TECHNICAL BULLETIN:

ESTIMATING CHILLER LOAD FROM PERCENT OF FULL LOAD AMPERAGE

The following technical bulletin presents *ERA*'s findings and suggestions for estimating the load on a centrifugal chiller by means of measuring and interpreting the percent of full load amps the chiller is drawing.

1. BACKGROUND.

Due to *ERA*'s practice involving many variable flow chilled water conversions over the years and *ERA*'s practice of building and commissioning digital control systems for select clients, we have developed significant expertise in this arena. Accordingly, this technical bulletin has been written so as to more easily share our expertise in this area with those with whom we are collaborating. As noted below, this document is copyrighted and those not sent this bulletin directly by *ERA* should contact *ERA* for permission and possible payment of use fees.

In recent years it has become fairly common practice to employ variable flow chilled water systems in buildings and facilities. A confounding problem for some control and building automation system designers/installers is how to control the plant, specifically when to bring additional chillers on line as load increases, and when to take chillers off line as load is decreasing (the "stage-up" and "stage-down" decisions). This is confounding because it has been strongly ingrained in the industry that chilled water systems are constant flow and that a multi-chiller plant can be controlled simply by watching the temperature of the chiller water returning to the plant, and when it starts to rise above an acceptable level, it means that more equipment must be put on line. The return water temperature may also be used to control the stage-down decision. Simply put, with variable flow systems, the temperature of the return water is very much unrelated to the load on the plant. In fact, when the load is light, the temperature is the highest - exactly the opposite of a constant flow system.

The simplest way to control a variable flow chilled water plant is to watch the load on the chillers and the plant in total. A properly sequenced chiller plant will result in no more than <u>one start per day for each chiller in the plant</u>. This can be accomplished if the actual load on the chiller is monitored by measuring chiller KW (or Amps if it is corrected for its non-linear relationship to KW) and a stage-up decision made when the on-line chiller(s) operate at more than 95% (adjustable for each stage) for a short time period (adjustable time period). A stage-down decision should be made when the total combined load of the on-line chiller(s) is less than approximately 80% (adjustable for each stage) of the next lower stage of capacity. For example, if two 300 ton chillers are operating, the stage-down decision would not be made until the total load on both chillers was less than approximately 240 tons. The problem with using temperatures is that they can fluctuate significantly over short periods of time and sensor inaccuracy, since there is such small room for error, can result in frequent cycling of chillers. We have seen plants where the chillers had more than 30 starts per days, which was eliminated when this control sequence was employed.

The purpose of this technical bulletin is revealed in the above comment... "or Amps if it is corrected for its non-linear relationship to KW". The following comments will explain a methodology which *ERA* has developed to employ % full load amps as a method to estimate the load on a chiller. But first a few comments on why this might be a good idea.

- first of all, it is altogether possible that the instruments needed are already in place and can just be monitored through the building automation system running the plant
- relative to other instrumentation, current transformers are relatively cheap and easy to install - for example split-core CT's are readily available and can be put in place without disrupting the existing electrical wiring
- watt transducers can be used and are relatively inexpensive as well, but even kw is not linear with load, so a reading from a watt transducer would have to be interpreted in similar fashion to a current reading
- directly measuring the actual load (in tons) is great, and so is watching all the control valve positions - but either of these require that a whole lot of instrumentation continue to function pretty darn well all the time - instead, using amps requires only one very simple instrument to work

2. SOME FUNDAMENTALS.

While the analysis provided below is relatively straightforward, it may be best to review a few of the fundamentals:

A. Chiller KW and Load.

If the performance data for chillers is examined closely, it can be observed that the part-load efficiency of centrifugal chillers varies a fair amount over it typical load range. Most chillers aren't real happy running at very low loads, and as a result generally find themselves running in the 30 to 100% load range most of the time. Examining the literature, we can see that the chillers get a bit more efficient as load drops off (KW/ton is less than nominal) and start to get less efficient as the low end of the load range approaches (at 10 to 15% the chiller may operate at 2 to 4 times its nominal KW per ton).

B. Power Factor and Induction Motors.

Power factor seems to be a relatively poorly understood electrical power issue. Apparent power is simply the product of volts and amps. However, in alternating current systems (such as most of the ones that power HVAC equipment), the timing of the sine wave patterns of voltage and current don't always perfectly coincide (known as out of phase) and it is this out of sync condition which makes real power different from apparent power. In fact, real power is the product of volts, amps and power factor (which is the Cosine of the phase angle, the out of sync angle, between the two sine waves, and varies in value from zero to one). Now it turns out that induction or squirrel cage motors are very prone to experience poor power factor, which drops off dramatically as the load on the motor drops off. Smaller motors are particularly sensitive, but larger motors will also, for example, operate at a power factor of as little as 0.6 at 20% of rated load. What this means is that real power can be a whole lot different than apparent power! For fun, it can be very interesting to put a power factor meter on an elevator and watch the power factor jump all over the place (these motors run at very low load on the "down" cycle).

The implication of all this for this discussion, is that the current required to produce a given amount of power increases dramatically as the power factor declines. This means that a completely unloaded motor may show that it is drawing 30 to 40% of full load amps - even when it is doing no work. Using amperage, then, to determine the work being done, is not a straightforward task at all.

3. ANALYSIS AND DISCUSSION.

Readers are referred to the accompanying spreadsheet which provides all the information needed. Each portion of the spreadsheet is discussed in the following:

A. Motor Data.

The left side of the spreadsheet shows data for typical large horsepower motors. This data was taken from published literature and, to make the math a bit more simple, an exponential equation was written which mimics the empirical data very closely. This relationship between load and power factor are plotted in the graph at the lower left. As you will see, this data is used later in the analysis. As a point of interest, if you've lots of time and can actually test the motor you wish to monitor, actual measured data could be analyzed and substituted for the typical data shown (but then that's probably not the point, is it?).

B. Chiller Data.

The next portion of the spreadsheet shows data for typical large centrifugal chillers, employing some condenser water reset (which also makes a difference as well). Again, this was taken from one manufacturer's data, but is pretty typical of centrifugal chillers in general. The data was read directly from the manufacturer's chart showing %KW against % load. It is expressed also in terms of percent of nominal KW/ton, both as a point of interest, and for later use. This is calculated by dividing %KW by % tons.

Next to this section is a table that will allow the actual chiller you are working on to be input to the spreadsheet and its data analyzed. In this section of the spreadsheet the calculations are as follows:

- "TONS" is calculated by multiplying % tons by the chiller capacity for the actual chiller
- 'KW" is calculated by multiplying tons by "CHILLER KW/TON" and by "%NOMINAL KW/TON"
- "POWER FACTOR" is determined from the first portion of the spreadsheet (it actually uses the same exponential formula from that section, based on % KW)
- "AMPS" is calculated by dividing "KW" by 3 phases, 277 volts and "POWER FACTOR"
- "% FLA AMPS" is calculated by dividing "AMPS" by the maximum value for "AMPS"

The next sub-section allows actual test data for the machine to be input, and then plotted on the first graph with the typical data if desired. Should the test points fall far off the "typical" curve, the assumed formula for power factor could be revised to thereby "calibrate" the model to the actual data. Caution is warranted here, as the form of the formula may need to be changed, and only if a goodly number of data points are gathered should this be attempted. After all, the whole point of this process is to find a quick, dirty, but pretty effective way to take a cheap instrument and actually exercise reasonable control over your chilled water plant.

C. Amperage Model.

The next portion of the spreadsheet shows the results of creating a simple exponential formula for modeling the chiller % full load amps at various load levels. The formula used is displayed on the spreadsheet as a footnote. In addition, the accuracy of the model is compared to the calculated values in the center of the spreadsheet which are based on typical motor and chiller performance empirical data. This is done to demonstrate that the simple exponential model is a generally faithful representation of the typical empirical data. As can be seen from the example, the rates of error are very small.

D. Tonnage Model.

The next portion of the spreadsheet shows the results of "reversing" the amperage model formula to create a simple exponential formula for modeling the chiller load in tons at various % full load amp levels. The formula used is displayed on the spreadsheet as a footnote. In addition, the accuracy of this simple model is also compared to the calculated values based on typical empirical data. As can be seen from the example, the rates of error are very small. Also of interest is the fact that the formula will produce negate values at very low load levels and therefore the formula needs to check for negative values as it intend to calculate the root of the number and there are few roots for negative numbers.

The use of the above data is to employ the tonnage model in a building automation system to measure % full load amps, and then estimate the chiller tonnage from it. While much "fine tuning" could be attempted, as a general rule, the formula can be used as-is for most centrifugal chillers and it will probably do a pretty good job, and allow reasonably accurate decisions for up and down staging to be made, as discussed above.

DATE: 09/21/97
INIT: JPW

CALCULATION OF CHILLER TONNAGE BASED ON % FLA:

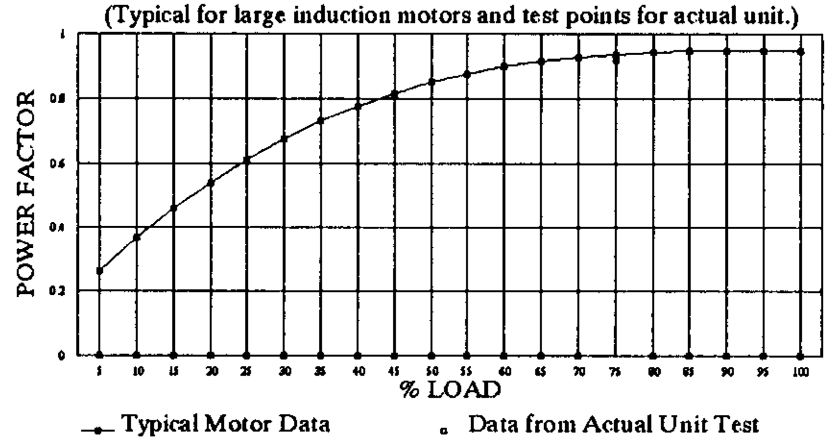
FILN: LOAD-ANL

MOTOR DATA		CHILLER DATA			DATA FOR ACTUAL CHILLER							%FLA MODEL		%TONS MODEL	
POWER FACTOR VS. % LOAD FROM TYPICAL MOTOR DATA		CHILLER % KW VS. % LOAD FROM TYPICAL CONSTANT SPEED CENTRIFUGAL CHILLERS			CHILLER CAPACITY = 200 TONS; CHILLER KW/TON = 0.55					ACTUAL TEST DATA (INSERT P.F. & USE "TEST" GRAPH)		SEE FORMULA BELOW		SEE FORMULA BELOW	
EXPONENT =	3.00											EXPONENT:	2.00		
% KW	P.F.	% TONS	CONV UNIT % KW	% NOMINAL KW/TON	TONS @ % TONS	KW @ % TONS	POWER FACTOR	AMPS	% FLA AMPS	% KW	P.F.	MODEL % FLA	WEIGHTED % ERROR	MODEL % TONS	WEIGHTED % ERROR
5	0.26	5	25	500	10	28	0.61	54	39	5		40	0.2%	0	-5.0%
10	0.37	10	26	260	20	29	0.63	55	39	10		41	0.3%	0	-10.0%
15	0.46	15	28	187	30	31	0.65	57	41	15		41	0.2%	12	-3.2%
20	0.54	20	30	150	40	33	0.68	59	42	20		42	0.1%	19	-0.9%
25	0.61	25	33	130	50	36	0.70	61	44	25		44	-0.1%	25	0.4%
30	0.68	30	35	117	60	39	0.73	63	46	30		45	-0.1%	30	0.4%
35	0.73	35	38	109	70	42	0.76	66	48	35		47	-0.1%	35	0.5%
40	0.78	40	42	105	80	46	0.79	70	50	40		50	-0.5%	41	1.3%
45	0.82	45	46	102	90	51	0.82	74	53	45		52	-0.7%	47	1.6%
50	0.85	50	50	100	100	55	0.85	78	56	50		55	-0.8%	51	1.4%
55	0.88	55	54	98	110	59	0.87	82	59	55		58	-0.6%	56	1.0%
60	0.90	60	58	97	120	64	0.89	86	62	60		62	-0.3%	60	0.4%
65	0.92	65	63	97	130	69	0.91	92	66	65		65	-0.5%	66	0.6%
70	0.93	70	68	97	140	75	0.92	97	70	70		69	-0.5%	71	0.6%
75	0.94	75	74	99	150	81	0.94	105	75	75	0.92	74	-1.4%	76	1.5%
80	0.94	80	79	99	160	87	0.94	111	80	80		78	-1.2%	81	1.3%
85	0.95	85	84	99	170	92	0.95	117	84	85		83	-0.9%	86	0.9%
90	0.95	90	90	100	180	99	0.95	126	90	90		89	-1.5%	91	1.4%
95	0.95	95	95	100	190	105	0.95	132	95	95		94	-0.9%	96	0.8%
100	0.95	100	100	100	200	110	0.95	139	100	100		100	0.0%	100	0.0%
												AVG ERROR:	-0.5%	AVG ERROR:	-0.3%

FORMULAS:
%FLA = (0.4 + (((%TONS/100)^EXPONENT)*0.6))*100
% TONS = 100*((((%FLA/100)-0.4)/0.6)^1/EXPONENT)

NOTE: %FLA/100-.04 MUST BE A POSITIVE NUMBER

POWER FACTOR VS MOTOR LOAD
(Typical for large induction motors and test points for actual unit.)



CHILLER POWER AND AMPS VS LOAD
(Conventional chiller, based on data from manufacturer's literature.)