematic of Motor System Resource Facility (MSRF)

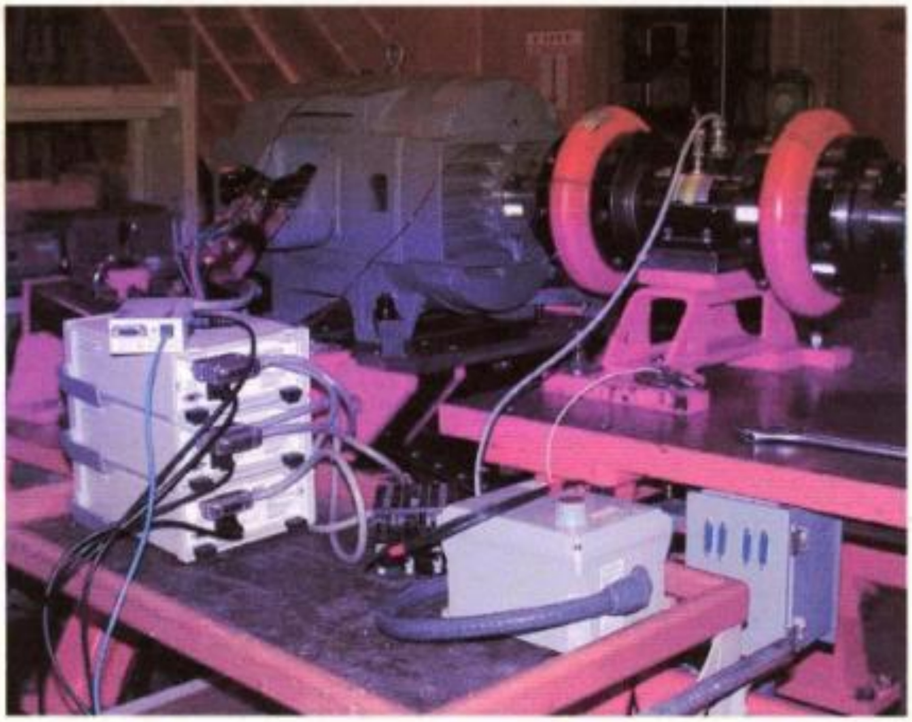


Fig. 2 480V Circuit Rider installed on 100hp motor in MSRF.

3. Test Results for 100hp Motor: Without and With 480V Circuit Rider Unit

The 480V Circuit Rider unit was tested with a 100hp, 230/460V induction motor (manufactured by US Electrical Motors). In order to provide a basis for justifiable comparisons, the 100hp motor input parameters were first characterized without the Circuit Rider unit. The tests without, and with the Circuit Rider unit were conducted at multiple load points, following the IEEE 112A standard format, with load points consisting of: 110%, 100%, 75%, 50%, 25%, and 0% (no-load).

3.1 100hp Motor Test Results: Without Circuit Rider Unit

For the 100hp motor tests without the Circuit Rider unit, the full set of data is given in Appendix 1, and the Summary is given in Table 1 below. As indicated in Table 1, the Power Factor decreases from 0.868 at 100% load, to 0.847 at 75% load, to 0.788 at 50% load etc.

Table 1. Summary of Characteristics for 100hp motor without Circuit Rider Unit

Load, in % rated	**110%**	**100%**	**75%**	**50%**	**25%**	**0%**
Power Factor, in pu	0.869	0.868	0.847	0.788	0.602	0.1
Line Current, in A	130.1	116.9	88.1	63.3	42.7	32.1
Efficiency, in %	91.44	92.17	93.19	93.02	90.24	19.4

3.2 100hp Motor Test Results: With 480V Circuit Rider Unit

The full set of data for the 100hp motor tests with the 480V Circuit Rider unit is also given in Appendix 1, and the Summary is given in Table 2 below. As shown in Table 2, with the Circuit Rider unit applied, the Power Factor improves from Table 1 with 0.906 at 100% load, 0.903 at 75% load, and 0.867 at 50% load. Fig. 3 demonstrates the Power Factor improvement with the Circuit Rider device graphically. Notice also the reduced current drawn by the motor with the Circuit Rider unit applied (Table 2), versus without (Table 1). This is also shown graphically in Fig. 4. Finally, as expected, the efficiency of the motor is unchanged.

Table 2. Summary of Characteristics for 100hp motor with 480V Circuit Rider Unit

Load, in % rated	**110%**	**100%**	**75%**	**50%**	**25%**	**0%**
Power Factor, in pu	0.903	0.906	0.903	0.867	0.765	0.1
Line Current, in A	125.4	112.0	83.1	57.3	34.2	20.9
Efficiency, in %	91.31	92.20	93.13	93.19	90.38	18.4

Fig. 3 Power factor values of 100 hp Induction Motor tested with and without Circuit Rider device

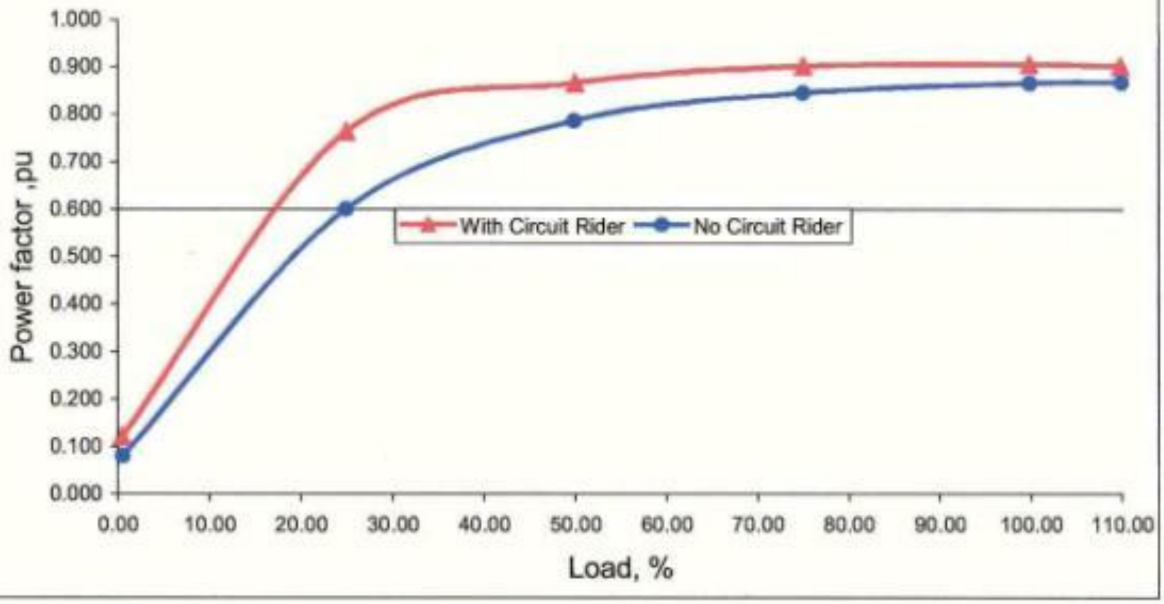
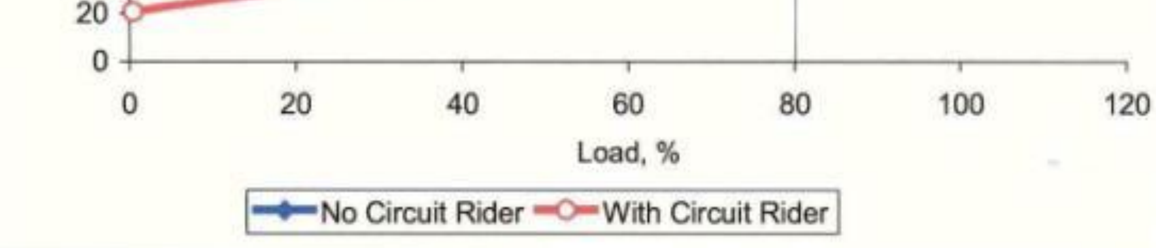


Fig. 4 Phase current of 100hp induction motor tested with and without Circuit Rider device



3.2.1 Significance of Power Factor Improvement and Current Reduction

Induction motors are inherently inductive loads. Therefore, the motor current "lags" the applied voltage, requiring both real power (P: Watts or W) and reactive power (Q: VARs) to be drawn by the motor. The Displacement Power Factor (DPF) is defined as the cosine of the phase angle between the phase voltage and current, as shown in eqn. 1.

$$\text{DPF} = \cos(\theta_v - \theta_i), \text{ or } \cos\theta, \text{ with } \theta = (\theta_v - \theta_i) \tag{1}$$

With distorted waveforms, e.g. containing harmonics of the fundamental frequency (60Hz in the U.S.), the true Power Factor (PF) can be found as the ratio of the Real Power (P), over the Total Apparent Power (S: Volt Amperes or VA) as shown in eqn. 2.

$$\text{PF} = \frac{P}{S}, \text{ where } S = \sqrt{P^2 + Q^2} \tag{2}$$

Where the Power Factor ranges from zero to one as shown in eqn. 3.

$$0 \le PF \le 1 \tag{3}$$

Now consider the standard three-phase real power (P) equation shown in eqn. 4 below:

$$P = \sqrt{3} V_{L,rms} I_{L,rms} \cos\theta \tag{4}$$

The utility will supply the necessary load power at rated voltage. With inductive motor loads, as the current pulls further away from the voltage, the Power Factor (cos θ) decreases, however the utility must maintain the necessary load power at rated voltage. Therefore, the current must increase. Thus, as Power Factor decreases, $I_{L,rms}$ must increase. This leads to the following:

1) More I^2R losses in the customer and utility system.
2) Greater voltage drops in lines/system, therefore utility must supply higher voltages.
3) Larger equipment requirements. (i.e. generators, transformers, lines must have higher ratings, or equipment life will shorten)

These circumstances mean higher costs to the utility, who needs to pass that on to the customer through "power factor penalty" costs.

3.2.2 Potential Savings to Customer with Circuit Rider Device

As described in Section 3.2.1, lower Power Factors translate into higher I^2R losses within customer facilities. Fig. 5 gives an illustration of the additional power losses incurred without the application of the Circuit Rider Device on the 100hp induction motor, as a function of the motor cable length. Figs. 6 and 7 give the savings per month with the Circuit Rider unit, in kWhr and dollars ($) respectively, based on 24/7 operation of the 100hp motor, using an energy rate of 5cents/kWhr.

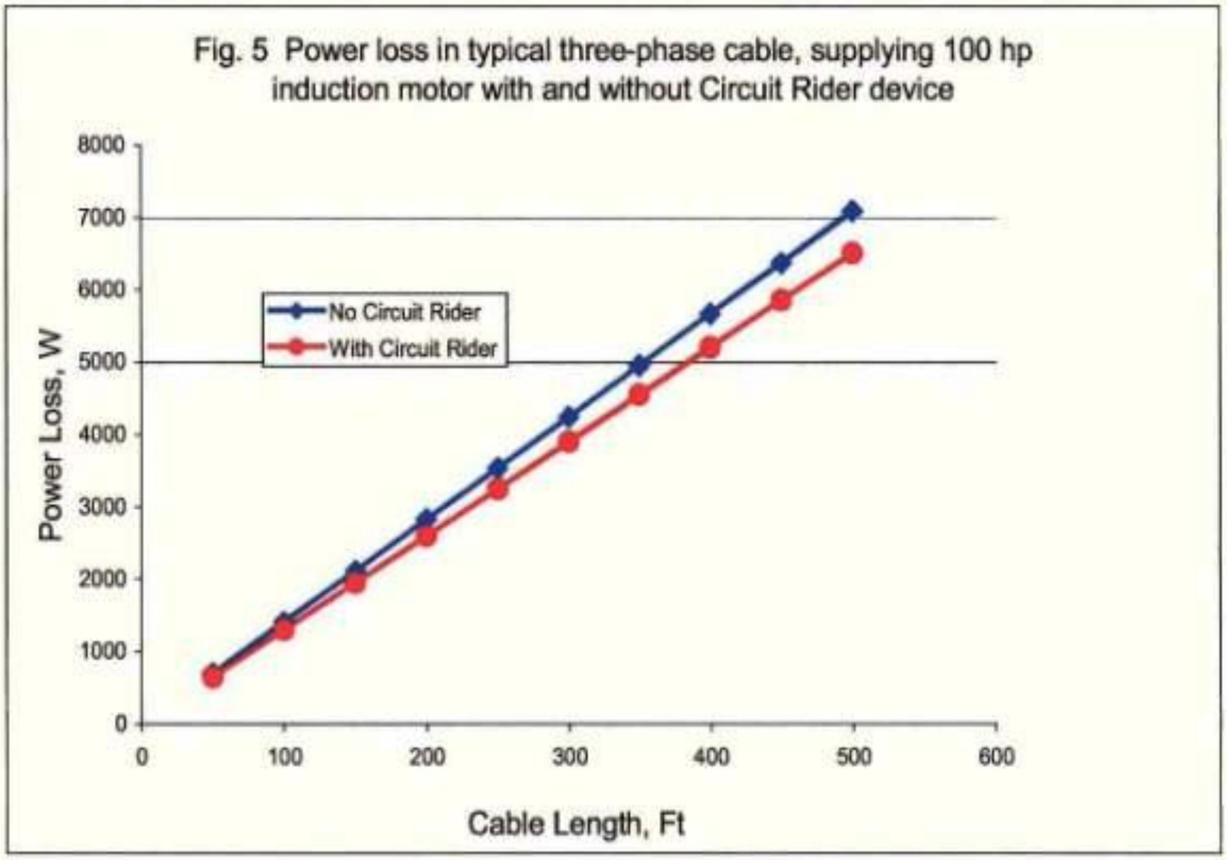


Fig. 6 Electrical energy savings over 1 month period with Circuit Rider Device

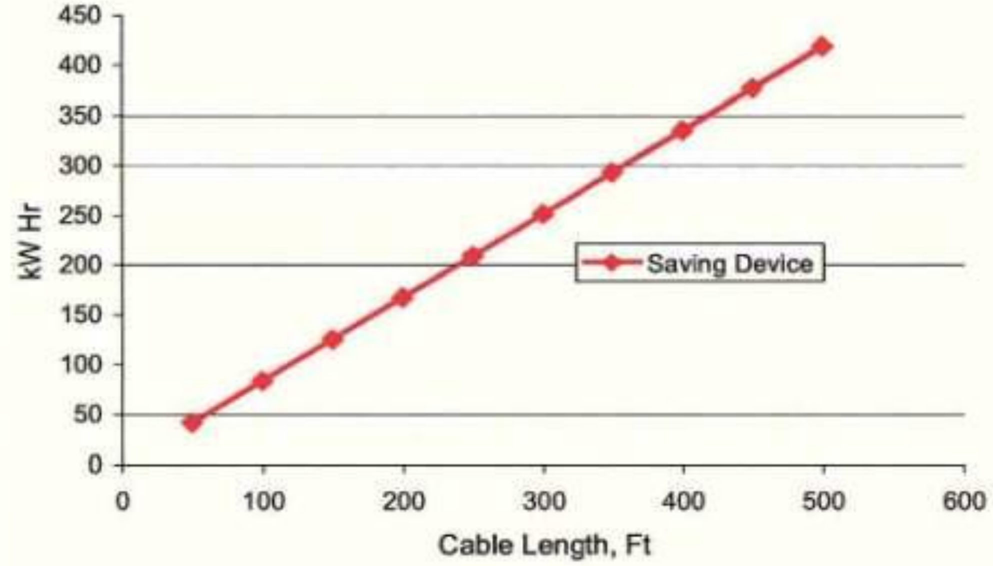
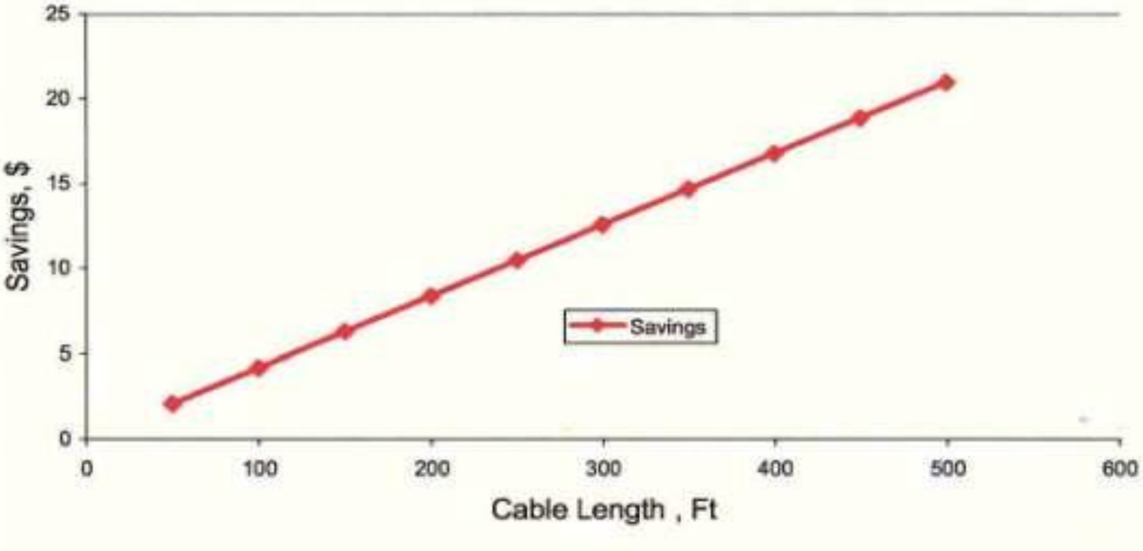


Fig. 7 Cost Savings over 1 month period with Circuit Rider Device



3.3 Example Power Factor Correction for Induction Motors

Consider a 230V, 100hp, three-phase induction motor with a rated nameplate efficiency of 97% and a power factor of 0.88 lagging. This example will demonstrate how power factor correction capacitors can be designed to improve the Power Factor to 0.95 lagging.

$efficiency \rightarrow \eta$

$$\eta = \frac{P_{out}}{P_{in}}$$

$$P_{mech} = 100hp \Rightarrow P_{out} = 100hp * \left(\frac{746W}{1hp}\right) = 74.6kW$$

$$P_{in} = \frac{P_{out}}{\eta} = 76.91kW$$

P_{old} + Q_{old}

$$|S|_{old} = \frac{P_{in}}{PF} = 87.39kVA \Rightarrow S = 87.39\angle\cos^{-1}(0.88)kVA = 87.39\angle 28.36°kVA = 76.91 + j41.54kVA$$

$$|S_{new}| = \frac{P_{in}}{PF_{new}} = \frac{76.91}{0.95} = 80.96kVA$$

$$S_{new} = 80.96\angle\cos^{-1}(0.95) = 76.91 + j25.28kVA = 80.96\angle 18.19°kVA$$

$$Q_{cap} = Q_{new} - Q_{initial} = j(25.28 - 41.51)kVAR = -j16.23kVAR$$

Therefore, with capacitors connected in a delta configuration.

$$Q_T = 3\frac{|V_L|^2}{X_{C\Delta}} \Rightarrow X_{C\Delta} = 3\frac{|V_L|^2}{Q_T} = 3\frac{(230)^2}{-16.23} = -9.78\Omega$$

$$C_\Delta = \frac{-1}{\omega X_{C\Delta}} = 271.2uF \qquad Z_Y = \frac{1}{3}Z_\Delta \Rightarrow C_\Delta = \frac{1}{3}C_Y$$

With capacitors connected in a wye configuration.

$$Q_T = 3\frac{|V_{LN}|^2}{X_{CY}} = -16.23kVAR \Rightarrow X_{CY} = 3\frac{|V_{LN}|^2}{Q_T} = 3\frac{\left(\frac{230}{\sqrt{3}}\right)^2}{-16.23} = -3.26\Omega$$

$$X_{CY} = \frac{-1}{\omega C_Y} \Rightarrow C_Y = \frac{-1}{\omega X_{CY}} \qquad \omega = 2\pi f = 377 rad/s$$

$$C_Y = 813.8uF$$

In summary, the delta configuration results in lower capacitor values, but with higher voltage ratings (line-to-line voltage rather than line-to-neutral).

THE MOTOR SYSTEMS RESOURSE FACILITY
(MSRF)

100hp Induction Motor, No Circuit Rider

Date: 19-Mar 2002

IEEE Std 112-1991 **Form A**

Method A: Input - Output Test of Induction Machine

Manufacturer:	US Electrical Motors	Hp:	100
Model No:	BO104DGF2U3	Volts:	460
Serial No:	HO15-2Z346R149M	Frequency:	60
Type:	R	FL RPM	1775
Time rating:	cont	FLA:	119.9
Design:	NEMA design B	FL PF:	0
Frame:	404T	Nom. Eff:	92.4
L. R. Code:		Phases:	0
Service Factor:	1.15	Ambient °C	40
		Ins. Class	B

Test point(Motoring)(Generating)	1	2	3	4	5	6
(t_t)Stator Winding Temp, in C	100.20	83.46	57.37	44.05	37.88	32.93
Ambient Temperature, in C	24.40	23.93	23.37	23.04	24.00	21.80
Frequency, in Hz	60	60	60	60	60	60
Observed slip, in r/min	30.0	24.0	15.0	9.0	4.0	1.0
Corrected slip, in r/min	26.3	22.2	15.1	9.5	4.3	1.1
Speed, in r/min	1770.0	1776.0	1785.0	1791.0	1796.0	1799.0
Torque, in Nm	442.5	400.7	299.3	198.6	99.1	2.2
(3)Shaft Power, in W	82021.7	74525.4	55948.3	37249.2	18629.6	414.5
Line Current, in A	130.1	116.9	88.1	63.3	42.7	32.1
Power Factor, in pu	0.869	0.868	0.847	0.788	0.602	0.082
Stator Power, in kW	89.870	80.850	59.900	39.940	20.590	2.106
(a)Stator I^2*R Loss, In W, at (t_s) °C	3436.2	2774.3	1574.4	812.0	370.8	208.8
(b)Stator I^2*R Loss, In W, at (t_t) °C	3604.9	2765.0	1440.3	709.1	316.6	175.0
(4)Stator Power correction=(a)-(b)	-168.8	9.3	134.0	102.9	54.2	33.8
(5)Corrected Stator Power, in W	89701.2	80859.3	60034.0	40042.9	20644.2	2139.8
Efficiency, in %	91.44	92.17	93.19	93.02	90.24	19.37
Ts = 84.35	Rs=0.13532					
Summary of Characteristics						
Load, in % rated	109.9	99.9	75.0	49.9	25.0	0.6
Power Factor, in pu	0.869	0.868	0.847	0.788	0.602	0.1
Efficiency, in %	91.44	92.17	93.19	93.02	90.24	19.4
Line Current, in A	130.1	116.9	88.1	63.3	42.7	32.1