Electrical Systems And Electric Energy Management

Main Topics Discussed

- Electric Rates
- Electrical system utilization
- Power quality
- Harmonics
- Power factor improvement

Review of Electric Cost Components

Energy cost - e.g. \$0.05/kWh

Demand cost - e. g. \$6.50/kW/mo

Fuel adjustment - e.g. \$0.005/kWh

Power factor penalty - e.g. \$6.50/kVA/mo or
kW billed = kW × (0.85/PF)

Ratchet clause - e.g. Maximum of (kW this month, or 70% of maximum kW in last 11 months)

Power Computation Formulas

Single-phase system

$P = \sqrt{1} \times V \times I \times PF$

Where PF = power factor

Three-phase system

$P = \sqrt{3} \times V \times I \times PF$

$\sqrt{3} = 1.732$

Examples

a) For a 10 ampere, 120 volt, electric space heater

$$P = 120 \times 10 \times 1.0 = 1200 \text{ watts}$$

b) For a three phase 460 volt, 20 ampere motor with power factor of 90% at full load

$$P = \sqrt{3} \times 0.460 \times 20 \times 0.9 = 14.34 \text{ kW}$$

Electric Motor Equations

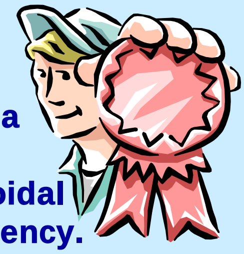
$$kW = \sqrt{3} \times kV \times I \times PF$$

$$kVA = \sqrt{3} \times kV \times I$$

$$PF = kW / kVA$$

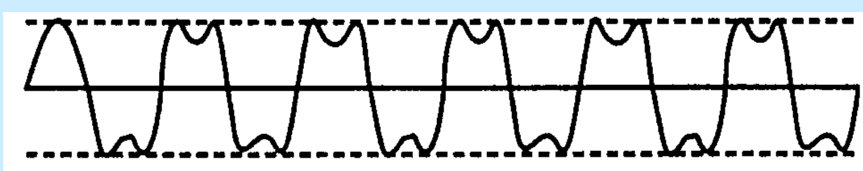
$$kW = \frac{HP \times 0.746 \text{ kW} \times \text{Load Factor}}{\text{Efficiency}}$$

Power Quality



- **Power Quality is related to how well a bus voltage—usually our facility load bus voltage—maintains a pure sinusoidal waveform at rated voltage and frequency.**
- **PQ issues involve all momentary phenomena including spikes, notches and outages; as well as harmonics and power factor.**
- **Modern electronic equipment both causes and is affected by the problem.**
- **Power Quality is becoming one of the most important issues in energy management today.**

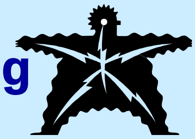
Harmonics



• Harmonics are a multiple of the fundamental frequency. If the fundamental frequency is 60 hertz, the 2nd harmonic is 120 Hz, the 3rd is180 Hz, the 4th is 240 Hz, etc.

• Harmonics are usually generated by solid-state-based equipment such as switching power supplies in PCs, DC drives, variable frequency drives (VFDs), electronic ballasts, arc welders and ovens.

Importance of Grounding



- Up to 80 percent of PQ problems in facilities today may be caused by wiring and grounding systems that met the NEC at the time, but do not meet the needs of today's sensitive electronic equipment.
- The first step taken to deal with PQ problems should be to inspect the wiring and grounding, and clean and tighten all connections. Loose connections come from vibration, oxidation, corrosion, and age.

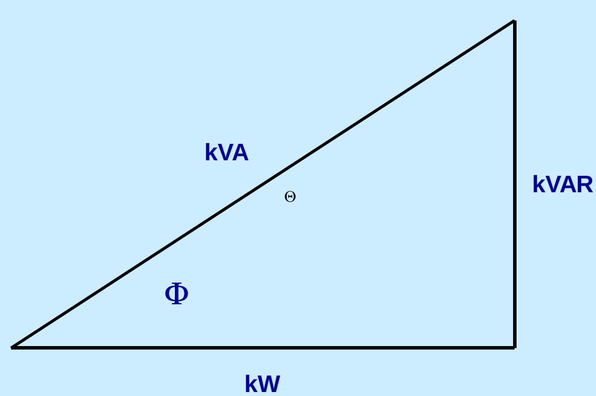
What Problems Occur Because of Harmonics?

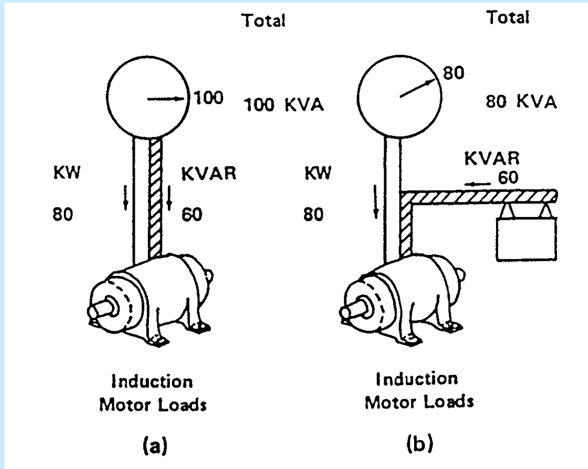
- Circuit breakers tripping
- Neutrals overheating (smoke, fire)
- Panel or transformer overheating
- RFI – Radio Frequency Interference
- Errors/damage in Electronic Equipment
- Digital clocks running fast
- Failures in power factor correction capacitors

Mitigation of Harmonic Problems

- Derate equipment (symptom treatment)
  - 50% Transformers
  - 70% Load centers
    - Circuit breakers
    - Neutrals
- Install preventive equipment
  - Inductors
  - Harmonic filters
  - Isolation transformers
    - Locate near drive if possible
    - Connect back to "strongest" point of power system – the load center

Power Triangle





Schematic arrangement showing how capacitors reduce total kVa by supplying magnetizing requirements locally.

Sample Power Factor Example

A facility is operating with a demand of 2000 kW. The 2500 kVa transformer is fully loaded. How many kVARS are required to bring the power factor back to unity?

$kW^2 + kVAR^2 = kVa^2$

$kVAR^2 = kVa^2 - kW^2$

$$kVAR = \sqrt{2500^2 - 2000^2} = 1500$$

Sample Power Factor Problem

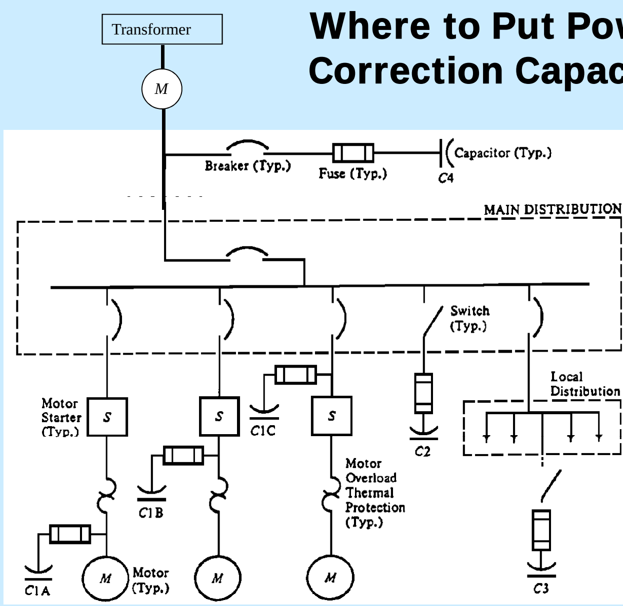
During my last energy audit I saw a 100 HP electric motor that had the following information on the nameplate: 460 volts; 114 amps; three phase; 95% efficient – all at full load . What is the power factor of this motor?

[(100 hp)*(0.746 kW/HP)/0.95] =[(1.73)*(0.46 kW)*(114 amp)*(PF)]

78.52 kW = (90.72 kVa)*(PF)

PF = (78.52 kW / 90.72 kVa) = 0.866

Where to Put Power Factor Correction Capacitors



Sample CEM Test Question

- A facility is operating at a power factor of 70% with a real power load of 2000 kW. How much corrective capacitance in kVAR is needed to improve the facility power factor to 90%?

- kVAR = Table Factor x Real power load in kW

Short Power Factor Table

Table 11.7 Power-Factor Improvement[a]

Original Power Factor (%)	Desired Power Factor (%)																		
	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.442	1.481	1.529
51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484
52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1:314	1.351	1.392	1.440
53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397
54	0.809	0.835	0.861	0.887	0.913	0.939	0.966	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356
55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316
56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277
57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239
58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202
59	0.618	0.644	0.670	0.696	0.722	0.748	0.775	0.801	0.828	0.856	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165
60	0.584	0.610	0.636	0.662	0.688	0.714	0.741	0.767	0.794	0.822	0.850	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131
61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096
62	0.515	0.541	0.567	0.593	0.619	0.645	0.672	0.698	0.725	0.753	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062
63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030
64	0.450	0.476	0.502	0.528	0.554	0.580	0.607	0.633	0.660	0.688	0.715	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997
65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966
66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.554	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935
67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905
68	0.329	0.355	0.381	0.407	0.433	0.459	0.486	0.512	0.539	0.567	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876
69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.620	0.654	0.866	0.720	0.758	0.798	0.840
70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811

CEM Review Questions

1. If power factor correction capacitors are located at the utility meter, but on the customer's side of the meter, the power factor out in the customer's facility will not be improved.

   A. True B. False

2. A facility has a 100 kW electric resistance oven for drying parts. What is the power factor of the oven?

   A. 0 % B. 50% C. 90% D. 100%

3. A facility has a motor that draws 200 kVA and has a power factor of 70.7%. How many kW and how many kVAR does it draw?

4. A facility has a motor that draws 200 kVA and has a power factor of 80%. How many kW and how many kVAR does it draw?

Electric Motors and Motor Management

Electric Motor Management Why Bother?

- Electric motors use over ½ all U.S. electricity
- Motor driven systems use over 70% electric energy for many plants
- Motor driven systems cost about $90 billion to operate per year
- A heavily used motor can cost 10 times its first cost to run one year

Electric Motor Management
Why So Difficult?

- Load on most driven systems is unknown at least on retrofits
- Very difficult to determine load accurately through measurements
- Electric motor management is FULL of surprises
- Yet, savings can be large (small percentage of a big number is a big number)
- Important note: Often oversized wiring (above code) is cost effective in heavily used systems as it reduces I^2R losses. (CDA and Southwire Corp.)

Electric Motor Management
Types of Motors

- AC Synchronous motors
  - One to two percent or so (but larger)
  - Large HP and slow speed applications typical
  - Similar in construction to induction motors, but more expensive
  - More efficient, can be run at leading PF
  - Can generate or absorb reactive power

Electric Motor Management
Types of Motors

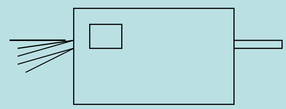
- DC Motors
  - Good for precise speed control and strong torque properties
  - Not efficient, (historically) high maintenance, and higher down time (commutator and brushes need inspection and maintenance)
  - Newer brushless motors much better
  - Less than 5% of the motors today are DC
  - Replacing with a VFD driven AC motor may be cost effective especially if down time is reduced

Electric Motor Management
Motor Types Cont.

- AC Induction motors
  - AC induction motors work on electromagnetic field principles
  - Lagging power factor
  - Many different types (ODP, TEFC, etc.)
  - Approximately 95% of motors today are induction
  - Concentration for this discussion
  - Run on single- or three- phase power (most)

Electric Motor Basics
Name Plates

- **HP ____ (shaft power design- output)**
- **NLRPM (synchronous speed)**
- **FLRPM (running RPM at design load)**
- **LRA (starting amps – 1 sec?)**
- **FLA (amps at design load and voltage)**
- **Volts (design voltage)**
- **Max. capacitor**
- **Efficiency (test vs. guaranteed)**
- **Service factor**



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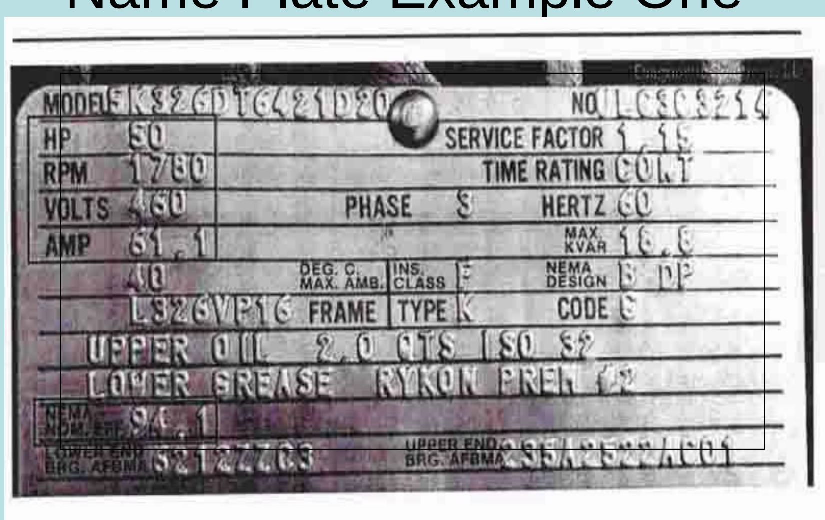
Name Plate Example One



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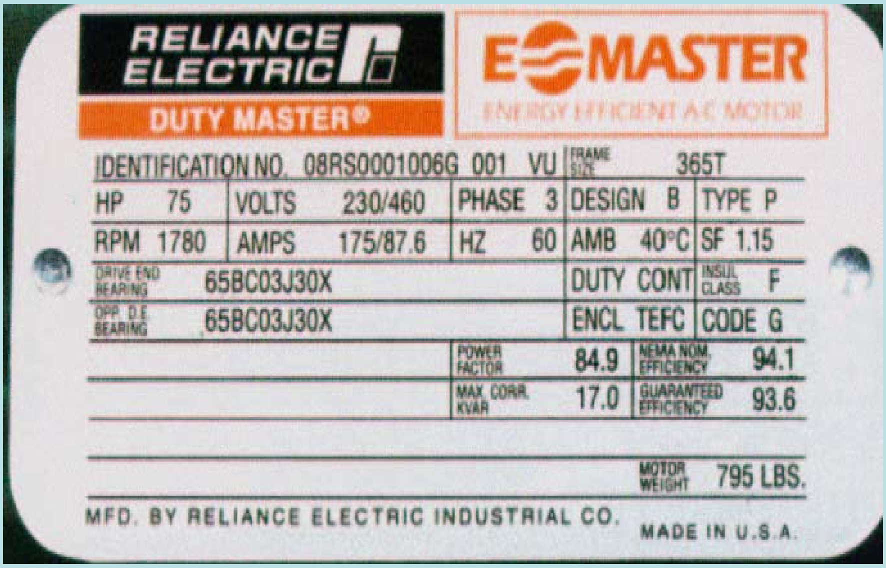


Terminology (NEMA)

- NEMA (National Electrical Manufacturers Association)
- Standard Efficiency Motors: Any Pre EPACT motor
- Energy Efficient Motors: Motors meeting EPACT requirements
- Premium Efficiency Motors: Motors exceeding EPACT requirements (extra efficient, ultra high efficient, but these terms are not used by NEMA)

Electric Motor Basics
Motor Speeds

- Alternating current, thus speed will vary with pole pairs (inside motor, pole pairs between stator and rotor)
- One pole pair (2 poles) - one RPM per cycle (60 cps or Hertz); two pole pairs – ½ rpm per cycle, etc.
- Thus

$$\text{SPEED} = \frac{60\,\dfrac{\text{cycles}}{\text{sec}} \times 60\,\dfrac{\text{sec}}{\text{min}}}{\text{number of pole pairs}}$$

- SPEED = 3600, 1800, 1200, 900, 720, etc.
  (no other choices) for 60 Hz power

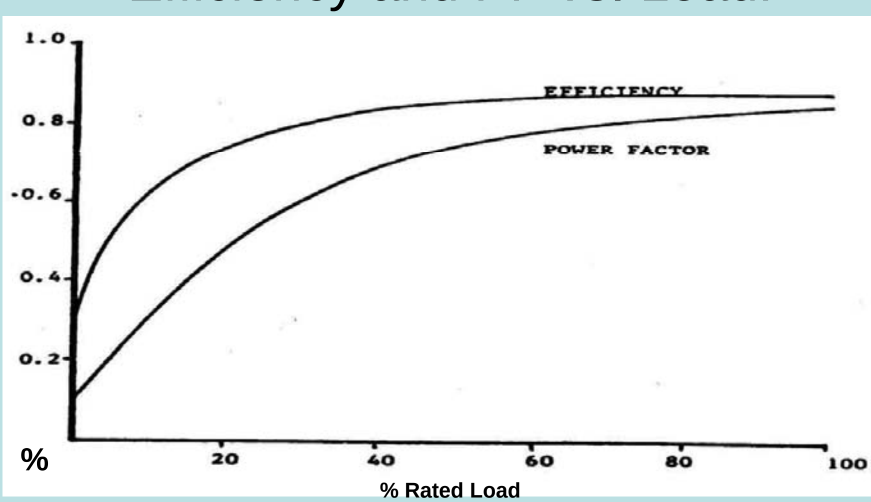
Electric Motor Basics
Slip

- Design Slip = (NLRPM – FLRPM)
- True Slip = (NLRPM – RPM measured)
- % Load = (True Slip)/(Design Slip)
- Perfect indicator but very difficult to measure accurately (+- 1% typical)
- Many don't use this - why?
  - Difficult to measure accurately
  - Large motors are more efficient than small motors (more later)

Electric Motor Basics
Slip Example

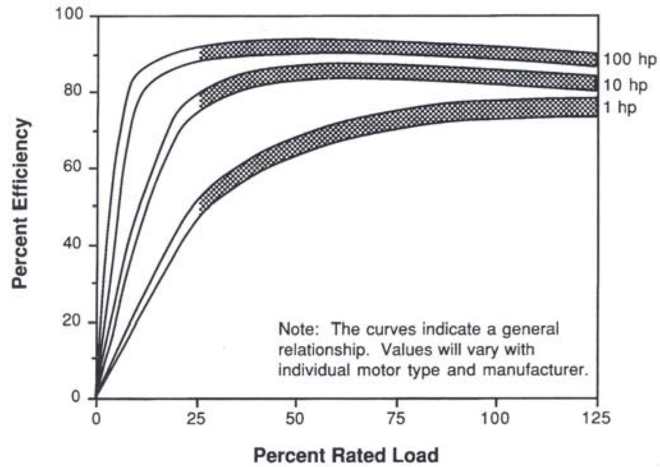
- FLRPM = 1760 (off name plate)
- Design HP = 50 (off name plate)
- Measured RPM = 1776
- NLRPM = ? (obviously 1800)
- Design slip = 1800 – 1760 = 40
- True slip = 1800 – 1776 = 24
- % load = 24/40 = 0.6 or 60%
- True load = 50HP(0.6) = 30 HP
- See plot next slide, motors run very well at 60% load
- This motor will run very cool, is not causing a problem, why bother!!

Efficiency and PF vs. Load:

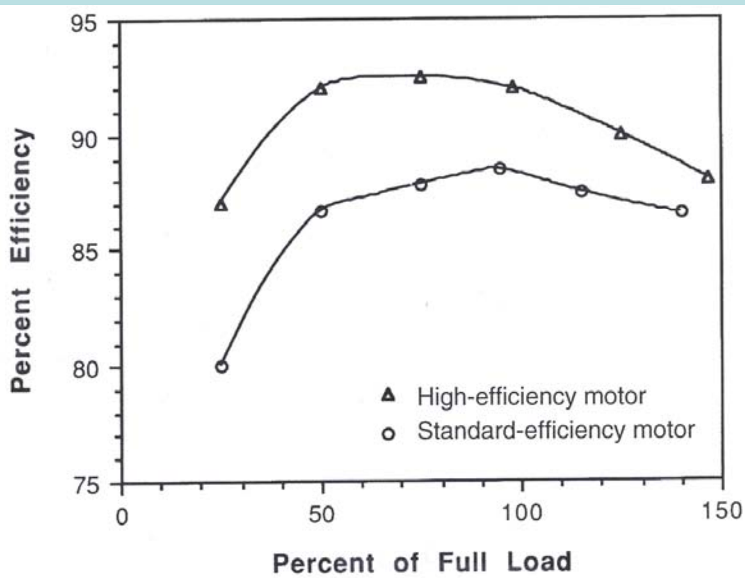


Source: Electrical and Energy Management, IEES, Ga,Tech., Atlanta, GA.

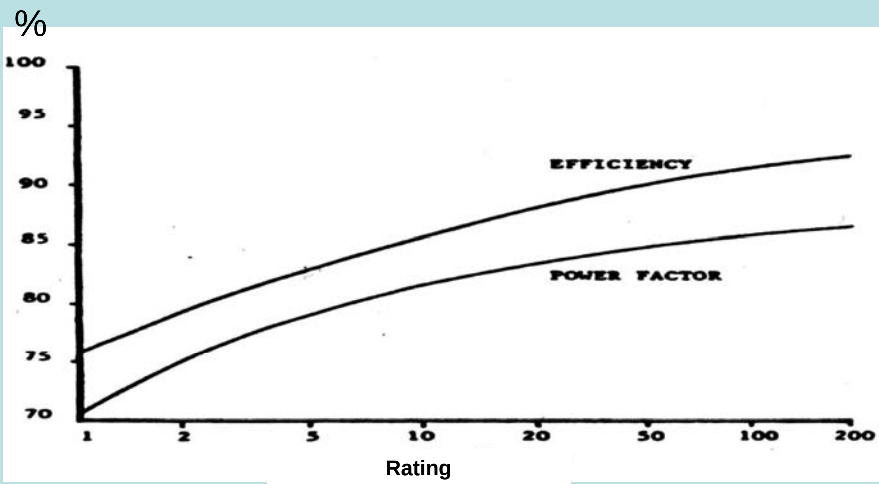
Typical Efficiency vs. Load Curves for 1,800 rpm, Three-Phase, 60 Hz, Design B Squirrel-Cage Induction Motors



Source: NEMA 1999



Efficiency and PF (Cos phi) vs. Size



Source: Electrical and Energy Management, IEES, Ga,Tech., Atlanta, GA.
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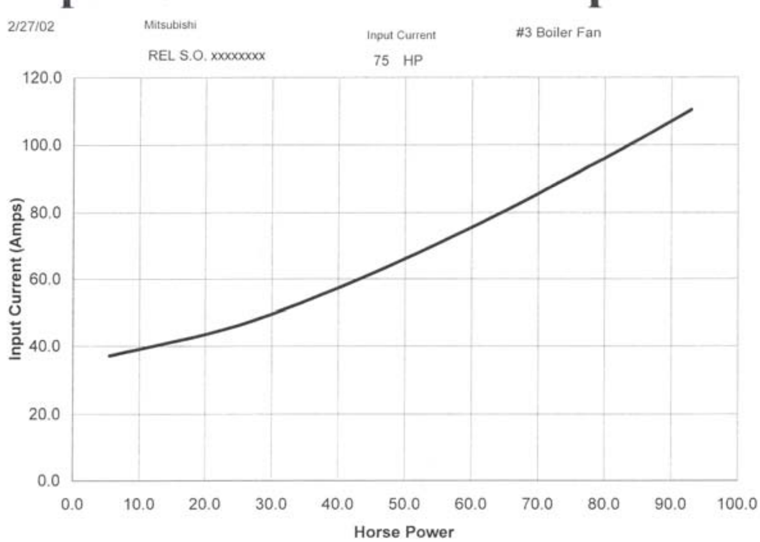
Input Current Versus Output Power

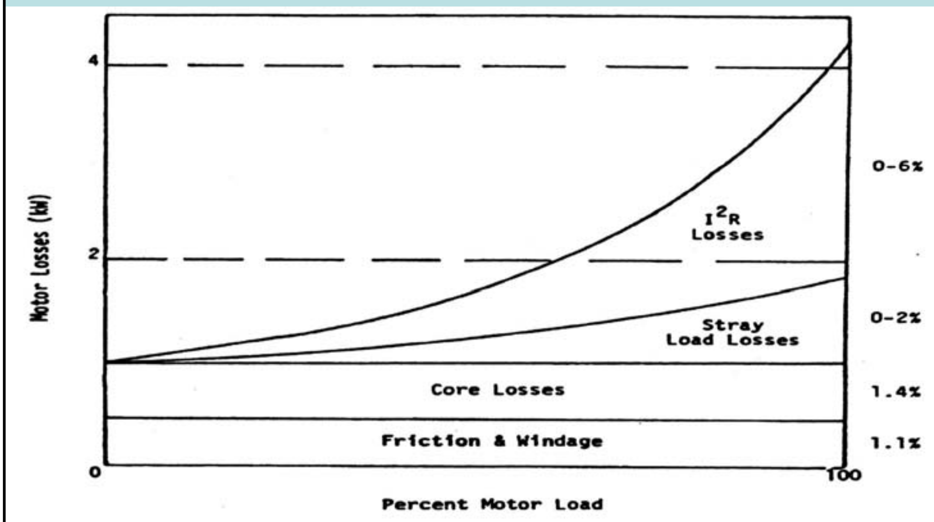


RELIANCE ELECTRIC

In-field electric motor efficiency measurement

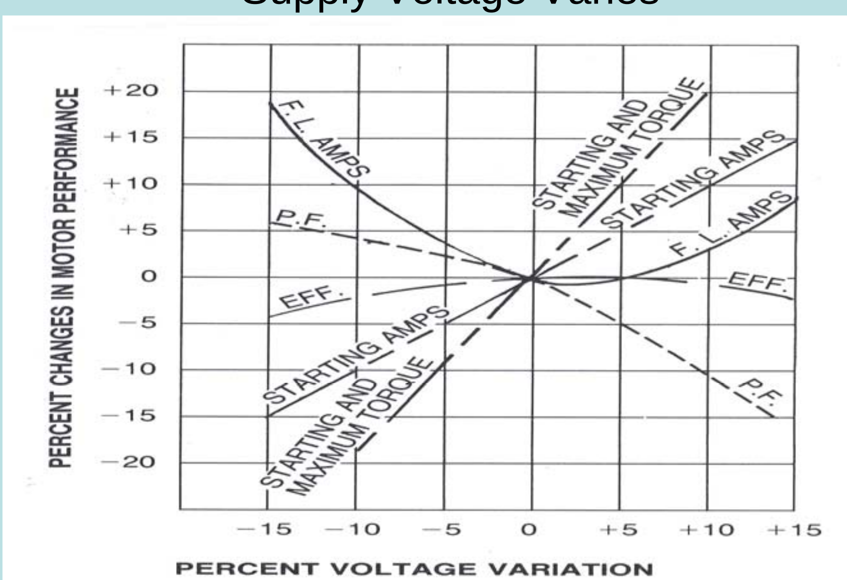
Rockwell Automation

Electric Motor Management—Losses in Motors



Note: This graph explains the efficiency drop off with load reduction Source: "Electrical Motors and Energy Conservation", Ronald Cota, Specifying Engineer, July, 1978.

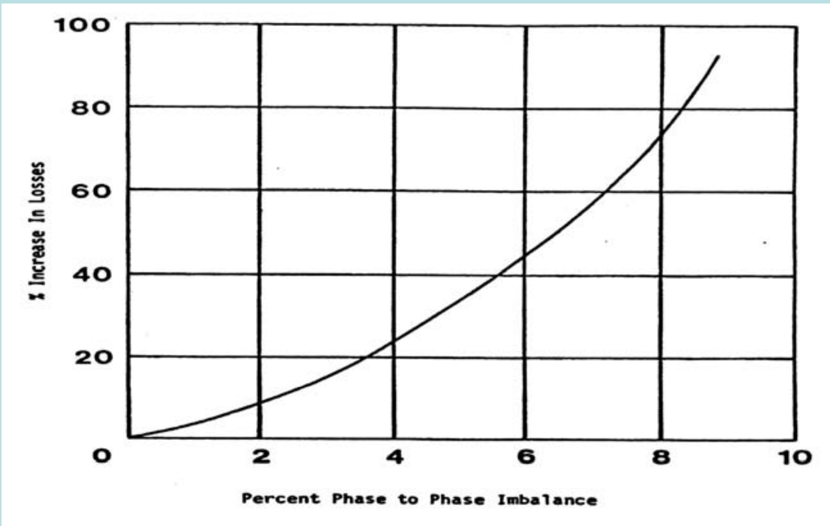
Motor Performance as Supply Voltage Varies



Voltage Imbalance

- Problems can occur because of voltage imbalance between the three phases. This can be a serious problem in motors.
- Percent voltage imbalance is found as the ratio of the largest phase voltage difference from average, divided by the average voltage.
- For example, if we have 220, 215 and 210 volts, the voltage imbalance is 5/215 = .023, or 2.3 percent.

Voltage Imbalance Impact



Source: Electrical and Energy Management, IEES, Ga,Tech., Atlanta, GA.

$$$$

- **Leave existing motors alone until they fail except:**
  - **Exceptionally oversized motors (25% loading or so)**
  - **Sizes that are needed elsewhere (requires inventory)**
- **When they fail, maybe buy new energy efficient motors (EPACT or Premium) instead of paying for rewind (much more on this later)**
- **If financial incentives are available, much more may be done**
- **Premium efficient motors need economic help in much of the country (PUC, Utility, motor mfgs.)**

Motor Basics-Motor Rewinds

- Most rewind motors over ___ HP
- Typical rewinds cost 60+% of a new motor
- New motor could be an energy efficient motor
- Motor efficiency often suffers during rewind. Average drop about 1% according to one study and sometimes significantly more.
- If efficiency drops, losses increases, motor runs hotter and won't last as long

Electric Motor Management
Energy Efficient Motors

- Energy efficient motor characteristics
  - More efficient, and often higher power factor
  - Save energy and reduce demand
  - Reduce load on cables, transformers, etc. (note double whammy with higher efficiency and higher PF)
  - Speed is slightly higher (can be critical)
  - Significantly larger inrush (LRA)

Energy Efficient Motors
Calculating Savings

- Power and energy savings depends of efficiency of standard vs. energy efficient motor

$$\text{Power savings} = kW_e = \left(\frac{HP \times 0.746 \times LF}{EFF}\right)_{Stan} - \left(\frac{HP \times 0.746 \times LF}{EFF}\right)_{EE}$$

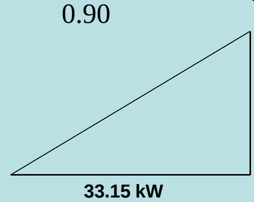
- Energy savings = Power savings x Time
  = kW_e X Operating hours

Electric Motor Principles Review

ELECTRICAL MOTOR PRINCIPLES

A three phase 50-hp motor with a load factor of 0.8 has an efficiency of 90%, what is the kW electrical power input?

1. $$\mathrm{kW} = \frac{50\ \mathrm{Hp} \times 0.746 \frac{\mathrm{kW}}{\mathrm{Hp}} \times 0.80}{0.90} = 33.15\,\mathrm{kW}$$



Electric Motor Principles Review

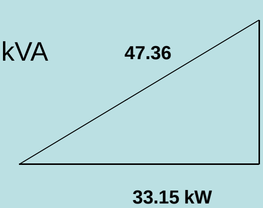
2. For the motor in 1. If the PF = cos θ = 0.7 and voltage is 480 V, what is the kVA and what is the amp draw?

PF = 0.7 = kW/kVA

0.7 = 33.15/kVA or kVA = 33.15/0.7 = 47.36 kVA

Also kVA = √3(kV)I = (√3)(0.480) I = 47.36 kVA

I = 47.36 / (√3 x 0.480) = 56.96 amps



Electric Motor Principles Review

3. Next, we want to correct the PF to 0.90. What size capacitor is needed and what is the impact on the amperage?

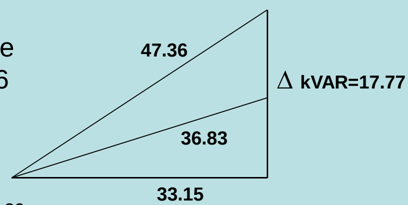
ΔkVAR = 33.15 (tan $\cos^{-1}$ 0.7 – tan $\cos^{-1}$ 0.9) = 17.77 kVAR

You will find the quantity in ( ) above in PF table (see Appendix)

New kVA = 33.15/0.9 = 36.83   kVA = 36.83 = (kV)I$\sqrt{3}$

I = 36.83/(0.480$\sqrt{3}$) = 44.30 amps

Thus, PF correction dropped amperage (upstream of the capacitor) from 56.96 to 44.30 amps or 22%



Also, new kVA = $\sqrt{3}$ kV I = 36.83 kVA

Tools to Help

- The following software packages are available free from OIT of DoE. Contact OIT Clearinghouse 800-862-2086 or clearinghouse@ee.doe.gov They are also downloadable from the DoE web site.
  - MotorMaster: An energy-efficient motor selection and management tool. Motor inventory management, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting
  - Pump System Assessment Tool (PSAT): Efficiency of pumping system operations. Pump performance and potential energy and other cost savings
  - ASD Master: Adjustable speed drive evaluation methodology and application software. Available from EPRI also.
  - Steam Sourcebook: Guide to improved steam system performance.

Motor Sample Problem

- A recent advertisement said a premium efficiency 50 hp motor is available at 94.5%. It would replace a motor that presently runs at 90.7%. Given the parameters below, calculate the cost of operating both motors and the savings for conversion:
  - Motor runs 8760 hours/year
  - Demand cost is $10 per kW month
  - Energy cost is $0.06/kWh
  - Motor runs at 80% load all the time

Motor Sample Problem

- Cost to operate existing motor
  - Demand
  - Energy
  - Total

Motor Sample Problem

- Cost to operate premium efficiency motor
  - Demand
  - Energy
  - Total
- Savings

Additional Motor Problems

- In session J, work problems J6,J7,J8 and J9.

Table 11.7 Power-Factor Improvement[a]

Original Power Factor (%)	Desired Power Factor (%) 80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	
50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.442	1.481	1.529	1
51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1
52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1:314	1.351	1.392	1.440	1
53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1
54	0.809	0.835	0.861	0.887	0.913	0.939	0.966	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1
55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1
56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1
57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1
58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.976	1.010	1.042	1.076	1.114	1.154	1.202	1
59	0.618	0.644	0.670	0.696	0.722	0.748	0.775	0.801	0.828	0.856	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1
60	0.584	0.610	0.636	0.662	0.688	0.714	0.741	0.767	0.794	0.822	0.850	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1
61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1
62	0.515	0.541	0.567	0.593	0.619	0.645	0.672	0.698	0.725	0.753	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1
63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1
64	0.450	0.476	0.502	0.528	0.554	0.580	0.607	0.633	0.660	0.688	0.715	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1
65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966	1
66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.554	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	C
67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	C
68	0.329	0.355	0.381	0.407	0.433	0.459	0.486	0.512	0.539	0.567	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	C
69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.620	0.654	0.866	0.720	0.758	0.798	0.840	C
70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	C
71	0.242	0.268	0.294	0.320	0.346	0.372	0.399	0.425	0.452	0.480	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0
72	0.213	0.239	0.265	0.291	0.317	0.343	0.370	0.396	0.423	0.451	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0
73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.369	0.396	0.424	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0
74	0.159	0.185	0.211	0.237	0.263	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.480	0.514	–3.546	0.580	0.618	0.658	0.700	0
75	0.132	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0
76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0
77	0.079	0.105	0.131	0.157	0.183	0.209	0.236	0.262	0.289	0.317	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0
78	0.053	0.079	0.105	0.131	0.157	0.183	0.210	0.236	0.263	0.291	0.319	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0
79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0
80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0
81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.295	0.329	0.361	0.395	0.433.	0.473	0.515	0
82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.269	0.303	0.335.	0.369	0.407	0.447	0.489	0
83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0
84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0
85						0.000	0.027	0.053	0.080	0.108	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0
86								0.026	0.053	0.081	0.109	0.137	0.167	0.198	0.230	0.265	0.301	0.343	0.390	0
87									0.027	0.055	0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0
88										0.028	0.056	0.084-	0.114	0.145	0.177	0.211	0.248	0.290	0.337	0
89											0.028	0.056	0.086	0.117	0.149	0.183	0.220	0.262	0.309	0
90												0.028	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0
91													0.030	0.061	0.093	0.127	0.164	0.206	0.253	0
92														0.031	0.063	0.097	0.134	0.176	0.223	0.
93															0.032	0.066	0.103	0.145	0.192	0.
94																0.034	0.071	0.113	0.160	0.
95																	0.037	0.079	0.126	0.
96																		0.042	0.089	0.
97																			0.047	0.
98																				0.
99																				

Motors, Drives and Air Compressors

Session 5.3.1

Electric Motor Management Drives

- Motors are fixed speed devices likely running between NLRPM and FLRPM
- Other speeds on the driven end have to be engineered (which will affect the load on the motor)
- Because of the “fan” laws (pumping or blowing) centrifugal devices are desired applications for varying CFM or GPM

Session 5.3.2

Electric Motor Management
Fan Laws
(Centrifugal Devices ONLY)

- $CFM_2 = CFM_1(RPM_2/RPM_1)$ 1st law
- $SP_2 = SP_1(RPM_2/RPM_1)^2$ 2nd law
- **$HP_2 = HP_1(RPM_2/RPM_1)^3$ 3rd law**

Electric Motor Management
Fan Laws Example

- A 40 HP centrifugal blower is on a forced draft cooling tower. It is basin temperature controlled but conversion to a variable speed drive is being considered. When the blower is running at ½ speed, what is the impact on the CFM and what is the HP requirement?

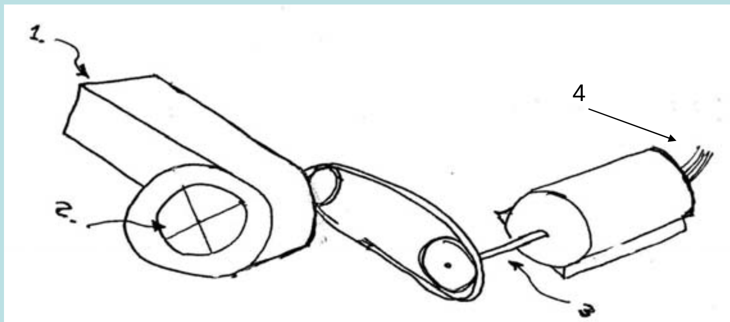
Electric Motor Management
Fan Laws Example

- New CFM is __________old CFM
- New HP requirement is:
- These type savings are why variable speed drives are so popular today

Electric Motors
Variable Volume Options

- Outlet damper control (see sketch, location 1)
- Inlet vane control (see sketch, location 2)
- Magnetic clutching (see sketch, location 3)
  - Eddy current clutch
  - Permanent magnetic clutch
- Variable Frequency Drives (see sketch, location 4)
- Hydraulic drives, variable sheaves, etc.

Electric Motors
Variable Volume Options Sketch

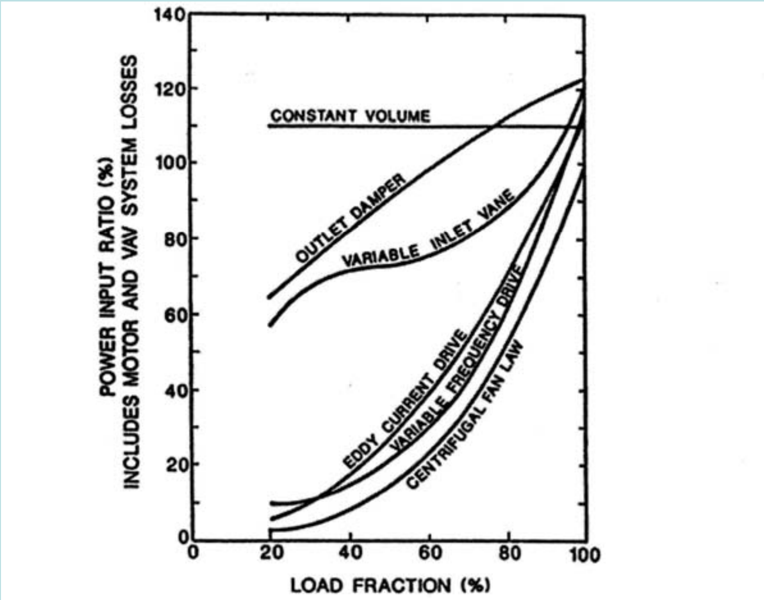


Session 5.3.7

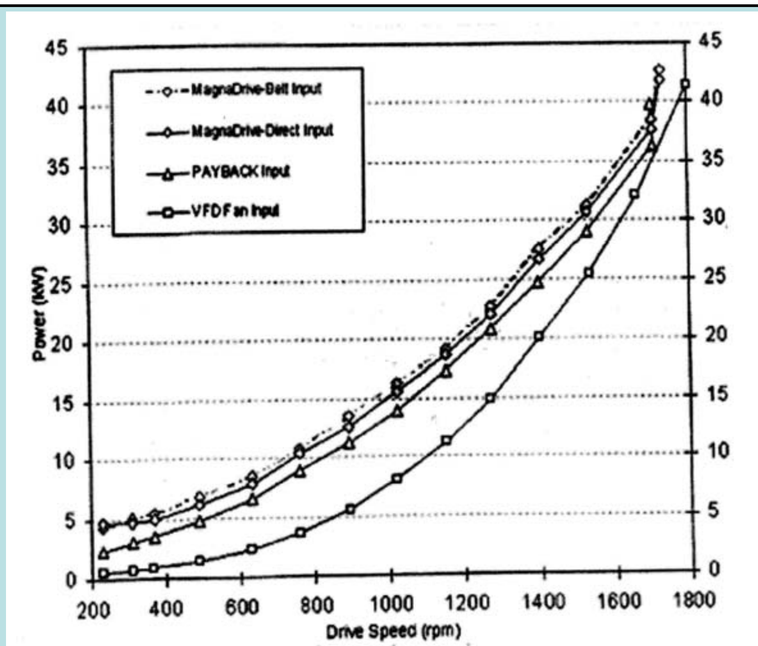
Variable Speed Drive Alternatives Performance

- The next page shows performance expectations from an older EPRI report
- The page after that shows performance from a more recent PNL test
- The third page shows an “average” VAV loading profile. It can be used as a default loading if better figures are not available. Quick Fan from DoE presents another default possibility.

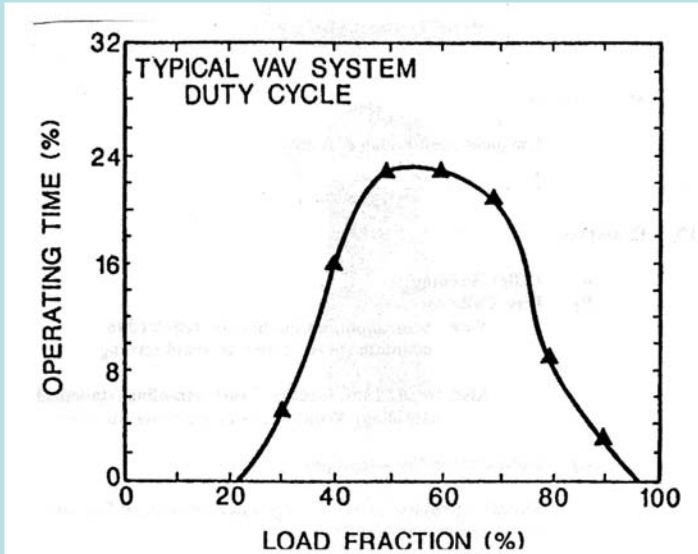
Session 5.3.8



Typical Power Consumption of Various Control Systems



VFD: Default Loading Profile



Variable Frequency Drive Example

- A large (50 HP) blower with inlet vane control drives a VAV system operating 6500 hours per year. Energy costs \$0.04/kWh. What is the total savings per year for removing the inlet vane control and replacing it with a VFD?
  - Assume the performance figures in slide 9 apply
  - Assume the loading figures in slide 11 apply.
  - Construct an Excel spread sheet to do the calculations (will be done for you on next page)

Variable Frequency Drive Example

<u>Profit Improvement With Variable Frequency Drives</u>

1 Load Ratio	2 Power Input Ratio (Old)	3 Power Input Ratio (VFD)	4 Duty Cycle Fraction	5 kWh Saved	6 Dollar Savings
0.20	0.57	0.09	0.00	0	0
0.30	0.67	0.11	0.05	6786	271
0.40	0.71	0.14	0.16	22103	884
0.50	0.72	0.2[illegible]	0.23	28985	1159.
0.60	0.75	0.29	0.23	25641	1026
0.70	0.80	0.43	0.20	17934	717
0.80	0.88	0.62	0.09	5671	227
0.90	0.99	0.85	0.03	1018	41
1.00	1.20	1.16	0.01	97	4

Total Annual Electricity Savings .... 108,235 kWh
Total Annual Dollar Savings $4,329

Annual Savings for a Large Air Handler

Variable Frequency Drive Example

- Calculation for 50% load row in Spread Sheet:

(50HP)(0.746kW/HP)(0.72-0.20)(0.23)(6500hr/yr)($0.04/kWH) = $1159

Spread Sheet repeats this for all rows

Electric Motor Management
Selection of Best Option

- Magnetic clutches (permanent magnet or eddy current)
  - Bulky and heavy on motor shaft
  - No harmonics
  - Close to same savings as VFDs, but less

Electric Motor Management
Other Drives

- Variable sheaves
  - Very closely approach fan laws
  - Repeatability and maintenance often a problem
  - Many lock blades and install VFDs
- Hydraulics
  - Effective
  - Expensive
  - Not often used as discussed here

Electric Motor Management Axial and Reciprocating

- Centrifugal laws do not apply
- More difficult to predict savings
- If linear, no “real energy savings” over present on/off operation (certainly improved soft start operations and perhaps control)
- Obviously, savings if converting from constant volume to variable volume

$$$$ Variable Speed Drive Applications

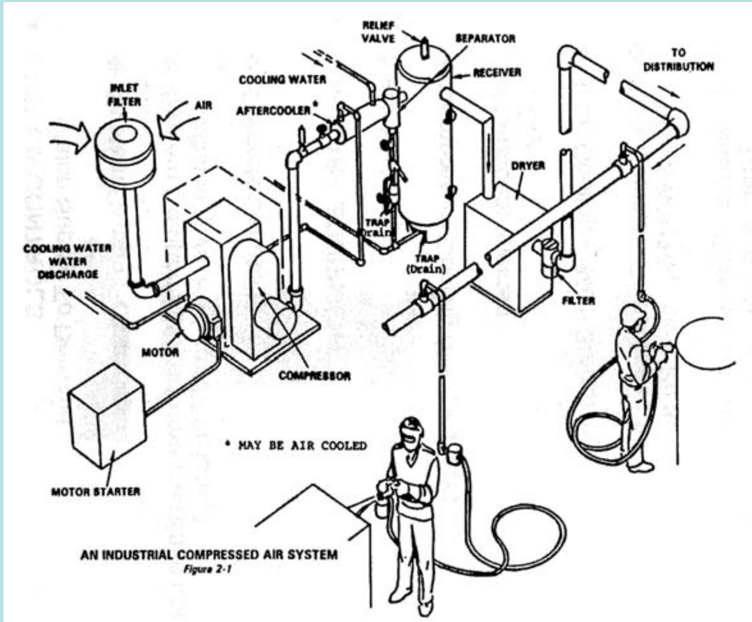
- Any large centrifugal blower or pump that runs a lot!
  - Constant volume? Convert to var. volume
  - Variable volume with inlet or outlet control
- Chilled water pumps, large campus
- Cooling water pumps
- VAVs using inlet vane
- Forced draft (blower) cooling towers

Compressed Air Management

- Most expensive utility for many companies
- Large cost reduction potential (20 to 30% common)
- Management
  - Demand side
  - Supply side

Compressed Air Management

- Each 100 hp compressor costs approximately $25,000 per year to operate
- Try it: 8000 hours/year, $80/kW-yr, $0.05/kWh, running at 70% load.
  - Cost:
- Typical first cost is $30,000 to $50,000



Air Systems Components Mgmt.

- Demand side: should be managed first
  - Air leaks: large cost (see diagram), often 20% or more of capacity goes to leaks (artificial demand). Air leak detection and repair is extremely cost effective.
  - Air motors: great torque properties, small handprint, will not spark, but VERY ENERGY INEFFICIENT (7 hp air vs. 1 hp electric common)

Air Systems Components Mgmt.

- Pressure supplied: proper level critical
  - Approximately 1% energy savings for each 2 psig drop (increase) in air pressure
  - Productivity cost can greatly exceed energy savings so be careful
  - Distribution drop should not be more than about 10% (90 psig at tank to supply 80 psig to tool) so receivers, better looping, etc. may enable pressure to be dropped without affecting tool

System Components

- Supply Side
  - Air Compressor
  - Aftercooler
  - Receiver tank (storage)
  - Dryer
  - Distribution lines
  - Users (demand side)

Air System Components Mgmt.

- Air Compressors
  - Screw: convenient, fairly efficient, skid mounted, most popular (100 HP or so)
  - Reciprocating: usually large, expensive, very efficient, part load well, often two stage
  - Centrifugal: usually quite large, modulates efficiently down to a point (surge), often VFD
  - Others: other types exist but these cover the vast majority

Air Systems Components Mgmt.

- Intake air should be as cool and dry as possible
- Intake air filter should be large with low pressure drop (2 psig), changed frequently
- Multi stage with interstage cooling helps
- Drivers can be electric motor (most), gas engine (load management or hybrid), or steam
- Significant waste heat available (250,000 Btu/100 HP.) Easy to recover on packaged screw air cooled machines.

Air Systems Components Mgmt.

- Sequencers: For multiple compressor dispatching
  - Use a remote (not in compressors) PID control loop to dispatch multiple compressors
  - Dramatically reduces control differential and smoothes operation
  - Can be extremely cost effective

Air Systems Components Mgmt.

- After coolers: Air leaves a compressor at approximately 100% RH.
  - Cooling removes significant moisture; must be trapped and drained (exhausted)
  - Air cooled or water cooled and they are quite cost effective; save energy in dryer and provide dryer air.
  - Water cooled more effective but water should be used elsewhere or reused through small cooling tower

Air Systems Components Mgmt.

- Receivers: storage devices to smooth demand on compressor
  - Further cooling removes more water (traps)
  - Can significantly reduce demand fluctuation on compressor controls
  - 2 to 4 gallons per CFM (but this varies a great deal)
  - Located before dryer (wet), after dryer (dry), throughout plant, and at large loads

Air Systems Components Mgmt.

- Dryers: Further reduce dew point to avoid moisture in plant equipment
  - Refrigerated: cools air to about 40 F and reheats by precooling incoming air. Thus, dew point around 40 F. Not dry enough for many plants.
  - Desiccant: chemically removes moisture saturating media which must be dried before reusing. Usually two stacks. Expensive but dew point around -10 F.
  - Deliquescent: similar to desiccant but wet material is removed and replaced.

Air Systems Components Mgmt.

- Distribution lines: get air where needed and provide further storage
  - Large lines are good for systems operating full time (often 4 inch)
  - All lines should be “looped” so air comes at any need from two directions
- Traps and drains: traps and drains located throughout system to remove moisture. Can be a large source of air leaks.

Appendix

Compressed Gas Systems

Compressed Gas Systems

- Gas systems fall into three categories
  - Compressed air systems, compressed on site
  - Compressed gas systems, with high pressure storage
  - Liquid storage

Compressed Gas Systems

- Most systems with pressures greater than a few psi have one thing in common: leaks.
- Compressed air system leaks result in more compressor energy and expense.
- Leaks in other systems result in loss of purchased gas.

Compressed Gas Systems

- Simple method to quantify the cost of compressed air leaks:
  - Shut off all normal plant air uses such as
    - air-driven pumps.
    - air hoses blowing directly on work surfaces (to blow away chips, for example).
  - Valve off the compressor at its outlet (or simple shut it off if no air bleeds back through it).

Compressed Gas Systems

- Simple method to quantify the cost of compressed air leaks (continued):
  - Do not valve off any major part of the system.
  - On a functioning pressure gage, measure the time (to the nearest second) needed for a 5 to 15 psi pressure drop.

Compressed Gas Systems

- Quantifying air leaks
  - Compute the volume of all the receivers and major air headers.
  - Small air lines (under about 1 inch diameter) can be neglected.
  - Leaving some volume out makes the calculation conservative.

Compressed Gas Leaks

- Quantifying air leaks
  - Apply the following formula to find standard cubic feet per minute (SCFM) lost

$$R = \frac{V\,(P_1 - P_2)}{(\Delta T)\,14.7}$$

R = average leakage rate (Scfm)

V = system volume (ft^3)

P_1 = initial pressure (psig)

P_2 = final pressure (psig)

ΔT = time interval over which leaks are measured (minutes)

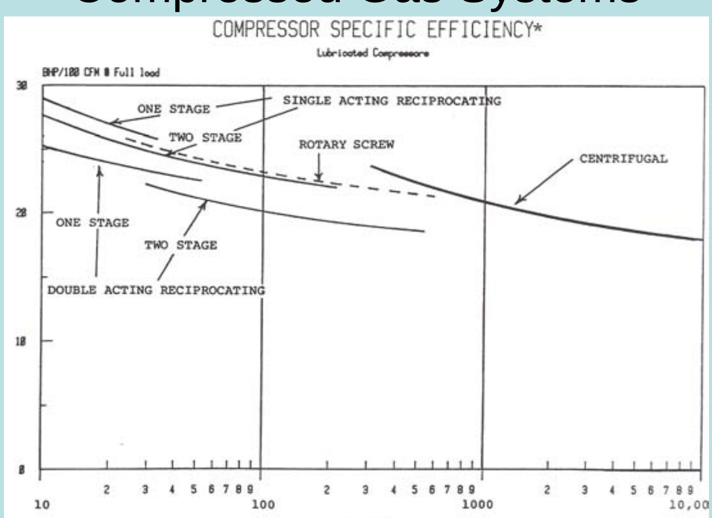
Compressed Gas Systems

- Quantifying air leaks
  - Find the compressor specific efficiency in BHP/SCFM from the curve on the next page.
  - Then multiply

    [R x specific efficiency x 0.746 kW/Hp x operating hours x cost of energy (in $/kWh)]/η

    to arrive at annual cost of leaks.

Compressed Gas Systems



*Compressed Air Systems, Varigas Research, Inc., Timinium, Maryland,1984 DOEICSI 40520 – T2, page 61.

Compressed Gas Systems

- Quantifying air leaks
  - The figure is for 100 psig. Other pressures require a correction factor.*

Pressure, psig	Correction factor
130	1.15
120	1.11
110	1.05
100	1.00
90	0.942
80	0.880

*Nutter, DW, Britton AJ, and Heffington WM, “Five Common Energy Conservation Projects in Small and Medium-Sized Industrial Plants”, Fifteenth National Industrial Energy Technology Conference, Houston, Texas, Mar 24-25, 1993. pp 112-120.

Compressed Gas Systems

- Quantifying air leaks
  - Other methods include measuring compressor run times and amp draws.
  - Drawbacks to all these methods include lack of location of leaks.
  - One method includes identifying the locations and trying to assign the size of an equivalent round hole to the leaks.
  - Then a chart such as the one on the next page is applied.

Compressed Gas Systems

- Quantifying air leaks
  - Leak rate in SCFM through equivalent area round holes*

Gauge Pressure Before Orifice in PSI	Diameter of Orifice 1/64"	1/32"	1/16"	1/8"	1/4"	3/8"	1/2"	5/8"	3/4"
1	.028	.112	.450	1.80	7.18	16.2	28.7	45.0	64.7
2	.040	.158	.633	2.53	10.1	22.8	40.5	63.3	9.12
3	.048	.194	.775	3.10	12.4	27.8	49.5	77.5	111
4	.056	.223	.892	3.56	14.3	32.1	57.0	89.2	128
5	.062	.248	.993	3.97	15.9	35.7	63.5	99.3	143
6	.068	.272	1.09	4.34	17.4	39.1	69.5	109	156
7	.073	.293	1.17	4.68	18.7	42.2	75.0	117	168
9	.083	.331	1.32	5.30	21.2	47.7	84.7	132	191
12	.095	.379	1.52	6.07	24.3	54.6	97.0	152	218
15	.105	.420	1.68	6.72	26.9	60.5	108	168	242
20	.123	.491	1.96	7.86	31.4	70.7	126	196	283
25	.140	.562	2.25	8.98	35.9	80.9	144	225	323
30	.158	.633	2.53	10.1	40.5	91.1	162	253	365
35	.176	.703	2.81	11.3	45.0	101	180	281	405
40	.194	.774	3.10	12.4	49.6	112	198	310	446
45	.211	.845	3.38	13.5	54.1	122	216	338	487
50	.229	.916	3.66	14.7	58.6	132	235	366	528
60	.264	1.06	4.23	16.9	67.6	152	271	423	609
70	.300	1.20	4.79	19.2	76.7	173	307	479	690
80	.335	1.34	5.36	21.4	85.7	193	343	536	771
90	.370	1.48	5.92	23.7	94.8	213	379	592	853
100	.406	1.62	6.49	26.0	104	234	415	649	934
110	.441	1.76	7.05	28.2	113	254	452	705	1016
120	.476	1.91	7.62	30.5	122	274	488	762	1097
125	.494	1.98	7.90	31.6	126	284	506	790	1138

*M.D. Oviatt and R.K. Miller, Industrial Pneumatic Systems, Fairmont Press, 1981, p. 64.

Compressed Gas Systems

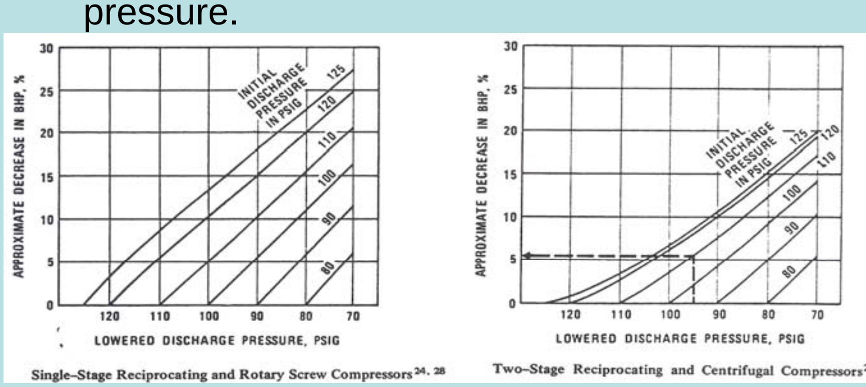
- Quantifying air leaks
  - Generally leaks are from broken regulators, loose or worn connections, or broken hoses.
  - They are relatively inexpensive to repair.

Compressed Gas Systems

- For relatively uncommon liquid storage or very high pressure gas, contact the tank owner or installer.
  - The owner or installer should help
    - determine the leak rate.
    - determine the cost.

Compressed Gas Systems

- Other energy conservation techniques
  - Do not compress air to an unnecessarily high pressure.



M D Oviatt and RK Miller, Industrial Pneumatic Systems, Fairmont Press, 1981, page 61.

Compressed Gas Systems

- Other energy conservation techniques (cont):

Relocate air intakes to cooler positions*	
Air Intake Temp, °F	Power Savings**, %
30	7.5
50	3.8
70	0
90	(3.8)
110	(7.6)

*MD Oviatt and RK Miller, Industrial Pneumatic Systems, Fairmont Press, 1981, p. 49.
** Relative to 70ºF

Compressed Gas Systems

- Other energy conservation techniques (cont):
  - Recover heat for personnel comfort from air compressor

Heat recovered from air compressors*	
Compressor Size, Hp	Heat Available, Btu/min
40	1870
100	4660
125	5830
150	6990
200	9330
300	14,000
400	18,700

*From Sullair screw compressor data

Compressed Gas

- AIRMaster+
  - Software tool sponsored by US Department of Energy
  - Estimates potential savings from selected energy efficiency measures and calculates paybacks
    - Reduce air leaks
    - Improve use efficiency
    - Reduce air pressure
    - Use unloading controls
    - Adjust set points
    - Reduce operating time
    - Add receiver volume

Compressed Gas

- AIRMaster+ available for download from http://www1.eere.energy.gov/industry/bestpractices/software.html