Electric Motor Efficiency under Variable Frequencies and Loads

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Abstract: This paper details a study performed by the Irrigation Training and Research Center to determine motor performances under varying speeds [induced by a variable frequency drives (VFD) controller] and loads. A further goal of the study was to provide sufficient information to designers so that they could estimate total pumping plant power usage with a VFD-controlled installation. Motors were tested with a VFD as well as across-the-line. On average, the relative efficiency of the electrical system with a VFD may be approximately 8% lower than the relative efficiency of a properly designed, full-load across-the-line system. If one considers actual field operating conditions this 8% is misleading because overall energy savings can be obtained with VFDs due to their ability to properly adjust speeds to meet actual field conditions.

CE Database subject headings: Variable frequency drives; Energy efficiency; Motors; Electricity; Pumps; Power usage; Irrigation.

Introduction

Electric-powered pumping by irrigation districts and farmers in the United States represents a major consumption of electricity. It is estimated (Burt et al. 2003) that the annual agricultural electric pumping usage in California is approximately 10 million MW h. Motors controlled by variable frequency drives (VFDs) have been used in many irrigation applications in attempts to save energy (ITRC 2002) and/or to improve control in pipelines or canals (Burt and Piao 2002).

Economic tradeoff analyses for comparison of VFD-controlled versus conventional single-speed motor applications for pumps require knowledge of how the efficiencies of the pump, motor, and VFD controller change as the pump flow rate or head changes. The annual energy cost is computed by knowing the hours of operation at various flow rates, the overall pumping plant efficiency at each flow rate, and the cost of power.

The procedures for combining pump curves at various speeds with irrigation system curves to determine pump efficiencies are well understood. Some pump companies such as ITT Goulds provide software that combines user-specified system curves at various revolutions per minute (rpm) for user-specified pumps (Turbine Pump Selection, Version 7, Engineered Software, Inc., Lacey, Wash., 2003).

Nominal full load efficiency standards for polyphase induction motors of various sizes have been specified by the U.S. Energy Policy Act of 1992. Those standards apply to all motors manufactured after October 1997. Motor Decisions Matter (2003), an industry group dedicated to improving motor application efficiencies, developed Table 1 for comparison.

Motor efficiency standards for other 2, 4, 6, and 8 pole motors can be found in Douglass (2005). For comparison, EPAct efficiency standards for 20 hp motors with open drip proof (ODP) enclosures are 90.2, 91.0, 91.0, and 90.2% for synchronous speeds of 3,600, 1,800, 1,200, and 900 rpm, respectively.

Motor efficiencies at a constant rpm will change as the load changes. The efficiency of a typical motor may peak at about 75% load, but it will drop rapidly below some threshold. Fig. 1 (Natural Resources Canada 2004) shows the approximate relationship for premium efficiency motors.

Wallace et al. (2002) examined the efficiencies of three motors (50, 100, and 200 hp) from each of seven manufacturers over a range (25–120%) of loads—all at the rated rpm of 1,800. At 25%, the efficiencies variations (high/low) were 94.9–90.9, 94.8–90.0, and 93.7–89.6 for 200, 100, and 50 hp motors, respectively.

The power factor (PF) of a motor at a constant rpm will also change as the load changes. Power factors listed in the Department of Energy's MotorMaster+ software (DOE 2005) vary widely among manufacturers, as did the efficiencies determined by Wallace et al. (2002). However, Fig. 2 provides a general illustration of how the PF varies with load (Natural Resources Canada 2004).

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Table 1. Full Load Motor Efficiencies at 1,800 rpm (Motor Decisions Matter 2005)

Size (hp)	Pre-EPAct	EPAct	NEMA premium
1.0	76.7	82.5	85.5
1.5	79.1	84.0	86.5
2.0	80.8	84.0	86.5
3.0	81.4	87.5	89.5
5.0	83.3	87.5	89.5
7.5	85.5	89.5	91.7
10.0	85.7	89.5	91.7
15.0	86.6	91.0	92.4
20.0	88.5	91.0	93.0
25.0	89.3	92.4	93.6
30.0	89.6	92.4	93.6
40.0	90.2	93.0	94.1
50.0	91.3	93.0	94.5
60.0	91.8	93.6	95.0
75.0	91.7	94.1	95.4
100.0	92.3	94.5	95.4
125.0	92.2	94.5	95.4
150.0	93.0	95.0	95.8
200.0	93.5	95.0	96.2

Note: Pre-EPAct: DOE's MotorMaster+ software version 4.00.01 (September 26, 2003) "Average Standard Efficiency" motor defaults; EPAct: Energy Policy Act of 1992; and NEMA Premium: NEMA MG 1-2003 Table 12–12.

For designers considering VFD applications, important questions are:

1. Will the relationships seen in Figs. 1 and 2 change with the introduction of the VFD?
2. Are there other losses that must be considered when computing the power requirement (quantity and quality) of a VFD installation?

A literature search indicates that when the economics of a VFD installation are computed, a variety of approaches for assuming motor efficiency have been used. The IAC (2006) computations assume a full-load motor efficiency at all speeds and loads. Rishel (2003) notes that "considering the thousands of variable-speed motors that are installed each year, it is the writer's opinion that an independent organization such as NEMA or IEEE should develop a program for determining the estimated efficiencies of induction motors at reduced speeds and loads . . . ."

There have been difficulties in accurately measuring the efficiency of a motor controlled by a variable speed drive. Nailen (2002) notes that in the 1980s an IEEE Working Group attempted to write a standard procedure for determining the efficiency of induction motors in VFD systems—an attempt that was abandoned at least in part because of technical difficulties. He also notes that conventional equipment for measuring input power is subject to error of unpredictable magnitude when nonsinusoidal current and voltage are being monitored.

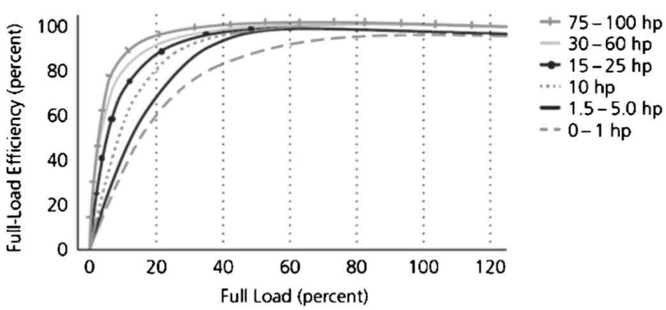

Fig. 1. Induction motor efficiency as a function of load (Natural Resources Canada 2004)

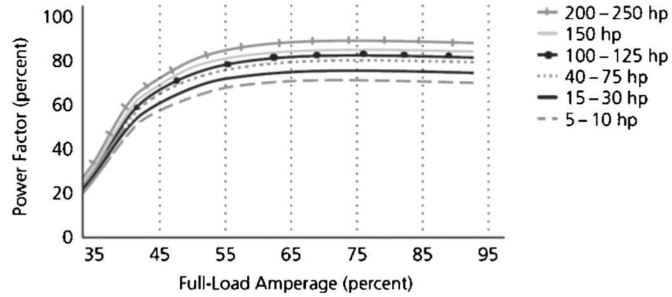

Fig. 2. Induction motor power factor (PF) as a function of full-load amperage (Natural Resources Canada 2004)

Wallbom-Carlson (1998) proposed an efficiency factor that includes losses from the VFD itself, losses generated in the motor by the VFD, and losses in the motor due to the motor duty-point movement (i.e., the change in input power requirement for the pump at the location of the intersection between the pump curve and system curve changes). He presented a theory of how a VFD efficiency factor (neglecting motor duty-point movement) would vary as a function of relative frequency. Estimates based on his proposal are seen in Table 2. The hypothesis was

$$\begin{aligned}&\text{Overall electrical efficiency}\\&\quad = (\text{VFD factor})\\&\qquad \times (\text{Motor efficiency at 100\% speed at specified load})\end{aligned} \tag{1}$$

Rooks and Wallace (2003) provided data from an unspecified motor manufacturer that was used with several assumptions to estimate the information shown in Table 3.

Research Objectives

The primary research objective of this study was to determine motor efficiencies under varying speeds (induced by a VFD controller) and loads. A broader objective was to provide sufficient information to designers and economists so that they could estimate total pumping plant power usage with a VFD-controlled installation.

Table 2. Idealized VFD Efficiency Factor (Motor Plus VFD Controller) That Ignores Motor Duty-Point Movement (Derived from Wallbom-Carlson 1998)

Rated motor frequency (%)	VFD efficiency factor
100	0.97
90	0.945
80	0.92
70	0.90
60	0.875
50	0.85
40	0.825

Table 3. Motor Efficiencies with VFD Control (Derived from Rooks and Wallace 2003)

Name plate rated hp at 60 Hz	Motor efficiency at various relative speeds (RS) and relative loads (RL) RS/RL		
	100/80	75/34	50/10
50	94.9	94.1	84.5
100	96.0	93.7	87.0
200	96.4	93.8	86.0

Procedures and Methods

The motor testing configuration at the Water Delivery Facility on the California Polytechnic State Univ. campus consisted of:

1. *Electrical supply (Fig. 3):* The electrical supply was configured to operate motors across-the-line (ATL) or via a 100 hp Danfoss VLT 8000 AQUA VFD controller. The configuration also included a Kooltronic RP52 14,000 BTU air conditioner connected to the VFD aluminum enclosure.
2. *Motor test stand (Fig. 4):* The motor was bolted on a machined rotating base plate. The torque developed by the motor was measured (Honeywell Model IC48 150 lb range load cell) by sensing the tension created by a long base plate arm extension at a specific distance from the center of the motor. The load on the vertical pump shaft was created by a Denison Hydraulics Goldcup Series P7P closed circuit piston pump.

The load creator (hydraulic pump) was designed and fabricated with the following criteria: (1) Adapt to different motor shaft sizes (lengths and diameters); (2) create a constant load anywhere between 1 and 100 hp; and (3) create a torque ranging from 25 to 500 ft lbs. Water to cool the hydraulic oil was filtered by three 36 in. sand media tanks and pumped through a BPS-70-12×5 brazed plate cooler manufactured by ThermaSys Corporation.

3. *Motors:* Twelve 60 Hz, 460V ODP vertical hollowshaft motors were tested. Table 4 provides the nameplate specifications.
4. *Measurements:* During each test, measurements were made of the following data:
   - rpm of the motor;
   - Torque developed by the motor, which consisted of the lever arm at which a force was measured and the force developed; and
   - Electric power characteristics before and after the VFD or ATL panel.

Fig. 3. Electrical supply for the motor testing

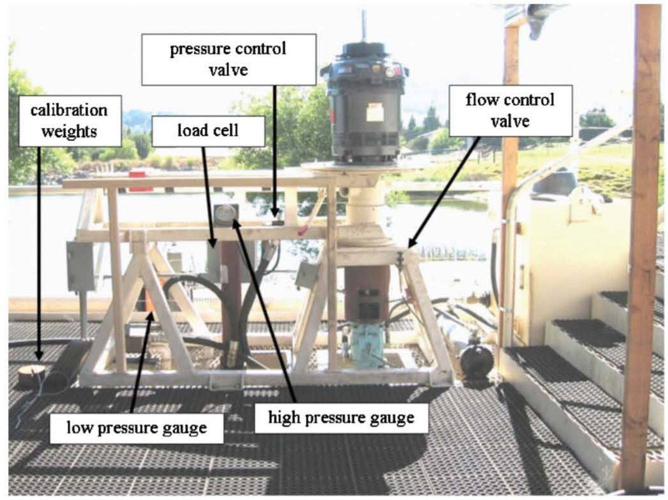

Fig. 4. Motor test stand

An overview of the measurements is provided in Fig. 5.

Data were automatically logged on two laptop computers (LT21 and LT11). Redundant data and some trial observations were manually logged. The LT11 computer was programmed with National Instruments Lookout HMI software to display and log the data.

rpm: A Monarch Instruments ACT-2A Panel Tachometer was used to measure the motor shaft rpm, with values downloaded to Lookout. Readings from a handheld Extech Instruments Combination Photo Tachometer/Stroboscope (Model 461825) that used reflective tape on the shaft were also taken. As long as the two readings were close (within ~5 rpm), the Lookout reading was recorded.

The convention used when reporting "100% rpm" was to use the actual across-the-line motor rpm and consider it to be 100%. For example, with a four-pole motor, when the VFD controller was used, the frequency was adjusted to achieve 1,765 rpm rather than 1,800 rpm when testing at 100% rpm.

Table 4. Motors Used in Testing and Their Name Plate Specifications

ITRC ID	Manuf.	Nom. hp	Nom. rpm	PF	EFI	Amps	Other
AO1	U.S.	20	1,765	85.6	87.5	24.3	VFD rated
AO2	GE	20	1,175	85	91	24.1	
AO3	U.S.	20	1,770	85.4	92.4	23.7	Premium
AO5	U.S.	75	1,780	85.3	95	87	Premium
AO6	GE	100	1,780	ns	91	124	
AO9	U.S.	40	1,780	85.7	88.5	49	
AO10	GE	75	1,785	85	95	87.1	
AO11	GE	50	1,775	ns	ns	61.1	
AO12	U.S.	50	1,780	87.5	94.5	56	Premium
AO13	U.S.	40	3,515	89.5	90.2	46	
AO14	U.S.	75	895	74.3	94.1	100	
AO15	GE	50	1,185	ns	91.7	61.2	

Note: ns=not stated on the nameplate; GE=General Electric; and U.S. =US Motors or Emerson.

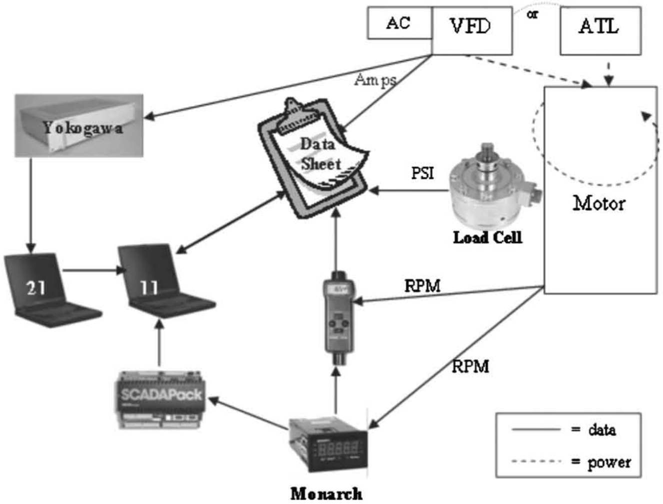

Fig. 5. Data collection

Torque: The load cell was placed at one of five locations (Table 5), each measured within ± 0.1 mm. The calibration of the load cell was checked at the beginning and end of each test set using standardized weights. Determining the proper way to mount and calibrate the load cell to obtain the correct horizontal force reading was one of the most challenging aspects of this project. Problems with vibrations, impact forces, and vertical forces due to the weight of the torque arm were all overcome.

The torque was calculated as

$$\text{Ft-lb of torque} = \text{Distance} \times \text{Force} \qquad (2)$$

The output horsepower of the motor was then computed as

$$\text{Output horsepower} = (\text{Ft-lb of torque}) \times (\text{rpm}/5{,}252) \qquad (3)$$

Electric power characteristics: This research measured both the efficiency of the VFD controller and the efficiency of the motor. Therefore, it was necessary to measure the electric power between the VFD controller and the motor. The wave forms of input to a VFD controller are sinusoidal, whereas the output wave forms are not. The controller output wave forms are chopped dc pulses that mimic an ac sinusoid—characteristic of a pulse width modulation (PWM) VFD controller. The signal from a PWM-type VFD overlaid on a sinusoidal signal is shown in Fig. 6.

Because of the nature of the output wave form, special electronic measurement equipment was needed. A Yokogawa/GMW Danfysik Ultrastab 866R multichannel current transducer system provided six transducers (one for each phase in and out of the VFD) with power and signal conditioning.

Data from the current transducer system were then fed into a Yokogawa WT1600 digital power meter and communication interface. The signals from the Yokogawa power meter were processed in a laptop computer (LT21) that was configured with

Table 5. Load Cell Locations on Pivot Arm for Measuring Torque; Average Distances between Points

Unit	Center to first	Center to second	Center to third	Center to fourth	Center to fifth
Feet	1.036	2.023	3.013	4.017	5.020
Millimeter	315.7	616.6	918.4	1224.3	1530.0

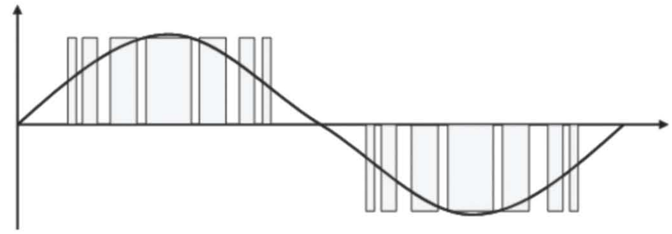

Fig. 6. Pulse width modulation signal compared to sinusoidal

LabView real-time module software. This processed data was then passed from laptop LT21 to LT11, where the data was logged and displayed in Lookout.

The electric power data collected were:

- Amperage on each phase before and after the VFD;
- Voltage on each phase before and after the VFD;
- VFD frequency;
- Active power before and after the VFD;
- Apparent power before and after the VFD; and
- Power factor.

IEEE Standard 112-2004: The Institute of Electrical and Electronics Engineers (IEEE) developed IEEE Standard 112-2004 for testing polyphase electric induction motors. Specifically, Efficiency Test Method B covers the type of procedure used in this research. Many portions of this test standard are used if one wants to separate the components (friction and windage, core, stator, and rotor) of motor losses. It also provides computational procedures for correction factors for stray-load, non-standard temperatures, and other factors. The procedures used in this research did not have a goal of identifying the component losses, and did not apply the IEEE Standard 112-2004 corrections because they were judged to have an insignificant impact on the conclusions of this research project

Ongoing quality control: Ongoing quality control of data was maintained by frequent calibration of the load cell, redundant measurements of the motor rpm, and the use of high quality electric power measurement equipment. Each motor was run continuously for a minimum of 12 h immediately before any measurements were made. To further check for errors, the full set of tests was duplicated for each motor on the same day, after completion of the first set of tests

Results

Power Factor

The curves in Fig. 7 show how the power factor (PF) varies with load when a motor is operated ATL. One curve is also included that contains the PF measured in all VFD tests. The Fig. 7 curves somewhat resemble the dimensionless curves seen in Fig. 2 from Natural Resources Canada (2004).

The important point from Fig. 7 is that when operated with this particular VFD controller, the PF is simply a function of the applied load, regardless of the nominal horsepower or nominal speed of the motor. This is highlighted in Fig. 8, which shows only the VFD curve from Fig. 7. Fig. 8 also shows that the lowest power factor measured was 0.65, which is considerably higher than the lowest PFs measured with ATL conditions at low output horsepowers. Because only one VFD controller was used, it is impossible to say how other VFD controllers would influence the PF.

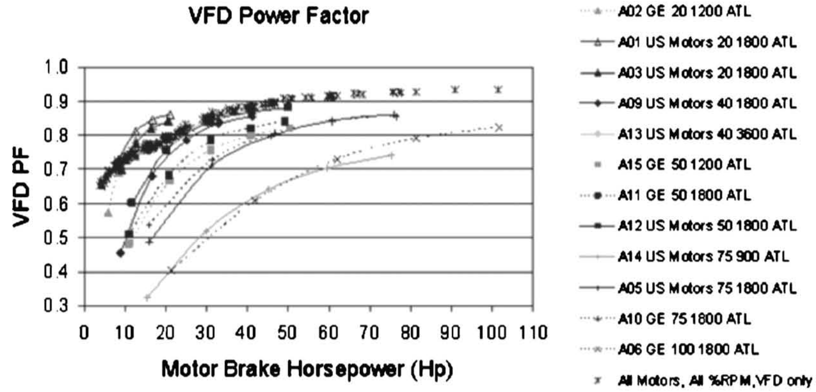

Fig. 7. Power factor versus load. One curve shows all VFD results; all others are across-the-line. Note: The legend for this figure is also applicable to Figs. 8–12.

VFD Controller Efficiency

The efficiency of the VFD controller was found to depend somewhat on the particular motor that was tested. In particular, the VFD efficiency when testing the 900 rpm (nominal) 75 hp motor averaged about 1% lower efficiency than with the 1,200, 1,800, and 3,600 rpm (nominal) motors.

Figs. 9 and 10 show VFD efficiencies at two rpms and various load factors. Other efficiencies were measured at increments of 10% nominal rpm, with similar results. These results coincide with the claims of high efficiency given by manufacturers of high quality, recent designs of VFD controllers. The efficiency does drop somewhat at very low loads, but in no case did it fall below 95%.

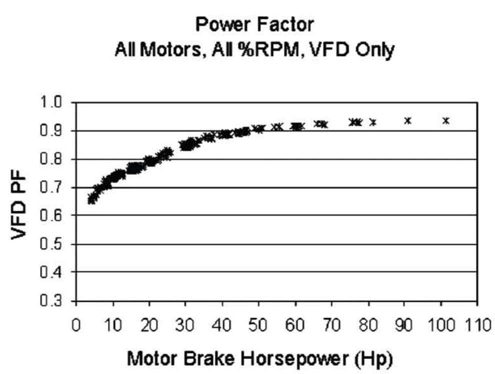

Fig. 8. Power factor versus motor output horsepower for all motors tested with Danfoss VFD controller. No across-the-line values. This curve was extracted from Fig. 7.

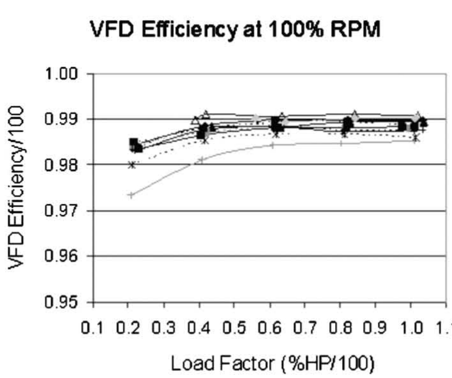

Fig. 9. VFD controller efficiency with various motors at 100% rpm and varying loads

Motor Efficiency

Fig. 11 depicts motor efficiencies for ATL operation. It is clear that there are differences between individual motors. The lowest efficiency is from a 20 hp U.S. Motors motor (A01) that is designated as suitable for a VFD, and the highest efficiency is from another 20 hp U.S. Motors motor (A03) that is designated as a "premium" motor. Four of the motors (A02, A03, A05, and A09) maintained a very high efficiency (close to 95%) across the span of relative loading.

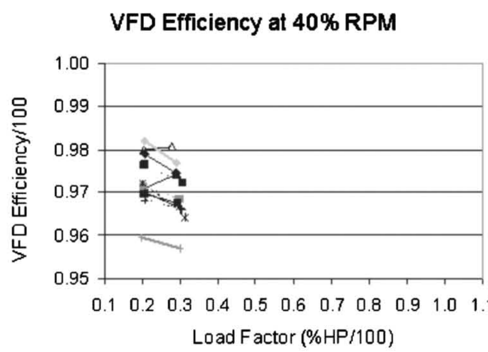

Fig. 10. VFD controller efficiency with various motors at 40% rpm

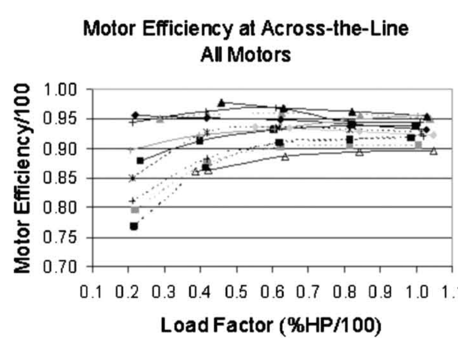

Fig. 11. Efficiencies of all motors, across-the-line, at various relative loads

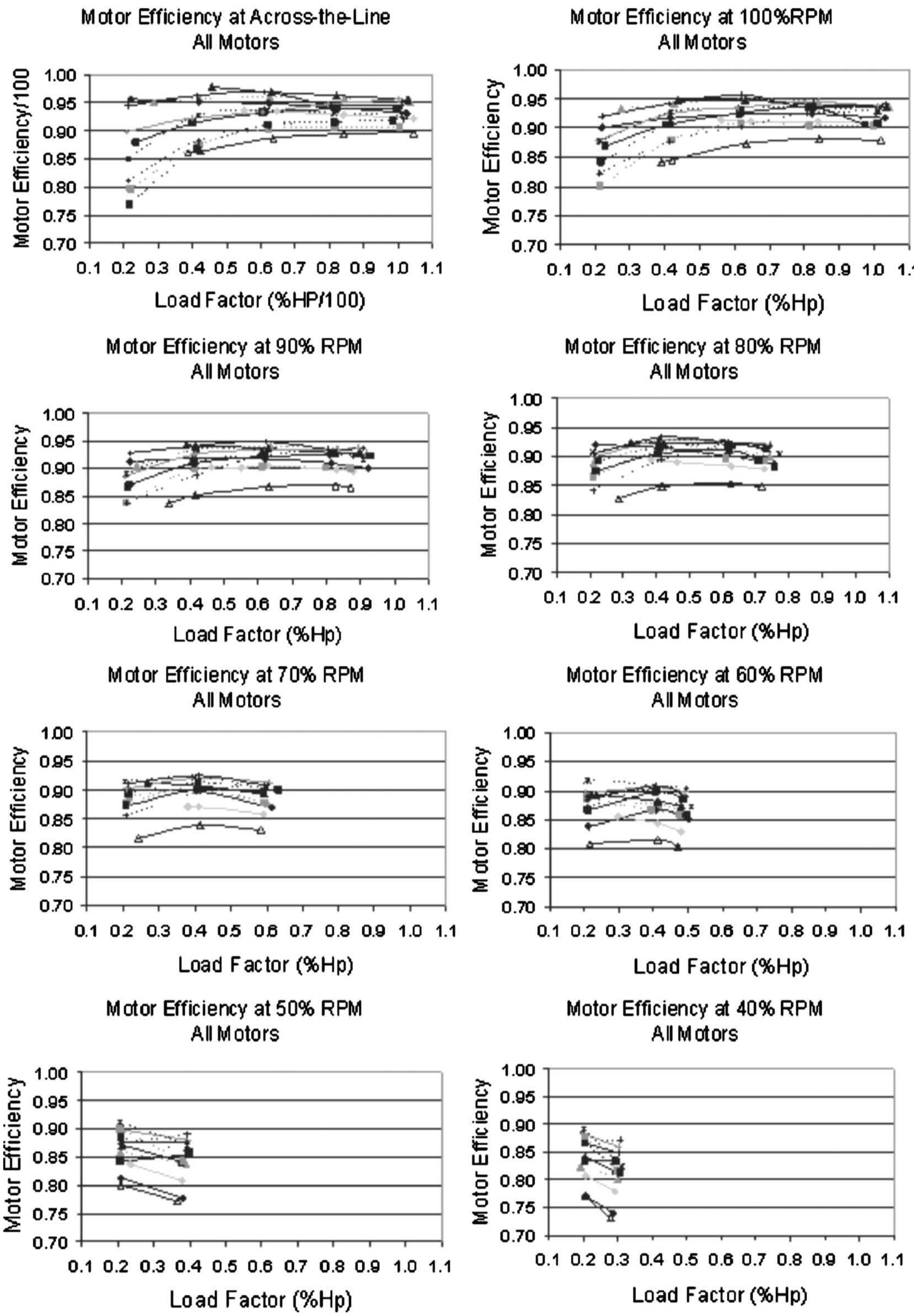

Fig. 12. Motor efficiency at 10% rpm increments under various loads

Fig. 12 shows the performance of motors under various relative loads, at different rpms—including a repeat of Fig. 11 in the upper left-hand corner for scale comparison.

A fundamental question is whether motor efficiencies stay the same if the motor is subjected to various loads when ATL, as compared to when the electric power comes through a VFD controller. Table 6 shows the pertinent values from the testing. The answers appear to be:

1. On the average, there is no apparent difference;
2. For an individual motor, differences as large as 18% were observed;
3. Relative motor efficiencies can be higher or lower with a VFD;
4. There appears to be more variation in performance between motors as the relative loads and relative rpms decrease; and
5. At 100% relative rpm, there was no more than $a \pm 5\%$ difference in motor efficiency;

There was no noticeable difference between premium and stan-

Table 6. Relative Motor Efficiencies with and without VFD Control

Relative rpm	Relative load	Ratio of VFD/ATL Average	Minimum	Maximum
40	0.2	0.99	0.86	1.10
60	0.2	1	0.87	1.18
60	0.4	0.96	0.9	1.03
100	0.2–1.0	0.99	0.94	1.04

Note: VFD/ATL=relative motor efficiency =(motor efficiency with VFD control)/ (motor efficiency across-the-line); Relative load=relative load placed on the motor, e.g., a relative load of 0.4 on an 80 hp motor equals 0.4×80 hp=32 hp; Relative rpm=relative rpm, e.g., a relative rpm of 60 on an 1,800 rpm motor equals $0.6 \times 1{,}800$ rpm=1080 rpm; Average=average value of all tests with this combination of relative rpms and loads; Minimum=minimum value of all tests with this combination; and Maximum=maximum value of all tests with this combination.

dard motors regarding their relative efficiencies at different relative rpms and relative loads.

Air Conditioning Power Requirement

Variable frequency drive controllers generate heat through their inefficiencies. Although the inefficiency may be small, 3% of a 100 hp unit represents 3 hp of heat that must be dissipated. Air conditioning (AC) units—either directly mounted to the VFD panel, or constructed to cool the entire motor control center building—are standard practice for irrigation applications.

None of the extensive literature that was examined regarding VFD efficiency made any mention of the additional power required for air conditioning. This research project did not examine the details of AC power requirements. Depending upon the heat released, ambient temperature, and AC design, the power requirement will vary. The authors suggest that if the VFD controller is 97% efficient, and the AC unit is 50% efficient, the additional power requirement for the AC unit can be estimated as:

$$(100\% - 97\%) \times 2 \times \text{Input HP} \tag{4}$$

For example, for a full load input of 110 hp to a VFD controller that operates at 97% efficiency, the additional power requirement at full load would be Additional power$=3\% \times 2 \times 110$ hp $=6.6$ hp

Conclusions

The results of this research lead to the following conclusions that appear to be either unknown or minimally advertised:

1. Commercially available variable frequency drive (VFD) controllers are available that provide significant improvement of the power factor of motors, when compared to across-the-line applications.
2. The efficiency of a VFD controller appears to be slightly impacted by the motor that it is controlling.
3. The following can be stated for the average condition when a motor is subjected to varying loads: The efficiencies of a motor that is operated by a VFD controller will be about the same as the efficiency of a motor that is operated across-the-line. However, some motors operate with either a higher or lower relative efficiency and simultaneously being controlled by a VFD controller instead of operating across-the-line.
4. The additional power requirement of an air conditioner for the VFD controller must be considered when determining the total power requirement for the unit and the initial and annual costs.

The data from this research confirm the following frequently noted points:

- Commercially available VFD controllers maintain high efficiencies across practical ranges of loads and frequencies.
- Efficiency computations for induction motors that operate under varying loads must consider the significant change in motor efficiency that can occur as the load changes. In particular, motor efficiencies can drop by about 10% as the relative load drops from 60 to 20%. The changes in motor efficiencies as the relative load varies from 100 to 60% are relatively minor.
- When working above relative loads of 40%, the inherent efficiency of the motor itself is more important than the variation in efficiency due to changing loads.

In summary, on the average, the relative efficiency of the electrical system with a VFD may be about 8% lower than the relative efficiency of a properly designed, full-load across-the-line system. This 8% value assumes no change in motor efficiency, a 3% loss in efficiency through the VFD controller, and a parallel 5% additional power requirement for the air conditioner

The 8% is a number that has not historically been available. At first glance, it appears that VFD-controlled applications may not be economical if there is a drop of 8% efficiency. However, the 8% is only part of the story. The 8% assumes that the across-the-line system was truly properly designed. A system with a VFD can adjust for errors, but an across-the-line system cannot adjust for errors in estimations of total head or flow rate requirements.

Further, the electric system efficiency is only one part of the overall electric pumping system. To determine the relative efficiency of an overall *electric pumping* system, one must also account for the changing pump efficiency over time and at different operating points, and the ability of a VFD-controlled system to reduce the total pressure or flow requirement when needed. This research project did not examine those benefits, although they have been well documented by ITRC and others. In addition, for many irrigation pumping applications the improved control of pressures or flows is the dominant benefit rather than power savings.

Acknowledgments

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