Electric Motor and Belt Retrofits: Measured Savings and Lessons Learned

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This paper presents an analysis of the measured changes in energy consumption for retrofits of electric motors and belt drives. The purpose of the paper was to study the effect of the correct application of motors and belts for proper operation and energy efficiency. The lessons learned are most applicable to motor retrofits, but also apply to any motor selection exercise, whether retrofit, new, or troubleshooting an improper application.

Three-phase motors ranging in size from fractional to 75 horsepower were replaced, as were belt drives ranging from 3 to 20 hp. The primary applications were fans and pumps in commercial buildings. The energy savings on individual motor applications ranged from −16 to 40%; belt drive savings ranged from −2 to 12%. The paper discusses the results and lessons learned, including what went wrong when savings predictions were not realized; how to select, specify and procure the most appropriate motor and belt drive for the application; and why, contrary to conventional wisdom, oversizing motors and switching from T-frame to U-frame motors often makes sense when retrofitting motors for energy efficiency. Motor and belt noise are also discussed.

INTRODUCTION

Background

At two sites, 3-phase alternating current, single-speed motors not controlled by adjustable-speed drives (ASDs), generally driving loads of nominally constant flow were selected out of the wider pool of motors. Motors eliminated from consideration included single-phase or direct-current units, those operating on ASDs, or with too little operating time for a cost-effective retrofit. This paper expands on the work of previous retrofits (e.g. Lobodovsky, Ganeriwal & Gupta 1989; Wilke & Ikuenobe 1987), in that motors as small as 1/3 hp were retrofitted, motors were upsized as well as downsized, and belt retrofits were included.

Scope

The retrofit projects were intended to capture savings from improving the energy efficiency of the motor itself, generally (with the exception of selected belt drives) independent of other system issues. Of course, many electric motor systems have larger savings opportunities in other areas ranging from load reduction to controls; it is beyond the scope of the projects and this paper to discuss those in detail, but the reader is encouraged to consult such references as Nadel, et al. 1991.

METHODOLOGY

Site A

At this site, both motor and belt retrofits were performed. As noted, the motors were previously screened for likely cost-effective retrofits. Funding was obtained based on economic analysis of the estimated retrofit savings. While such analysis is beyond the focus of this paper, it is well covered by, e.g. Biesemeyer & Jowett 1994, and Nadel et al. 1991. The retrofit process consisted of:

- measuring input voltage and power and motor and device speed(s);
- selecting replacement motors using MotorMaster (WSEO 1995) database and manufacturers' catalog and technical information;
- installation; and
- measuring input voltage and power and motor and device speed(s).

For belt applications, once the motor was selected, the retrofit involved:

- selecting belts using manufacturer's selection software;
- re-measuring input voltage and power and motor and device speed(s);
- installing belts;
- re-measuring input voltage and power and motor and device speed(s).

Voltage and power were measured using portable electronic meters, and shaft speeds were measured using a stroboscopic tachometer. In order to estimate motor loading, the input power and estimated motor efficiency were used. We chose this method over the method of using motor input current (Biesemeyer & Jowett 1994) due to the wide range of motor loading we found.

With the initial survey data, we selected replacement motors using the MotorMaster database (WSEO 1995) and manufacturers' catalog and technical information. After retrofit, measurements were repeated. In the case of fans, inlet and discharge pressure readings were also taken as a check on the constancy of conditions before and after retrofit.

In selecting the belts, the manufacturer's computer software was used, taking care to use the actual hp loading rather than the motor rating (which would result in compounded safety factors and therefore bigger, more expensive, and more energy-absorbing belts than needed).

Site B

The methodology for Site B was similar to Site A, though no belt retrofits were attempted.

SAVINGS RESULTS

The range of savings for a typical set of motors from the retrofit at Site A is shown in Table 1. The ''Predicted kW At Original Speed'' is the pre-retrofit kW multiplied by the ratio of motor efficiencies; ''Predicted kW At New Speed'' adjusts the first prediction by the cube of the ratio of the driven shaft speeds. Using the speed-adjusted prediction, the ''Expected % Savings'' relative to pre-retrofit is calculated. The ''Real % Savings'' are calculated directly from the actual pre-retrofit and post-retrofit kW measurements, with no correction. The ''Corrected % Savings'' are adjusted using the cube of the ratio of the driven shaft speeds, in order to isolate the effective difference in motor efficiency. Real savings ranged from −16% to 40%, compared to an expected range of −4 to 25% based on motor efficiencies and adjusting for speed changes. Accounting for the differences include uncertainties in determining existing motor efficiencies, manufacturing tolerances in new motors, variations in the air or water distribution systems that the motors are powering, and measurement uncertainty. On average, the 7.8% real savings agrees well with the 7.5% expected. Correcting for the speed changes, the savings due to improved motor efficiency are a bit higher, with a kW-weighted average of almost 10%. These results are consistent with previous findings (Biesemeyer & Jowett 1994; Wilke & Ikuenobe 1987).

The belt retrofits at Site A are shown in Table 2. Because the synchronous belts are only available in discrete ratios and are not adjustable, they were selected to run the fans slightly slower than in the original case. Based on this speed change, an expected kW (assuming constant belt efficiency from V-belt to synchronous) is shown. The ''kW at Constant Belt Efficiency/At Speed w/New Motor'' shows what the kW input would be if the speed didn't change and the belt efficiency were constant; note that these numbers are same as the measured kW input after the motor retrofit, as shown in Table 1. The next column adjusts the new-motor kW by the cube of ratio of the driven shaft speeds. The ''Input kW'' is measured, resulting in the ''Real % Savings'' (calculated directly from before and after the belts were installed). The corrected % Savings adjusts the real savings to eliminate the effect of the speed change, showing the difference due to the belt change alone. The ''Overall Real % Savings'' for the three pieces of equipment shown reflect the post-belt-retrofit actual input kW compared to the original motor and belt. In summary, an actual savings of over 7% was realized for the belt change, but once the speed change is accounted for, the new belts show a loss of efficiency of about 2%. This result is counter-intuitive based on the literature (De Almeida & Greenberg 1995), and suggests that further analysis is warranted, perhaps in a laboratory setting where better control over the variables is possible. Though the results for the retrofits shown were consistent, a larger sample size is also needed to reach more conclusive results.

Table 3 shows results for Site B. Real savings ranged from −21 to 5%, with an average of just under −1%. The ''Corrected kW'' and ''Corrected %'' savings use the cube of the ratio of the driven speeds as an adjustment factor relative to the ''Real'' (calculated directly from measurements) numbers. Adjusting for these speed changes shows a range of −11 to 34% savings, with an average of just over 4%. Variations are due to the same factors noted above for Site A. This set of retrofits is a prime example of the importance of keeping driven equipment speeds at or below pre-retrofit conditions. Because the power required by most of these systems varies with the cube of the speed (Nadel et al. 1991), a small increase in speed results in a relatively large increase in power, reducing or even negating the reductions due to increased motor efficiency.

MOTOR SELECTION: RECOMMENDATIONS AND TIPS

In the process of selecting motors for one of the retrofits, it became apparent that the issues of voltage, sizing, and frame type are crucial to optimization.

Voltage Games

Motors operate at their nominal performance levels when operated on a balanced source of three-phase voltage at the voltage level given on the nameplate (Nadel et al. 1991). The most common commercial and industrial power systems

Table 1. *Typical Savings from Motor Retrofits, Site A*

Equip. No.	Pre-Retrofit Motor Information: Nameplate Data: hp	Pre-Retrofit: Nameplate Data: NEMA Nominal Eff.	Pre-Retrofit: Assumed Eff.	Pre-Retrofit: Field Data: DriveN Shaft Speed	Pre-Retrofit: Field Data: Input KW	% Rated hp	Post-Retrofit Motor Information: Design Data: Hp	Post-Retrofit: Design Data: Minimum Nom. Eff.	Post-Retrofit: Design Data: % Rated hp	Post-Retrofit: Field Data: DriveN Speed	Post-Retrofit: Predicted kW: At Original Speed	Post-Retrofit: Predicted kW: At New Speed	Post-Retrofit: Field Data: Input kW	Results: Expected % Savings (@ new speed)	Results: Real % Savings	Results: Corrected % Savings
AC 015	3		79%	871	3.52	123%	5	91.2%	74%	863	3.03	2.95	2.28	16.2	35.2	33.3
AHU 001	1.5		75%	1020	0.78	53%	1.5	89.0%	53%	1,009	0.66	0.64	0.47	18.0	39.9	37.9
BL 001	7.5		83%	473	5.36	80%	7.5	93.3%	80%	447	4.79	4.04	4.06	24.6	24.3	10.3
BL 002	20		91%	823	16.16	99%	25	94.9%	79%	819	15.53	15.30	14.40	5.3	10.9	9.6
BL 003	7.5		83%	441	4.58	68%	7.5	93.3%	68%	437	4.09	3.98	3.75	13.1	18.1	15.9
BL 004	10		84%	497	8.48	96%	15	93.7%	64%	522	7.63	8.84	9.80	−4.2	−15.6	0.3
BL 005	3		79%	485	3.18	112%	5	92.3%	67%	498	2.71	2.93	2.98	7.8	6.3	13.4
BL 006	3	81.9%		716	2.52	92%	3	91.6%	92%	724	2.25	2.33	2.27	7.6	9.9	12.9
BL 007	5	85.5%		769	2.59	59%	5	91.0%	60%	788	2.44	2.62	2.69	−1.1	−3.7	3.6
GP 001	7.5	84.0%		1763	5.08	76%	7.5	93.3%	76%	1,787	4.58	4.77	5.12	6.2	−0.7	3.3
GP 002	7.5	84.0%		1768	4.98	75%	7.5	93.3%	75%	1,786	4.48	4.62	5.16	7.2	−3.7	−0.6
GP 018	1	77.0%		1760	0.96	99%	1.5	89.6%	66%	1,778	0.83	0.85	0.74	11.4	22.9	25.2
GP 020	0.75		70%	1754	0.59	74%	0.75	86.5%	74%	1,770	0.48	0.49	0.50	16.8	15.4	17.7
				Totals	**58.78**						**53.48**	**54.36**	**54.22**	**7.5**	**7.8**	**9.6**

Notes:
1. Equipment abbreviations: ACs, AHUs, and BLs are all fans; GPs are pumps.
2. Where nameplate efficiencies were not listed, efficiencies were assumed using Nadel et al., 1991.
3. % Rated hp was calculated from the input kW, efficiency, and nameplate hp rating data.
4. Minimum Nominal Efficiency is the minimum acceptable nominal efficiency, at the quartile rating closest to the % Rated hp for the new motor (e.g. for AHU001, the efficiency listed is for 50% load).
5. See text for explanation of other columns.

are 208 and 480 volts; 240 is less common; and industry uses some 600-volt systems. Since there is some voltage drop expected between the source and the load, motors are designed for 200 volts (for 208-volt systems), 460 (for 480), 230 (for 240), and 575 (for 600). The most common motors are 230/460 volt (the windings are reconnected to accommodate either voltage); some are 460 only, and some are 200 only. There are motors labeled 208-230/460, which are really designed for the higher voltage but can be operated on 208-volt systems. The performance of such motors (or those rated for 230/460 but operated on 208) will vary from their nominal performance, as shown in Figure 1 (U.S. Motors 1995). In particular, the starting torque is limited, and the full-load torque as well; typically manufacturers reduce the nominal service factor (overload capacity) from 1.15 to 1.0. So all other things being equal, it is best to use 200-volt motors on 208-volt systems. But there are three good reasons to consider the 230-volt designs for 208 use: (1) the starting inrush current, which is typically 5–10% higher for premium-efficiency motors than for standard designs, is lower than at nameplate voltage (high inrush current is stressful to the electrical distribution system); (2) the slip is higher (the motor runs at a lower speed), at least in part compensating for the typically lower slip of the premium-efficiency

__Table 2.__ Savings from Belt Retrofits, Site A

	Pre-Belt Retrofit	Conditions w/New Motors and New Belts	kW at Constant Belt Efficiency			Results for Belts		
Equip. No.	DriveN Speed	DriveN Speed	At Speed w/ New Motor	At Speed w/ New Belt	Input kW	Real % Savings	Corrected % Savings	Overall Real % Savings
90 BL 002	819	794	14.40	13.12	13.40	6.9	−2.1	17.1
90 BL 005	498	474	2.98	2.57	2.63	11.7	−2.4	17.3
90 BL 006	724	707	2.27	2.11	2.16	4.8	−2.2	14.3
		Total	**19.65**	**17.80**	**18.19**	**7.4**	**−2.2**	**16.8**

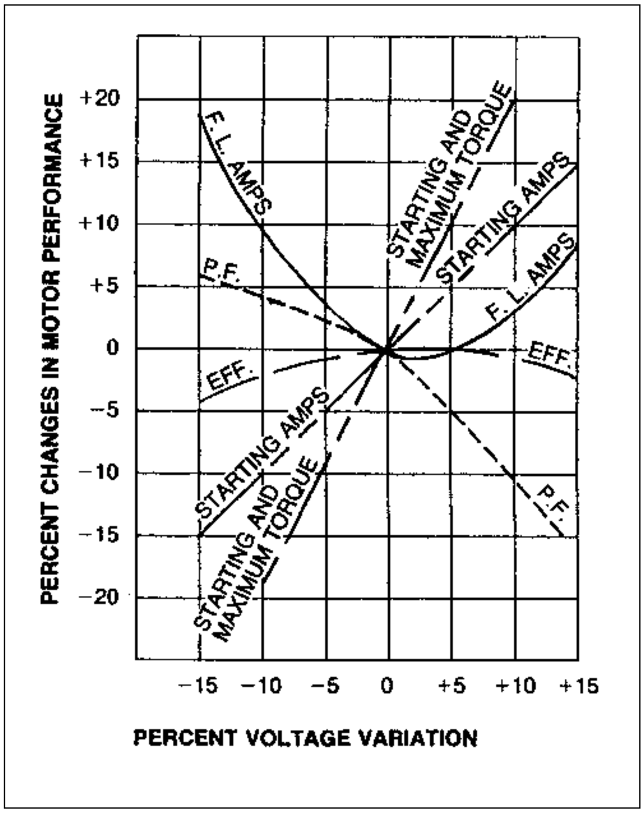
Note:
1. See text for explanation of column derivations.

__Table 3.__ Summary of Power Change from Motor Retrofits, Site B

		Pre-Retrofit		Post-Retrofit		Savings Results			
						Real		Corrected	
Equip. No.	HP	Fan Speed	kW	Fan Speed	kW	kW	%	kW	%
SF43	50	602	24.9	603	23.8	1.1	4.4	1.22	4.9
EF73	30	913	14.4	913	14.53	−0.13	−0.9	−0.13	−0.9
SF08	15	862	11.8	864	11.16	0.64	5.4	0.72	6.1
EF09	5	1754	3.46	1754	3.51	−0.05	−1.4	−0.05	−1.4
SF28	30	N/A	25.8	N/A	26.1	−0.3	−1.2	N/A	N/A
SF37	15	790	9.61	814	11.59	−1.98	−20.6	−1.08	−11.2
SF38	15	533	8.08	545	9.06	−0.98	−12.1	−0.42	−5.2
SF39	15	578	12.72	631	12.19	0.53	4.2	4.36	34.3
		TOTAL:	**110.77**		**111.94**	**−1.17**	**−1.1**	**4.63**	**4.1**

Notes:
1. See text for explanation of column derivations.
2. All eight applications are fans.

Figure 1. *Effect of motor input voltage on performance. Source: U.S. Motors 1995*



motor; and (3) the power factor is higher, reducing the current flow in the motor circuit and thereby improving the efficiency of the electrical distribution system. Note that the efficiency loss (0–2% for operation at 90% of nominal voltage) shown in Figure 1 is for full load only; at 75% load, the change is negligible; at 50% load, there is an efficiency increase of 0 to 1% (U.S. Motors 1995).

The Sizing Shuffle

The conventional wisdom of motor application warns of oversizing motors, correctly pointing out that motors running below about 50% load lose efficiency (Nadel et al. 1991). So the prudent retrofitter will look for opportunities for downsizing motors when replacing them. But energy savings can also result from *upsizing* motors that are running at more than about 75% of their rated load (Baldwin 1989; Nailen 1993). For example, a 20-hp standard-efficiency motor running at 90% load and 86% efficiency could be replaced with a premium-efficiency 20-hp motor, 90% loaded at 93.9% efficiency, or a 25-hp motor, 72% loaded at 94.6% efficiency. The new, larger motor will save 8% more than the new, same-size motor. The extra cost of about $120 will pay back in four years, assuming 4800 hours per year of operation and $0.08/kWh cost. Keep in mind, though, that the upsized motors must physically fit, and might create problems with the capacity of the motor starter and distribution wiring supplying it (the running current should be lower than the replaced motor, but the starting inrush current will be higher).

U-Frame to T-Frame or the reverse?

The motor frame series is a standard set of physical dimensions for each combination of motor speed, enclosure, and hp rating, established by the National Electrical Manufacturer's Association (NEMA 1991). The dimensions include holes for mounting bolts, shaft location, shaft length and diameter, etc. The T-frame series, established by NEMA in 1964, is the current frame series. The U-frame series was the previous series, established in 1952; U-frame motors are physically larger than T-frame motors for the same output rating. A classic retrofit is to replace an old standard-efficiency U-frame motor with a premium-efficiency T-frame. A standard series of adapter plates (which raise up the T-frame shaft to the previous location of the U-frame shaft, and adapt the mounting holes) is available to make the size transition more convenient. However, it is still possible to buy new U-frame motors from several manufacturers, largely due to the insistence of the automobile industry, which never adopted the T-frame standard. Starting in the early 1990's, at least one manufacturer has taken advantage of the fact that if the same techniques used to make premium-efficiency T-frame motors are applied to the U-frame motors, the resulting ''Super-U'' motors will be more efficient than the premium T-frames. This is due to the fact that the larger U-frames have more room for the increased copper and steel common to the higher-efficiency designs. The result is that for the old U-frame motors, the best (and easiest, since no transition base is needed) retrofit may well be to use a Super-U. For existing T-frames where size constraints are not critical (such as most belt-driven fans and compressors), the Super-U may also be the most efficient and reasonably easy to adapt. One caution, though, is that the Super-U motors are usually more than twice as heavy as the T-frames, creating installation difficulties in applications where the motor must be literally muscled into place or those where the weight overwhelms the equipment design (e.g. for vibration isolation). Another consideration is that these motors, which are available only in the totally-enclosed, fan-cooled (TEFC) enclosure, tend to be somewhat noisier than their T-frame TEFC counterparts, which are in turn slightly noisier than the T-frame open-enclosure units.

CONCLUSIONS

Lessons Learned

Motor selection is tricky. In addition to the voltage and weight issues already discussed, efficiency, loading, enclosure, frame size, locked-rotor code, and speed must all be considered.

While high efficiency is the key to energy savings, often there are trade-offs, such as between efficiency and speed. For direct-drive applications such as pumps, the higher speed of premium-efficiency motors can reduce or eliminate savings (Biesemeyer & Jowett 1994; Nailen 1993). Thus, selecting a slightly lower efficiency motor with greater slip (lower speed) can result in lower kW than the maximum-efficiency, yet higher speed motor. Though in general higher-efficiency motors have lower slip and thus run slightly faster than standard-efficiency motors, there is a big range of slip for a given efficiency (Howe & Shepard 1992), so careful speed vs. efficiency selection pays off.

Motor loading must be estimated in order to choose the proper replacement size (higher, lower or the same hp), and to know which efficiency (at 50, 75, or 100% load) to specify. While the slip method of estimating motor loading is now discredited, either the input current method or the input power method give reasonably accurate results (Biesemeyer & Jowett 1994).

For some outdoor applications, an open enclosure may be more efficient, but an enclosed motor must be used due to weather exposure. Some indoor applications, which normally use open enclosures, may get greater savings from a TEFC motor (often a Super-U).

The starting inrush current is indicated by the motor's ''locked-rotor code'', which gives the maximum inrush kVA per horsepower. Premium-efficiency motors tend to have higher inrush currents; especially where the motor size is increased, they may require upgrades to the electrical distribution system to reliably start the motor without tripping overload devices.

The frame size must be considered, especially if upsizing the motor for higher efficiency: will the extra labor cost of making the motor fit be worth it? Also, the NEMA-designated frame ignores the overall length of the motor, which is often greater for the premium-efficiency designs; in tight installations, the extra length can be a problem.

Careful selection and installation planning pay dividends. By making sure the motor is the right size and type for the application, and by assisting the installer with the proper accessories (belt sheaves, transition bases, etc.) the retrofit process is greatly facilitated.

Motor and belt vendors are unfamiliar with efficiency optimization. As a result, specifications and ordering procedures need to be extra clear to avoid confusion and wasted effort. The purchaser must make it clear that the efficiency at the load level specified is the dominant criterion for motors; provide information in a format that is convenient for the vendor, and don't provide extraneous information. Watch out for compounded safety factors in belt selection procedures.

Variables and uncertainties in individual applications make savings predictions difficult. These variables include motor efficiencies (of the existing, and to a lesser extent, the new motor), load variations, and the accuracy of measurement.

On average, premium-efficiency motors save about as much energy as predicted. Once the (usually) random effects of the individual variations are averaged out, premium efficiency motors do save significant amounts of power and energy.

Synchronous belts are harder to install, noisier, and use more energy than V-belts. Although their alignment specifications are the same as V-belts, synchronous belts demand closer adherence to the spec. The belt and sprocket teeth make a whining sound due to their meshing and unmeshing as the belt travels over the sprocket, a possibly objectionable additional sound. While careful selection generally results in a net reduction in input power due to the belt, once the power is corrected for the slightly reduced speed, the surprising, though as yet inconclusive, result is that the belts use about 2% more energy than V-belts.

Speed is very important in optimizing motor-driven systems. Unless the system is delivering an inadequate flow already (which means it needs more than a motor retrofit), the driven speed of the pump or fan with the new motor should run at or below the speed before retrofit. For example, 2% increase in speed, with resultant 6% power increase, can easily wipe out the savings from the more-efficient motor; on the other hand, a 2% decrease, resulting in a negligible 2% loss in flow, can easily double the overall savings from the retrofit. Select motors and belt drives carefully, and make sure belt sheaves are adjusted or changed to operate the load at the proper speed after the new motor is installed. If a speed increase is inevitable, be sure to discount savings expectations accordingly. An alternative in direct-driven pumping systems is to trim the impeller, though the cost-effectiveness of this measure needs to be carefully considered.

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