An Application of Adjustable Speed Drives for Cooling Tower Capacity Control

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Cooling towers in process or condenser water loops offer an attractive application for adjustable speed drives (ASD's). Towers are typically modulated over the full 0 to 100 percent capacity range. In most cases capacity control has been achieved by cycling fans on and off. Using ASD's for capacity control allows fans to be left on, but slowed down to take advantage of the cubic relationship between fan speed and horsepower.

Three 50 horsepower ASD's were installed on a three cell, 4,500 ton cooling tower for a central chilled water plant in a semiconductor manufacturing facility in northern Texas. The drives were controlled by the existing programmable logic controller for the central plant. The control scheme was developed to optimize tower efficiency by running the maximum number of fans at the slowest possible speed.

Data on cooling tower capacity requirements and fan operating parameters was logged on a thirty minute interval using an energy management system. An analysis of the data showed that the ASD control of tower capacity versus on/off control reduced the annual tower energy requirements by 163,000 KWH per year, saving approximately $6,400.

This paper describes the data analysis and economics of the ASD installation, design and operating constraints, control scheme optimization and an estimate of additional savings achievable by eliminating a gearbox constraint.

Introduction

Cooling towers are found in a wide variety of forms and locations worldwide. They are used for process water cooling, condenser water cooling and for other commercial, industrial and power generation cooling requirements. The most common method for controlling the temperature of the water leaving a cooling tower is to cycle the tower fans on and off. This method of control, while adequate, has several drawbacks. On-off control requires an inherent deadband to avoid excessive cycling of the equipment. Typically a minimum of a five to ten degree Fahrenheit (three to six degree Celsius) deadband is required. The temperature swings associated with this type of control cause variations in the efficiency and operating characteristics of the equipment served by the cooling tower. The frequent cycling of the cooling tower fan causes wear on motor starters, motors, drivetrains and gearboxes. Even with periodic maintenance, the wear on drivetrain components caused by high starting torques can eventually lead to complete failure of one or more components. Replacing the on-off controls with a fully modulating control scheme using adjustable speed drives (ASD's) can eliminate many of the shortcomings of cycling the fans and provide the added benefit of reducing the cooling tower energy consumption. The application is particularly attractive, because cooling towers in temperate climates operate at substantially less than full load for significant portions of the year.

Three ASD's were installed on a 4,500 ton, three cell, crossflow cooling tower at a semiconductor manufacturing plant in northern Texas. The ASD's are controlled by a programmable logic controller (PLC) that is connected to the energy management system (EMS) for the site. The EMS was programmed to log cooling tower parameters on a one half hour increment on an ongoing basis.

Estimates of ASD savings require developing an annual operating curve for the device being analyzed. The operating curve for a cooling tower is based on the tower capacity required to transfer heat from the process to the atmosphere. Capacity requirements are a function of the process load to be removed and the ability of the atmosphere to absorb water evaporated from the tower. Estimating the annual process load fractions is difficult, but matching the process load fractions to coincident wet bulb temperatures is almost impossible without logged data.

The installation and data presented in this report provide an opportunity to examine the measured response of the ASD's to capacity requirements and the success of the ASD's at meeting economic and operating expectations.

System Description

The cooling tower serves two 1,200 ton centrifugal chillers and one 1,500 ton centrifugal chiller in one of the central utility plants (CUP's) at a 1.2 million square foot semiconductor and defense systems manufacturing plant north of Dallas, Texas. The CUP serves three buildings in the complex. The largest load on the chillers is to provide cooling water for a large, critical process load. The remaining load is comprised of HVAC loads and other process loads in the three buildings. Chiller capacity requirements typically vary from approximately 1,600 tons in the winter months to 3,900 tons in the hottest summer months. Since the process load is present year-round, cooling tower capacity is required in all but the most bitterly cold periods or during periodic shutdowns.

The climate in northern Texas is one of extremes. Winter temperatures often dip into the teens (-7 to -11°C), while summer temperatures may exceed 100 F (38°C). Periods of high humidity are common from late Spring through late Summer. There are more than 1,600 hours per year where wet bulb temperatures exceed 70°F (21°C).

The cooling tower is a twenty year old, three-cell, crossflow tower. The tower had been upgraded during the early 1980's with velocity stacks for the fans, PVC film fill, a more efficient water distribution system and new fan blades. The distribution system on the tower was fed from three inlet pipes that branched from a common condenser return pipe from the chillers. The three cells drained to a common basin at the base of the tower. Each of the three fans was powered by a standard efficiency, 50 horsepower TEFC motor. Power was transmitted to the fixed pitch fans through driveshafts connected to right angle, speed reducing gearboxes at the base of each fan.

The ASD's were of the pulse width modulated (PWM) type. PWM ASD's were chosen because of their high power factor at lower speeds. PWM ASD's were readily available for 50 horsepower motors. The ASD's were purchased with factory installed bypass capability, four to twenty milliamp control signal inputs and an LED display for reading drive parameters at the field mounted cabinet. Additional switches and contacts were installed to allow the ASD's to be isolated and to provide a positive signal to the PLC that the drive was in "Drive" mode instead of "Bypass" mode. The drives were installed in an unconditioned space with numerous transformers, electrical switchgear and a large, diesel powered emergency generator. The space had thermostatically controlled ventilation fans to remove excess heat in the summer months, but no other heating or cooling. The ASD cabinets were fitted with small ventilation fans to remove excess heat from the inside of the cabinets. A dedicated air conditioning system for cooling the drives was contemplated, but deferred. Several years of operation with no overheating problems has indicated there is no need to provide additional cooling to the drive cabinets.

The three ASD's were installed during a modification of the CUP motor control center. Control of the on/off status of the fans and tower capacity was provided from the existing PLC for the CUP. The only changes made to the existing electrical wiring on the tower were the addition of switches to allow isolation of each fan for maintenance purposes and the addition of vibration switches.

Reliable cooling tower operation was critical to providing chilled water to the process cooling system. Several steps were taken to insure reliable cooling tower fan functioning. First, the decision was made to install three individual drives instead of one large drive. This choice allowed the other drives to compensate for a failed drive and provided greater control flexibility. If a drive failed, the other two fan speeds were automatically ramped up by the PLC to match the demand. Second, full bypass capability was ordered as a factory option. The bypass feature allowed the ASD's to function as standard motor starters if the drive section failed. This feature is offered as an option by most ASD manufacturers. Finally, numerous alarms were programmed into the EMS to inform the CUP operators a problem had occurred.

Several constraints governed the operation and control of the ASD's. The first and most limiting was a 50 percent minimum speed requirement imposed by the existing gearboxes. The existing gearboxes were original equipment and were designed for single speed operation. The gearboxes relied on the lower gears slinging oil from a sump to lubricate the upper bearings. Replacing or retrofitting the gearboxes with forced lubrication units was not cost effective at the time of the ASD installation. The second constraint was to avoid too frequent cycling of the fans. Although ASD's provide a soft start for the equipment, frequent cycling still imposes excessive wear on the electrical components and to a lesser degree the mechanical components. The third constraint was to avoid wide temperature swings in the condenser water. The chillers surged at low condenser water temperatures and developed high head pressure at high condenser water temperatures. A proportional-integral control loop was programmed into the PLC to prevent too frequent cycling and to insure stable temperature control.

Several potential constraints often associated with ASD's did not cause a problem with this installation. Harmonics can be introduced into the incoming power distribution system by ASD's. The harmonics can overload transformers serving the ASD equipment if transformers are not designed to handle the harmonic load or if the ASD load is a significant portion of the total load on the transformer. The manufacturer of the transformer serving the three ASD's was contacted to determine if there would be a problem. The manufacturer stated that ASD loads less than twenty percent of the rated capacity of the transformer would cause no problem. The maximum load from the ASD's was approximately 150 KVA on a 2,000 KVA transformer (approximately eight percent). No problems were anticipated, nor have any surfaced. A constraint not applicable in the initial installation, but potentially a factor as the gearboxes are replaced is the minimum speed for the motors. The motor manufacturers stated the motors would overheat at speeds less than 15 percent of rated RPM. A final constraint that also did not surface was the resonant frequency of the fan systems. At certain fan speeds the natural frequency of the fan systems could have caused excessive vibration. During PLC programming, the fans were manually stepped through the operating speeds to check for excessive vibration at specific speeds. No vibration problems were found in the 50 to 100 percent of full speed range. To be safe, the fans were equipped with vibration switches to avoid damage in extreme cases. The resonant frequency may surface after the gearboxes are replaced and minimum speeds lowered. The typical avoidance method for vibration caused by natural frequencies is to program the PLC to lock out the fan speeds that cause resonance.

The overall goal of controlling multiple cooling tower fans using ASD's is to run the maximum number of fans at the slowest speed that satisfies the load to take advantage of the cubic relationship between fan speed and power. If no operating constraints were imposed, the ideal control scheme would be to ramp three fans in unison from 0 to 100 percent to match capacity requirements. The constraints imposed by minimum fan speeds add considerable complexity to the control scheme and sacrifice energy efficiency. Simplified graphs of the control scheme for the ASD and for on/off control are shown in Figures 1 and 2.

In the actual control algorithms, there are overlaps (deadbands) at each of the fan changeover points to prevent too frequent cycling of the equipment. Capacity is modulated using the temperature of the condenser water leaving the tower as a process variable in a proportional/integral control loop in the PLC. Because the process variable changes slowly, a low value of gain and a relatively long reset time were programmed into the proportional/integral loop. This slow response did not adversely affect the condenser water temperature--condenser water temperature did not typically vary more than one half degree on either side of the set point. The slow response also helped to prevent frequent cycling of the tower fans.

Data collection was achieved by programming the plant energy management system (EMS) to continuously log the tower capacity requirements on a half hour interval. Each entry provided a snapshot of the requirements at the instant it was logged. The EMS was incapable of averaging the capacity during the half hour interval, so the logging interval was kept as short as the EMS memory would allow.

Data Summary

The input power to each drive was measured in five Hertz increments using a recording power analyzer over the 0 to 65 Hertz output range of the ASD's. The fan speed was measured concurrently using a stroboscopic tachometer. The resulting curves are shown in Figure 3.

The input power curve was modelled using a four term power series. The equation representing the KW curve is given by Equation (1):

$$KW = (9.207E\text{-}5)(Freq)^3 + (1.463E\text{-}3)(Freq)^2 + (4.332E\text{-}2)(Freq) + 3.175E\text{-}1 \tag{1}$$

The measured power factor is shown in Figure 4. As can be seen in the graph, the choice of PWM ASD's for this project prevented power factor problems at low fan speeds.

Cooling tower capacity requirements were sorted into 101 bins, each representing one percent of tower capacity. The number of entries in each bin equalled the total amount of time during the year the tower operated within the bin range. A frequency histogram summarizing the operating hours for each bin is shown in Figure 5.

The most obvious feature in the frequency distribution is the large cluster of hours at or near 100 percent capacity. The tower is slightly undersized for the high wet bulb conditions in the summer. A trade-off was made at the time the tower was installed in the early 1970's between first cost and the ability to provide 80°F (27°C) condenser water over the full year. This was not an atypical design

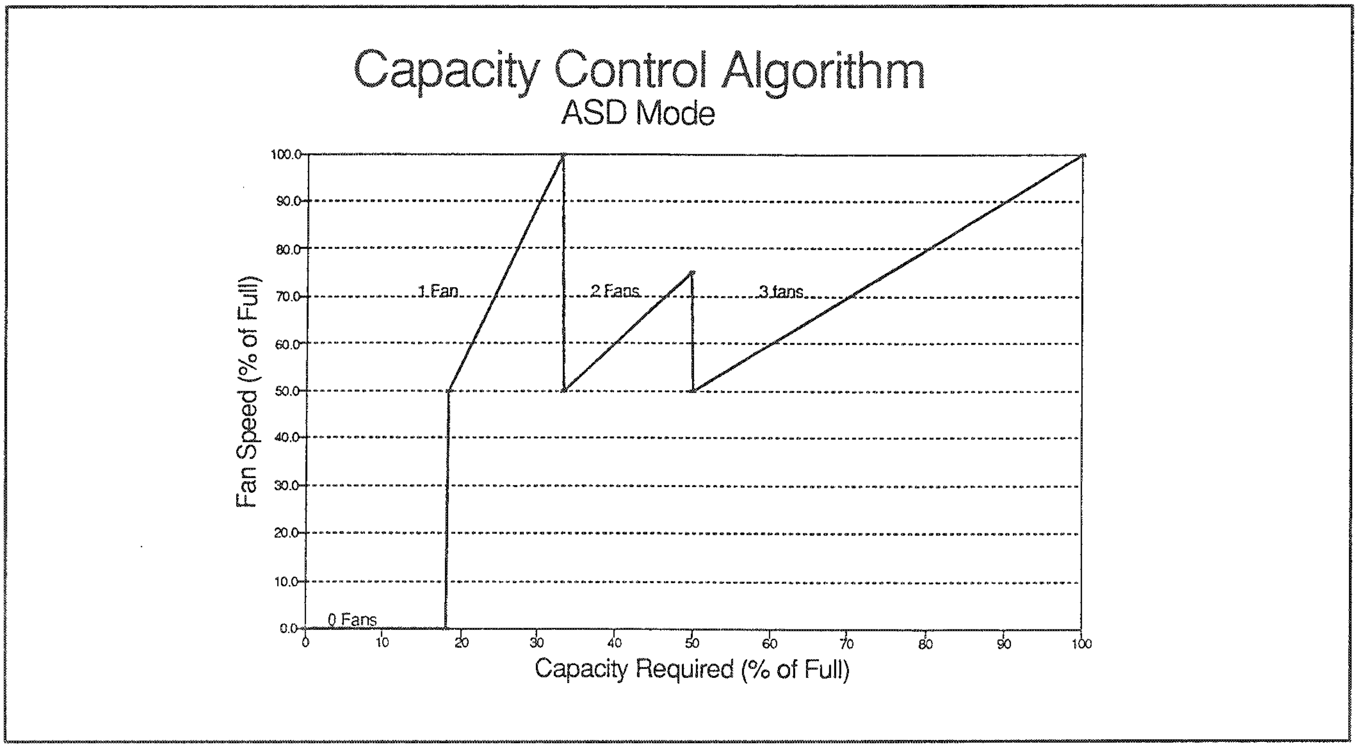

Figure 1. Simplified Control Scheme for ASD Control

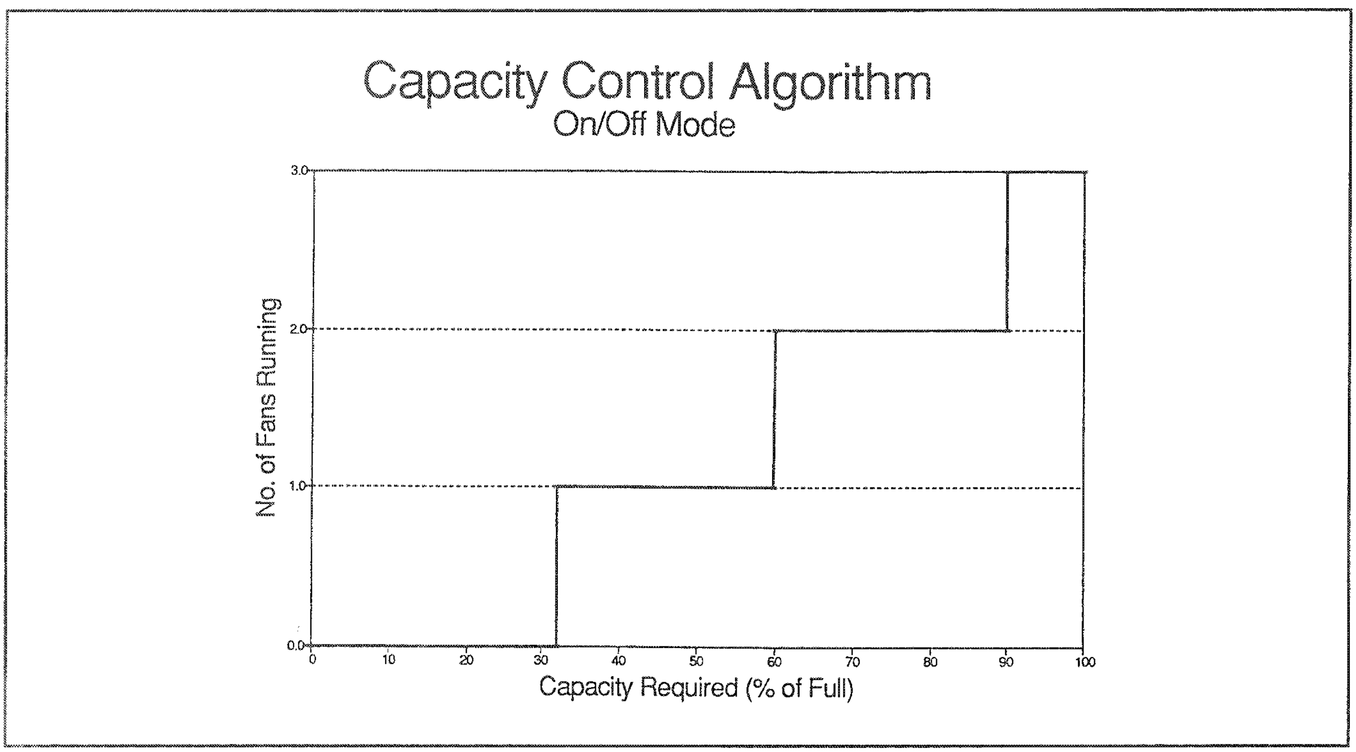

Figure 2. Simplified Control Scheme for On/Off Control

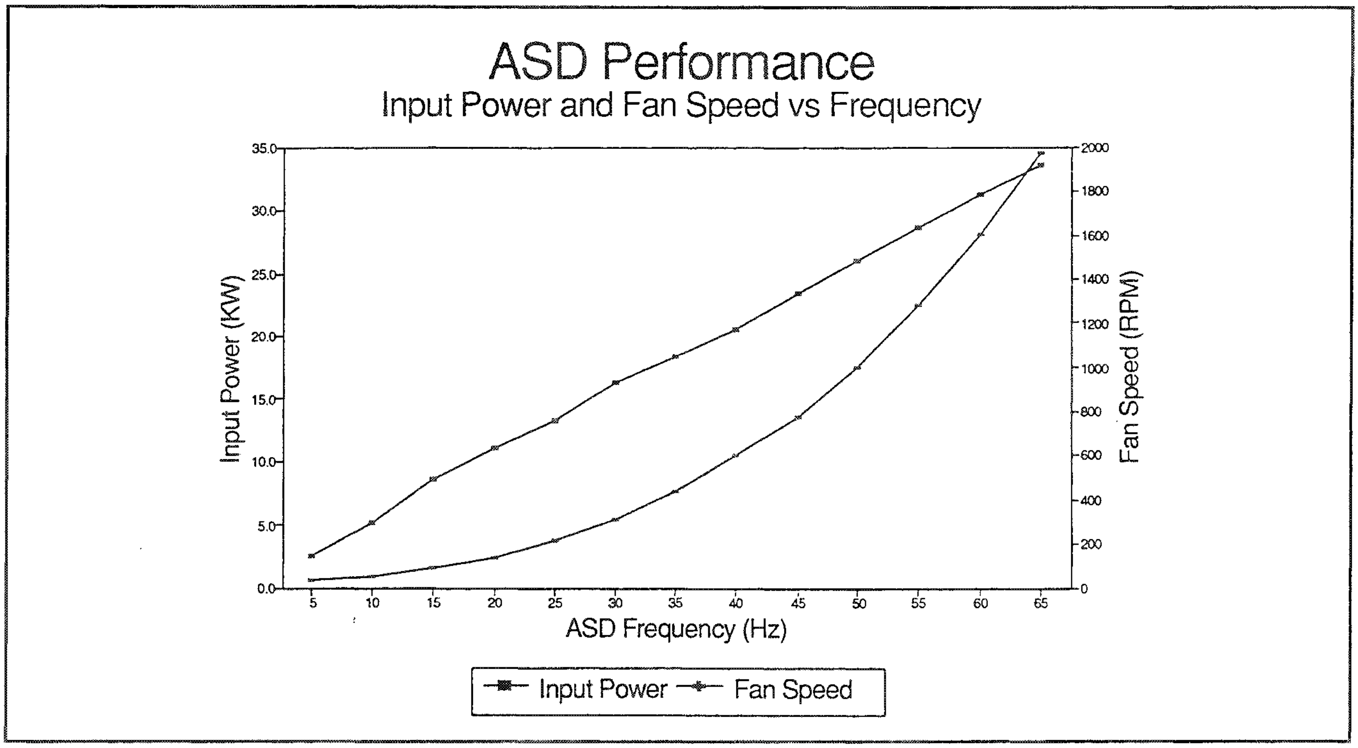

Figure 3. Measured ASD Performance

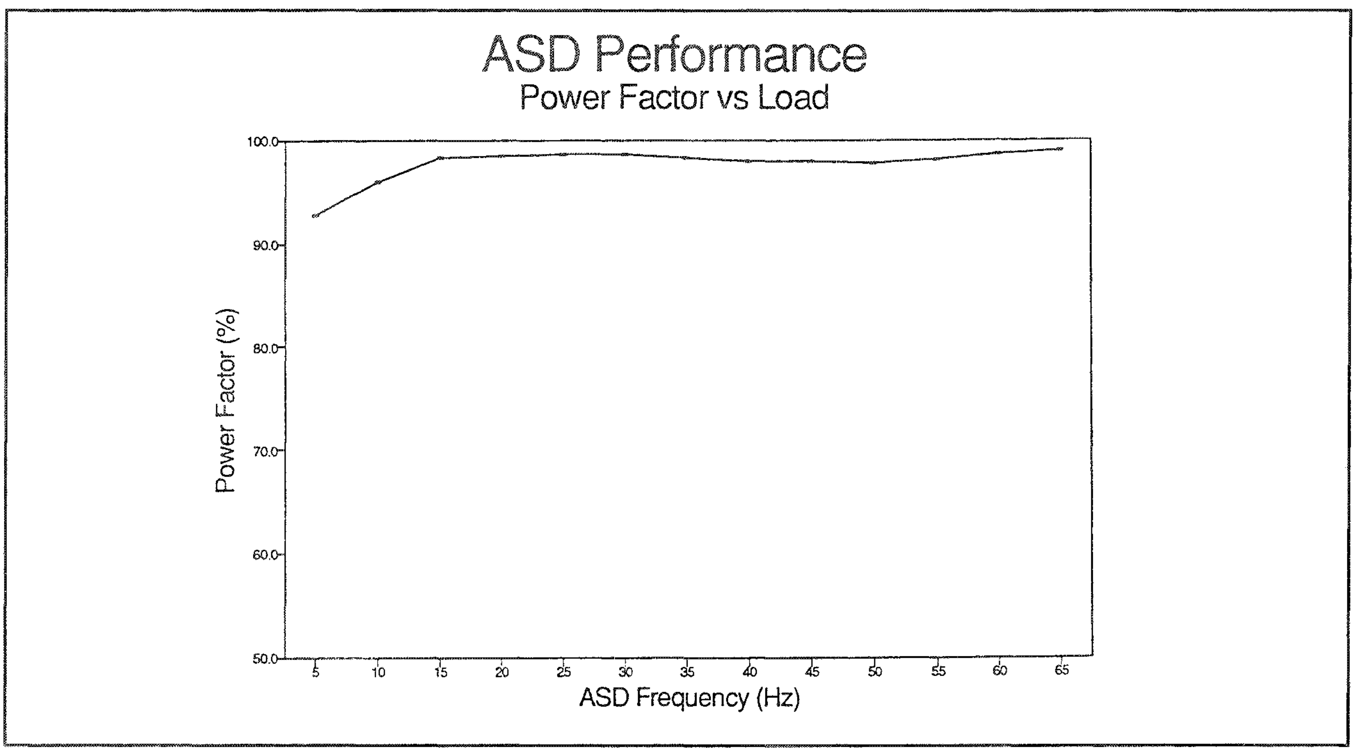

Figure 4. Measured Power Factor

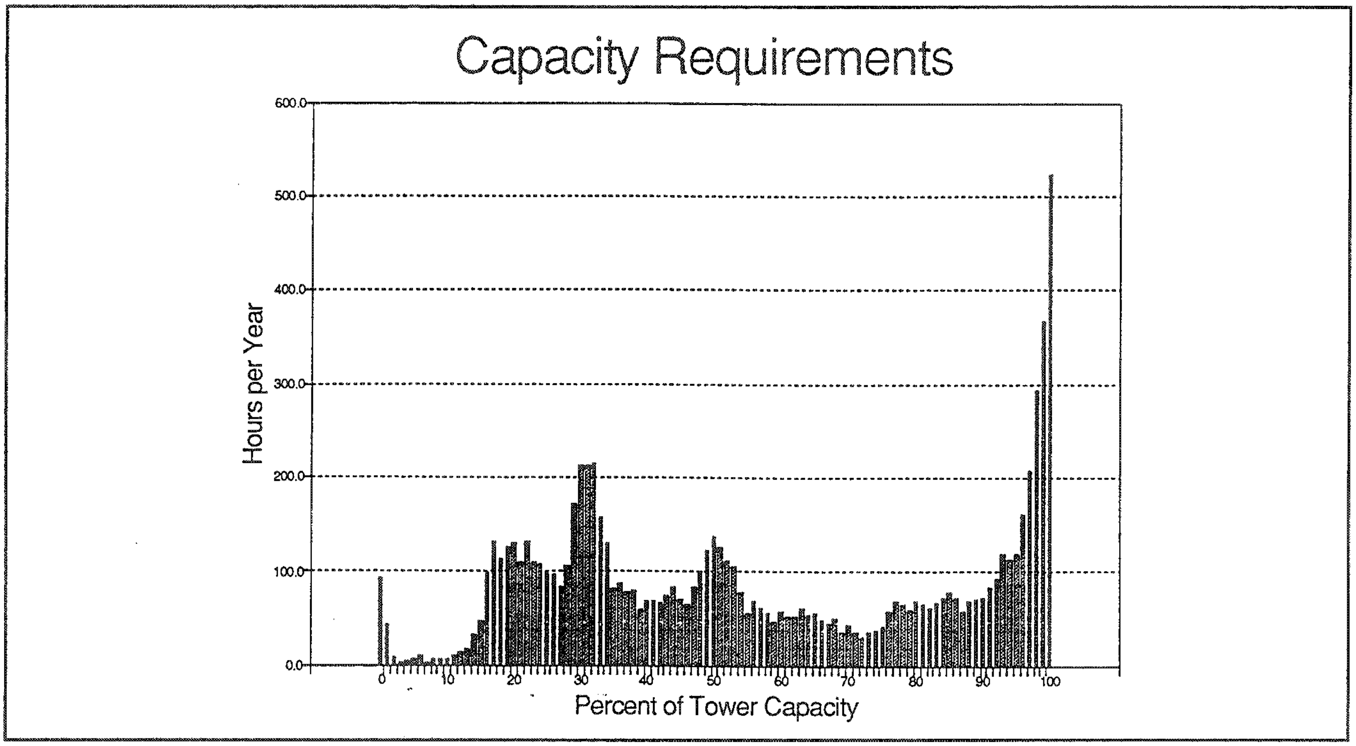

Figure 5. Annual Capacity Frequency Distribution

decision, since the chillers can operate with inlet condenser water temperatures slightly in excess of 90°F (32°C), although at lower efficiency than the 80°F (27°C) design temperature. The overall effect of the high end clustering was to lessen the energy savings from the ASD's. Other less pronounced clustering occurred at the changeover points for the number of fans operating. The PLC spent extra time searching for the proper combination of fans and speeds to satisfy capacity requirements at the changeover points.

Power requirements for each capacity bin were calculated by applying Equation (1) to the corresponding drive state for the bin. Power requirements for the on/off control mode were calculated by multiplying the measured input power to the fan by the number of fans required for each capacity bin. The power requirement for each bin was multiplied by the annual operating hours in the corresponding bin to determine the annual energy requirements for the bin. The sum of the bins for ASD operation and for on/off operation yielded the annual energy consumption for each mode. The difference between the modes was the energy savings achieved from using the ASD's for cooling tower capacity control.

Analysis

The annual energy savings achieved from using the ASD's for tower capacity control are shown in Table 1.

Table 1. Energy and Cost Savings (50% Minimum Fan Speed)

	Annual KWH	Annual Cost
ASD Mode	307,000	$12,200
On/Off Mode	470,000	18,600
Savings	163,000	6,400
Percent Reduction	35	35

The ASD's provided a 35 percent reduction in energy use and cost despite the clustering of capacity requirements near 100 percent capacity. If the 50 percent minimum fan speed constraint was eliminated by replacing the gearboxes with forced lubrication gearboxes, the fans could be slowed to 15 percent of full speed, the minimum motor speed. The energy savings gained from a 15 percent minimum fan speed are estimated in Table 2:

Table 2. Energy and Cost Savings (15% Minimum Fan Speed)

	Annual KWH	Annual Cost
ASD Mode	286,000	$11,300
On/Off Mode	470,000	18,600
Savings	184,000	7,300
Percent Reduction	39	39

Since the new gearboxes cost several thousand dollars each, the additional four percent savings ($900 per year) achievable by replacing all the gearboxes was not economically justifiable. The old gearboxes are, however, being replaced with new, forced lubrication gearboxes as they wear out.

Economics

The ASD's were installed as part of an upgrade to the motor control center for the West CUP. Because the work was done in conjunction with other upgrades, some cost savings was achieved. The existing PLC for the CUP was utilized to provide control signals for the ASD's. Because the PLC was in a different building than the ASD's, relatively lengthy cable runs were necessary. The overall cost to purchase and install the ASD's was approximately $23,000. The original estimate of energy savings from the ASD installation was approximately $8,000 annually. The difference between the estimated annual energy savings and the actual savings is attributable to difficulty in estimating load, wet bulb conditions and capacity requirements on an annual basis without logged data. It cannot be stated with certainty at this time whether there have been savings in maintenance costs because of reduced mechanical wear on components. There has been a gearbox failure since the drives were installed. The gearboxes were well into their useful service life at the time the ASD's were installed, so it is not likely the ASD's caused the failure. There were also several component failures in the drives themselves. All failures were caused by defects in the drives as received from the manufacturer. Examples of manufacturing defects were wires pinched between panels in the cabinet, poorly engineered contactors that caused the contactors to hang in the "On" position and stripped threads on the lugs holding the wires into the contactors causing overheating. Because of the problems that have surfaced, no definitive conclusion can be made on maintenance savings. The potential cost savings associated with more stable condenser water temperatures to the chillers has not been documented. No baseline information was available on chiller operation before the ASD's were installed.

The energy savings from the ASD installation showed a marginally acceptable payback despite the lack of any utility incentives and a relatively low electricity rate. The energy savings from this installation probably lie in the middle of the range of savings for ASD's installed on cooling towers. Since the load on the CUP described in this study was approximately 40 percent process load, the energy savings are lower than could be expected for CUP's serving purely HVAC loads and higher than could be expected for cooling towers serving strictly process or generation loads.

Several potential savings measures have been suggested since the installation of the ASD's. One measure is to program the PLC to reset the condenser water set point to follow the outside wetbulb temperature in cooler months. As the wetbulb temperature drops, the tower can produce lower leaving water temperatures. Lower condenser water temperatures typically allow more efficient chiller operation down to the point where the chillers begin to surge. This measure would require the installation of a transmitting weather station and some PLC programming changes. These changes will be made as time permits. A second suggestion is to recalibrate the drive output to allow the motors to run into their service factor during periods of high wetbulb, so additional tower capacity can be made available. The trade-off with this measure is between more efficient chiller operation and increased cooling tower fan energy consumption. In addition, the potential for motor overheating will have to be evaluated.

Conclusion

Controlling cooling tower capacity with ASD's is a logical application of the technology. ASD's provide a means of fully modulating tower capacity to match loads over a wide range of weather conditions. ASD's eliminate the shock loads placed on mechanical parts of the tower by frequent cycling of fans to match reduced loads. ASD's allow the temperature of the water leaving the tower to be controlled to within a few degrees instead of the five degree (3°C) or greater swings with on/off control. ASD's allow flexibility in cooling tower operation. Options like wetbulb reset and utilizing the service factor of the motors to meet high capacity requirements are achievable with little more than PLC program modifications. In addition to these benefits, the data collected in this study show ASD's provide an opportunity to operate cooling towers with 35 to 40 percent less energy than conventional on/off controls. The problems with power factor and harmonics that are often associated with ASD's did not appear in this installation. Based on this installation, the application of ASD's to cooling tower capacity control is an attractive, energy saving measure for industries and utilities to pursue.