

VARIABLE FREQUENCY DRIVE (VFD) CONSIDERATIONS FOR IRRIGATIONC. M. Burt¹F. Gaudi²X. Piao³**ABSTRACT**

This paper covers considerations in VFD applications, plus details a study performed by the Irrigation Training and Research Center (ITRC) to determine motor performances under varying speeds (controlled by a VFD) and loads.

Keywords: variable frequency drives, energy efficiency, motors, electricity, pumps, power usage, irrigation

INTRODUCTION

Variable frequency drive-controlled (VFD) motors have been used in many California irrigation applications to save energy (ITRC, 2002) and/or to improve control in pipelines or canals (Burt and Piao, 2002). Over the past 10 years our knowledge of proper applications and hardware has improved, and the prices of good equipment have dropped. These factors combine to make VFD applications quite appealing.

This paper presents a discussion of VFD concepts, the results of some research conducted at the Irrigation Training and Research Center (ITRC) at Cal Poly (funded by CSU/ARI and the California Energy Commission, and US Bureau of Reclamation), as well as examples of successful applications in irrigation districts.

Motor Performance at a Constant RPM (Constant Electric Frequency)

Nominal full load efficiency standards for polyphase induction motors of various sizes were specified by the US Energy Policy Act (EPAct) 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.

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Table 1. Full Load Motor Efficiencies at 1800 RPM

Size (hp)	Pre-EPAct ^a	EPAct ^b	NEMA Premium ^c
1.0	76.7	82.5	85.5
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

- Pre-EPAct: DOE's MotorMaster+ software version 4.00.01 (9/26/2003) "Average Standard Efficiency" motor defaults
- EPAct: Energy Policy Act of 1992
- NEMA Premium: NEMA MG 1-2003 Table 12-12

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%, 90.2% for synchronous speeds of 3600, 1800, 1200, and 900 RPM, respectively.

Single speed motor (i.e., a constant RPM) efficiencies will change as the output load changes. The efficiency of a typical motor may peak at about 75% load, but it will drop rapidly below some threshold load. Figure 1 shows the approximate relationship for premium efficiency motors.

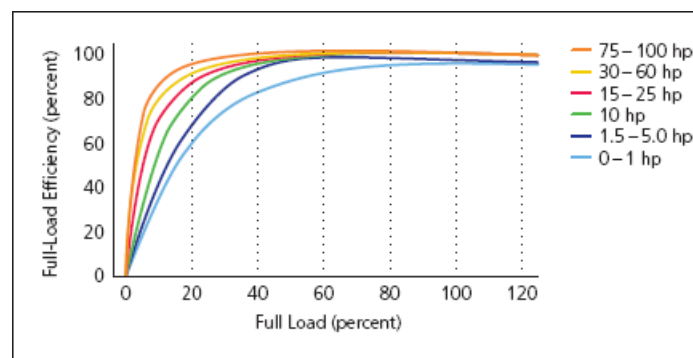


Figure 1. Induction motor efficiency as a function of load (Energy Innovators Initiative, 2003)

Wallace et al (2002) examined the efficiencies of three motors (50 HP, 100 HP, and 200 HP) from each of seven manufacturers over a range (25% to 120%) of loads – all at the rated RPM of 1800. 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) influences the wire sizing to the motor, and the possibility of a motor overheating. The lower the PF, the larger the current requirement for a specific load will be. The PF of a motor at a constant RPM will change as the load changes, similar to the efficiency change. 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, Figure 2 provides a general illustration of how the PF varies with load for constant RPM applications.

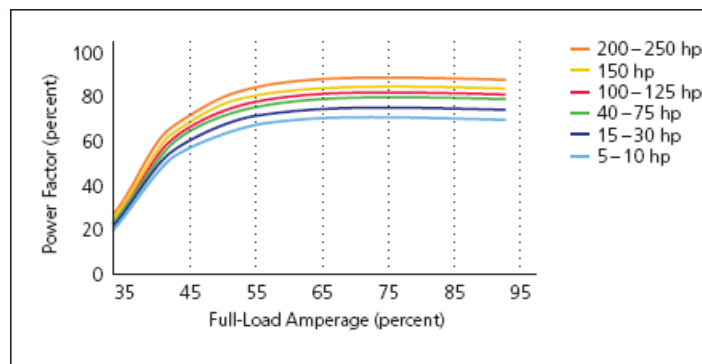


Figure 2. Induction motor power factor (PF) as a function of full-load amperage (Energy Innovators Initiative, 2003)

Variable Frequency Drive Fundamentals

As long as the frequency of the incoming power to the motor remains constant, the RPM of the motor will remain relatively constant. This is because the motor rotor turns when the moving magnetic field induces a current in the shorted conductors. The synchronous speed of the magnetic field is:

$$\text{Synchronous RPM} = \frac{F \times 120}{P}$$

where F = the frequency in Hz, and
 P = the number of stator poles in any multiple of two.

For example, the synchronous speed of a four-pole motor is 1800 RPM in a 60-Hz system. Because induction motors must rotate slower than the magnetic field to produce torque, there is a slight speed difference (called “slip”) between the rotor and magnetic field. The result is that the actual speed of a 4 pole motor is closer to 1750 RPM rather than 1800 RPM.

Special panels with electronic components to change the frequency from 60 Hz (in the US) to some other frequency are called “VFD controllers”. They are often used to convert existing motors to variable speed applications, although with new installations the motors are generally specified as being suitable for VFD applications.

The wave forms of input to a VFD controller are sinusoidal, while 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 Figure 3.



Figure 3. Pulse Width Modulation signal compared to sinusoidal. Courtesy ITT Flygt (2002)

Pump Operation with VFD Controlled Motors

There are 3 reasons to consider using a VFD controller with pumps:

1. Proper matching of the pump characteristics with the system. This first reason is poorly acknowledged in economic comparisons. Reality is such that in the field, reasonable engineers and salespersons will almost always overdesign pumps. It is very simple – if the pump is too small, there will be complaints. If, on the other hand, the pump delivers a bit more pressure than needed, there is rarely a complaint. Reasons to overdesign include:
 - a. Pumps eventually have wear, and the impellers are in effect “trimmed” over time.
 - b. Pumps rarely have certified performance. The pump curves are accurate within some loosely defined plus/minus accuracy. A designer must err on the side of caution.
 - c. The hydraulics of the system are not precisely known. Losses through various fittings can be quite different from theoretical values, and often the as-built system includes valves, fittings, etc. of different models than what were specified. Even good designers typically add a certain pressure requirement for “miscellaneous” (a factor of safety).
 - d. Source water levels change with time. River levels go up and down. Aquifer depths change from year to year, and throughout the year. There is no one “correct” lift value; the designer must design a pump for the maximum value.
2. Flow rate requirements may change with time. When the flow rate requirement for a system decreases, the operators must either bypass the extra flow, or dissipate the extra pressure developed with a lower flow rate. Both situations require more power consumption by the pump motor than what would ideally be needed. In these cases, a VFD-controlled pump can often save energy during periods of low flow.

3. Precise control of water levels or pressures requires the ability to fine-tune flow rates. VFDs provide that capability. For automatic control of canal water levels, for example, ITRC frequently uses VFD-controlled pump motors. Power savings is only a secondary concern.

Figure 4 illustrates several points about VFD control of pump motors that can be useful to know for automation projects.

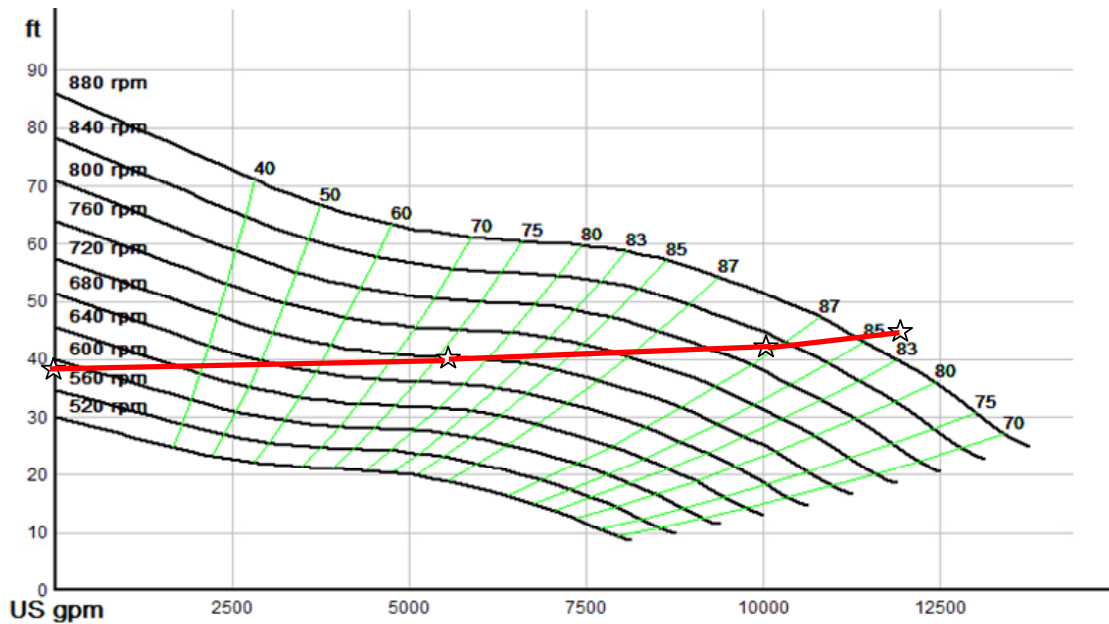


Figure 4. System curve overlain on pump curves of various RPMs. Pump curves were developed in software available from Goulds Pump (Goulds, 2003).

Points from Figure 4 include:

1. Figure 4 illustrates a common irrigation district situation in which there is a static lift from the source to the discharge. In this case, it is about 40’.
2. The RPM at zero flow rate is not zero. Rather, in this case it is about 590 RPM, which is 67% of the maximum (880 RPM) shown on the pump curves. This is important, because the fan that cools the motor should still be effective at 67% speed.
3. The change in GPM per 40 RPM change in speed is quite variable. For control, this means that the required change in pump speed to accomplish a change of flow of, say 50 GPM, is quite different depending upon what the RPM is.
4. The system curve extends past the 880 RPM curve. VFD controllers are capable of operating a motor at higher-than-nominal speed, as well as at a lower-than-nominal speed. This, of course, requires sufficient sizing of the VFD controller.

Efficiency of Electrical Components with VFD Systems - General.

For designers considering variable frequency drive (VFD) applications, important questions are:

1. Will the relationships seen in Figures 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 ...”.

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. He presented an estimate of how a VFD Efficiency Factor (neglecting motor duty-point movement) would vary as a function of relative frequency. His estimate is seen in Table 2. The hypothesis was that

Overall electrical efficiency = (VFD Factor) × (Motor efficiency at 100% speed at specified load)

Table 2. Idealized VFD Efficiency Factor (motor plus VFD controller) that ignores motor duty-point movement (Wallbom-Carlson, 1998).

% of Rated Motor Frequency	VFD Efficiency Factor
100	.97
90	.945
80	.92
70	.90
60	.875
50	.85
40	.825

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.

Table 3. Motor Efficiencies with VFD control (Rooks and Wallace, 2003).

Nameplate 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

Efficiency of Electrical Components with VFD Systems – ITRC Research

ITRC conducted extensive testing of the efficiency of a VFD controller (100 HP Danfoss VLT 8000 AQUA VFD controller) with a variety of electric motors. The configuration also included a Kooltronic RP52 14,000 BTU Air Conditioner connected to the VFD aluminum enclosure. Figure 5 shows the panel arrangement. Details of the testing and results are presented in Burt et al (2007).



Figure 5. Electrical supply for the motor testing

For testing, individual motors were bolted on a machined rotating base plate (see Figure 6). 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.

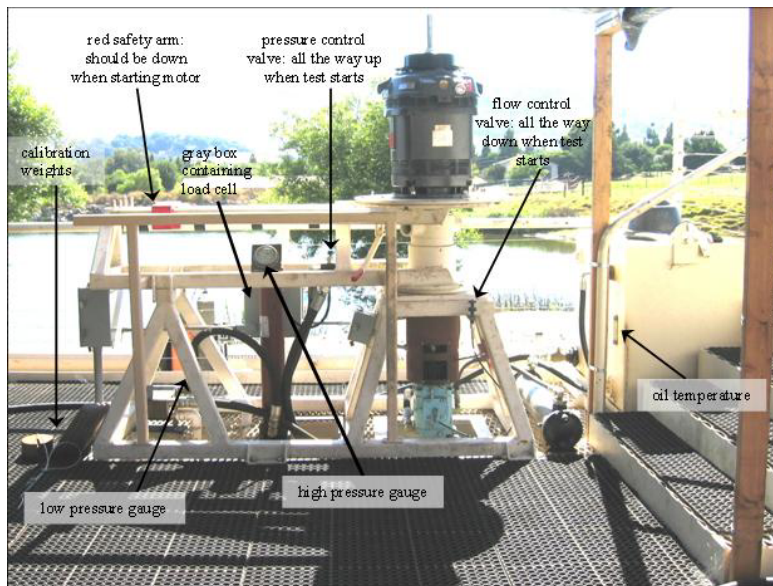


Figure 6. ITRC motor test stand.

Twelve 60 Hz, 460V ODP vertical hollowshaft motors were tested. Table 4 provides the nameplate specifications.

Table 4. Motors used in testing and their nameplate specifications.

ITRC ID	Manuf.	Nom HP	Nom. RPM	PF	EFI	Amps	Other
AO1	US	20	1765	85.6	87.5	24.3	VFD rated
A02	GE	20	1175	85	91	24.1	
AO3	US	20	1770	85.4	92.4	23.7	Premium
AO5	US	75	1780	85.3	95	87	Premium
AO6	GE	100	1780	ns	91	124	
AO9	US	40	1780	85.7	88.5	49	
AO10	GE	75	1785	85	95	87.1	
AO11	GE	50	1775	ns	ns	61.1	
AO12	US	50	1780	87.5	94.5	56	Premium
AO13	US	40	3515	89.5	90.2	46	
AO14	US	75	895	74.3	94.1	100	
AO15	GE	50	1185	ns	91.7	61.2	

Notes: ns = not stated on the nameplate

GE = General Electric

US = US Motors or Emerson

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 6 transducers (one for each phase in and out of the VFD) with power and signal conditioning. Data from the Current Transducer System was 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 LabView Real-time Module software. This processed data was then passed from laptop LT21 to a second laptop (LT11) on which National Instruments Lookout HMI/SCADA software was installed.

Power Factor. The curves in Figure 7 show how the Power Factor varies with load when a motor is operated across-the-line (ATL).

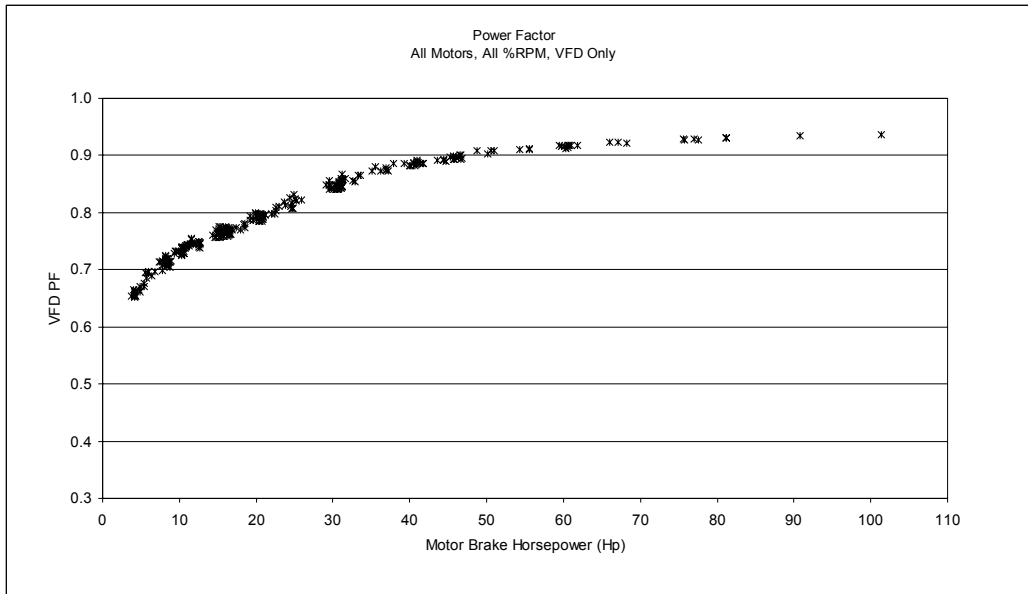


Figure 7. Power Factor versus motor output horsepower for all motors tested with Danfoss VFD controller.

VFD Controller Efficiency. The efficiency of the VFD controller itself 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 1200, 1800, and 3600 RPM (nominal) motors.

Figures 8 and 9 show VFD efficiencies at two RPMs and various Load Factors. Other efficiencies were measured at increments of 10% nominal RPM, with similar results.

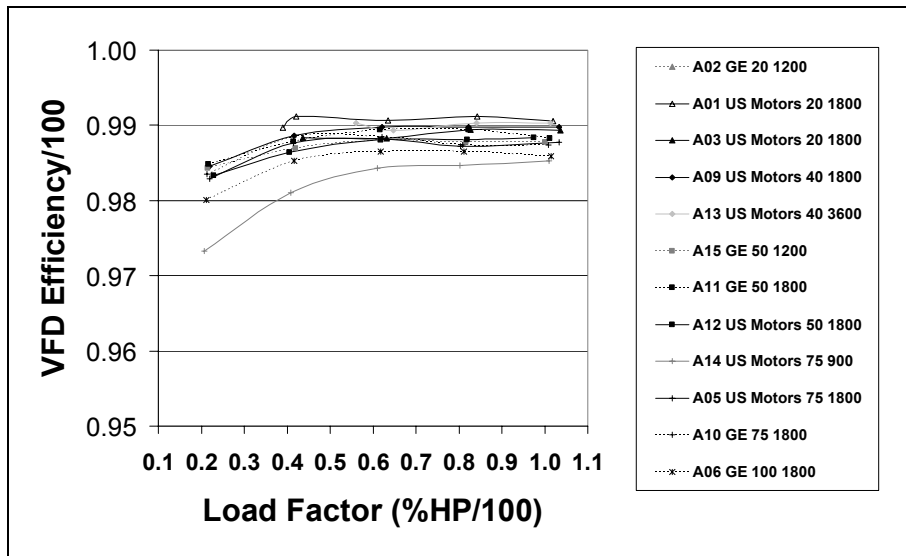


Figure 8. VFD controller efficiency with various motors at 100% RPM and varying loads.

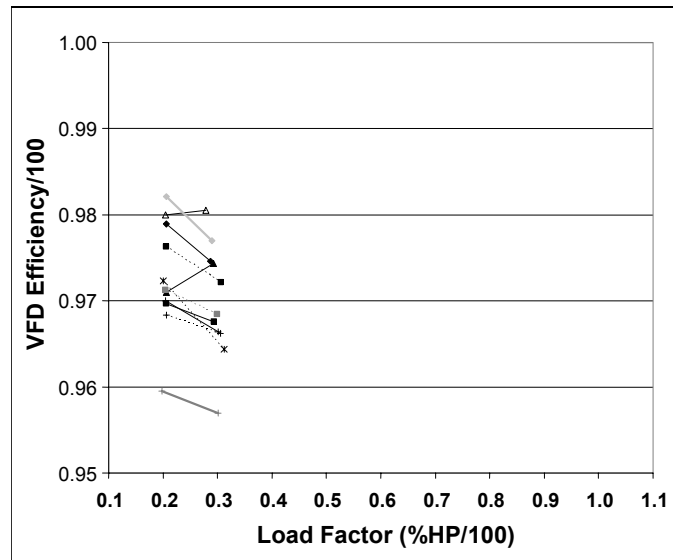


Figure 9. VFD controller efficiency with various motors at 40% RPM. Same legend as Figure 8.

Motor Efficiency. Figure 10 depicts motor efficiencies for across-the-line operation. It is clear that there are differences between individual motors. The lowest efficiency is from a 20 HP US Motors motor (A01) that is designated as a being suitable for a VFD, and the highest efficiency is from another 20 HP US 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.

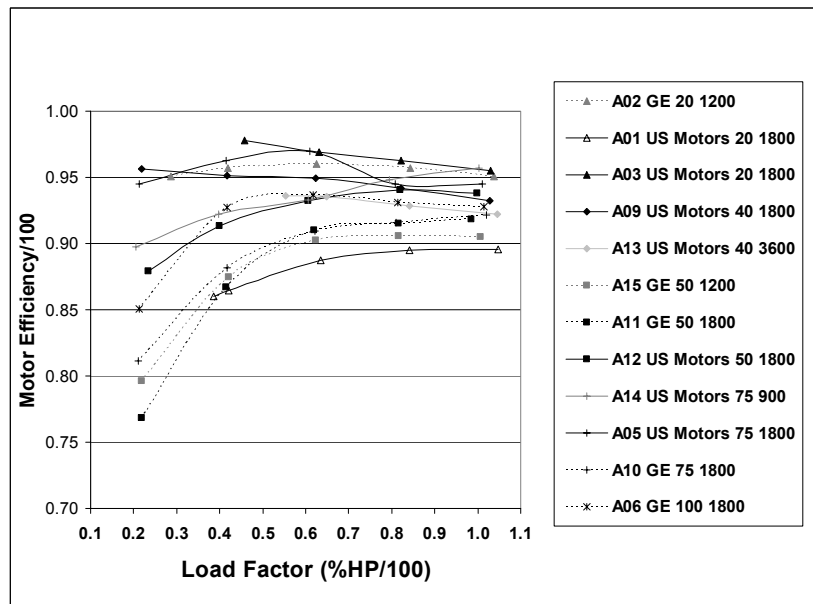


Figure 10. Efficiencies of all motors, across-the-line, at various relative loads

Figure 11 shows the performance of motors under various relative loads, at different RPMs – including a repeat of Figure 10 in the upper left hand corner for scale comparison.

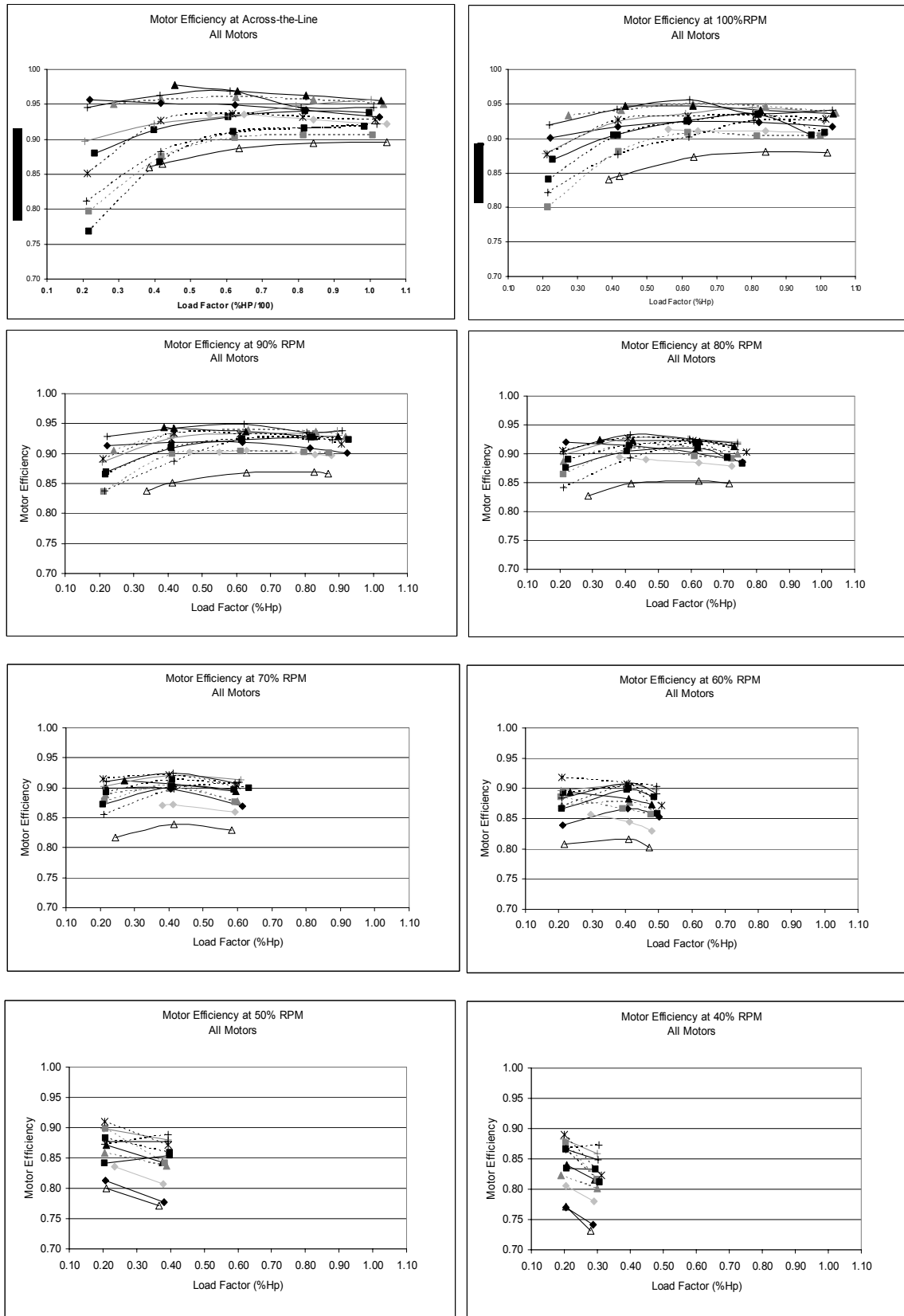


Figure 11. Motor efficiency at 10% RPM increments under various loads

Air Conditioning Power Requirement. The inefficiencies of variable frequency drive controllers are manifested as heat generation. Although the inefficiency may be small (3-5%), 3% of a 100 HP unit represents 3 HP of heat that must be dissipated. Air Conditioning units – either directly mounted to the VFD panel, or constructed to cool the entire motor control center building – are standard practice for irrigation applications. The authors suggest that if the VFD controller is 97% efficient, the additional power requirement for the AC unit can be estimated as $(100\% - 97\%) \times 2 \times \text{Input HP}$. 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 (assuming 50% efficiency of the AC unit) would be:

$$\text{Additional Power} = 3\% \times 2 \times 110 \text{ HP} = 6.6 \text{ HP}$$

CONCLUSIONS

1. There are a variety of reasons to use variable frequency drive controllers for pumps – only some of which involve power savings.
2. Proper application of VFD-controlled pumps in irrigation automation requires a good understanding of pump curves and hydraulic system curves.
3. 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.
4. The efficiency of a VFD controller appears to be slightly impacted by the motor that it is controlling.
5. The efficiencies of a motor that is operated by a VFD controller will be about the same as the efficiencies of a motor that is operated across-the-line.
6. 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.

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 design, full-load across-the-line system. This 8% value assumes:

- No change in motor efficiency
- A 3% loss in efficiency through the VFD controller
- A parallel 5% additional power requirement for the Air Conditioner

However, it was pointed out in this paper that it is standard for pumps to be oversized, and for operating conditions to change over time. Therefore, one must look at much more than the electrical system efficiency to estimate power savings. It is entirely possible for a pump to deliver twice the pressure needed (and therefore consume twice the power needed), yet operate at a high mechanical and electrical efficiency. In general, anecdotal evidence and some limited data from irrigation districts show that with VFD pump applications, power consumption is reduced.

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