Abstract:
Variable Frequency Drives (VFDs) are the preferred method of capacity control for evaporative cooling equipment, including cooling towers, closed-circuit cooling towers, and evaporative condensers. By precisely matching fan motor speeds to the required heat rejection, VFDs can significantly reduce energy consumption and operating costs of the entire system while providing operational benefits to the owner. This paper will explore the benefits of VFD operation while providing guidelines on proper application.

Introduction and Background:
It is well-known that water-cooled systems offer significant energy advantages over air-cooled alternatives, due to increased moisture in the air that can absorb additional heat. Controlling a cooling tower fan motor with a VFD will reduce operating costs through reduced energy consumption when compared to cycling fans on and off. Because there are many considerations when determining how to optimize system efficiency, the following analysis will not include recommendations for control but rather how to apply a VFD if it will control the cooling tower fan motor.

As VFD prices have dropped by around 50% since 1995, they have become increasingly cost effective for heat rejection applications. Additionally, VFD enclosures have become more compact due to pulse-width modulation (PWM) technology and 24VDC bypass contactors.

VFDs reduce energy use by reducing the fan speed to match the rejected heat load requirements. For example, VFDs can reduce fan energy consumption by about 80% when operating at half speed (see Figure 1 for details). Sound reduction during startup and operation also benefits the environment when the equipment lies in the vicinities of residences and office buildings alike. In addition to energy and sound benefits, VFDs also provide maintenance benefits over standard motor starters.

While the positive effects listed above demonstrate why users specify VFDs, it is often unclear as to which options should be selected for specific applications. In addition to energy benefits, the following paper discusses application-specific requirements, including harmonic distortion, line noise, and line bypass.

Energy Efficiency:
The primary purpose of controlling a motor with a VFD is to save energy and operating costs. Energy codes, such as ASHRAE 90.1 and California Title 24, mandate that heat rejection equipment have the ability to adjust fan speeds to 2/3 of design speed for 7.5HP motors and larger. Prior to cost-effective VFD implementation, facilities often utilized the following two-motor systems to comply with energy requirements:

1) Main motor for full-speed operation (100% of maximum energy consumption), pony motor at 2/3 design speed (35% of maximum energy consumption)
2) Two speed motor
   a. Full-speed (100% of maximum energy consumption)
   b. Half-speed (12.5% of maximum energy consumption)

Figure 1 demonstrates the theoretical relationship between fan speed and energy consumption. It is important to understand that the cubic relationship between power and speed yields a steeper power increase with increasing fan speed towards the top of the curve. This concept should be considered when determining how to maximize system efficiency.

VFD Installation:
Past experience with VFDs has led building owners to follow strict requirements regarding the type of VFD enclosures and installation locations. A UL508C listing ensures compliance with power conversion standards required by the National Electrical Code (NEC). Engineers are encouraged to comply with this requirement along with general requirements listed in the code.

As the reliability of VFDs continues to improve, more owners request that VFDs be mounted outdoors near the operating equipment in order to conserve building space. NEMA 3R enclosures, which are rainproof and suitable for outdoor applications, are be-
coming more common in mild environments. Engineers often specify NEMA 3R stainless steel or fiberglass or NEMA 4X enclosures in environments where corrosion resistance may be desired. NEMA 4 enclosures, which are totally enclosed and suitable for wash-down applications, are less common than NEMA 3R enclosures due to the high cost of rejecting the heat load from the enclosure.

Buildings located in hotter climates, such as the southern United States, often require that VFD enclosures remain indoors, where they are not in direct sunlight. Contractors often provide either a NEMA 1 enclosure, with relatively inexpensive covers, or a NEMA 12 enclosure, a dust-tight but more expensive and larger enclosure. NEMA 1 enclosures are the smallest enclosures and are well-suited for areas with limited available space. Most manufacturers approve VFD operation in ambient temperatures up to 104°F, however owners often feel more secure knowing that the VFD is located in a conditioned room. If the owner or engineer requires a higher operating temperature than the manufacturer specifies, a larger VFD, which the manufacturer can determine, may be derated for the higher temperature operation.

Various motor manufacturers state that VFD power wiring can have unlimited length when terminated to an inverter duty motor. Critical applications, such as data centers and hospitals, often require output dV/dt filters between the VFD and the motor in order to prevent voltage spikes. These voltage spikes may eventually damage the motor windings and lead to motor failure.

Most VFD manufacturers include a line reactor at the input, reducing the chances for an overcurrent trip while limiting the surge current associated with VFD switching frequency. A 3% line reactor is suitable for the majority of cooling tower applications, however 5% line reactors may be more suitable for critical environments; contact the VFD manufacturer for details regarding reactor selection.

Specifications often require that the VFDs be equipped with a two- or three-contactor bypass in order to operate the motor across-the-line before the Building Management System (BMS) is implemented. It is highly recommended that all VFDs for cooling tower fan applications include a bypass in order to hedge against unanticipated failures and to perform drive maintenance. Where space is limited, a 24VDC contactor bypass is recommended due to its reduced size compared to 120VAC contactors. Other advantages of 24VDC contactors include lower cost and a safer operating voltage.

Following the required wiring specifications in the National Electrical Code can prevent problems in the field. For example, VFD grounding has become increasingly important, as improper grounding has been recognized as a common failure mode. Building operators have identified breakdowns in fan motor bearings that propagate by a residual current, which passes from the motor through the drive shaft, a path of lower resistance when the VFD is not properly grounded.

Harmonic limitation is often specified, requiring system conformance to IEEE-519, “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.” A common misconception, sometimes even perpetuated by the specifications themselves, is that IEEE-519 is a VFD standard; however, this is not the case. IEEE-519 applies to the entire electrical system and heavily depends on kVA and impedance of the transformer that supplies the VFD.

An article by Eaton Electrical, titled “Harmonic Analysis and IEEE 1992 Guidelines,” describes the load points downstream of the transformer where harmonic analyses apply. If excessive voltage distortion is present, “clean drives,” or 18-pulse VFDs, can be used to impede voltage spikes and harmonic noise. Otherwise, standard 6-pulse VFDs are recommended due to lower cost and reduced size. Typical applications for these drives include hospitals and data centers, where large quantities of electrical equipment may create noise that will affect VFD performance. Contact the VFD manufacturer for a harmonic analysis based on specific jobsite conditions in order to determine the onsite harmonic conditions.

**Operation:**

A VFD modulates the cooling tower fan motor speed based on an analog input signal from a temperature sensing device or a BMS. A 4-20mA signal has become a preferred control signal, because amplitude is less susceptible to signal loss and electrical noise than voltage.

The BMS can control the VFD through an analog signal that runs directly into a drive input or via a communications interface. Common communication protocols include BACnet, Modbus, and Lonworks. The communications protocol card with the VFD should match that of the BMS; consult with a controls contractor to determine the most suitable protocol for specific applications.

The internal VFD software can be configured to control the motor based on the leaving water or fluid temperature from a temperature sensor. The software’s Proportional Integral Derivative (PID) algorithm will control the motor speed appropriately once the user scales the current signal over a temperature range. If a temperature sensor is used for condenser loop control, it should be installed in the leaving water temperature or fluid piping close to the cooling tower for an accurate reading.

For multiple fan applications, it is recommended that all cooling tower fans should be operated simultaneously at the same speeds when driven by VFDs. As described in the energy analysis section of this report, marginal increases in fan speed require exponential increases in power consumption. It is more energy efficient to run two fans at 50% speed than to operate one fan at full speed (refer to Figure 1), and simultaneous cooling tower cell operation maximizes the total heat transfer surface available.

Operators must also ensure that the motors are not driven below minimum speed, per the cooling tower manufacturer’s requirements. Belt drive fans can typically operate at as low as 10% of full speed, which will permit an adequate amount of motor cooling. Standard gear drive systems should operate at no less than 25% of full speed operation due to lubrication requirements. If an external oil pump is installed in the gearbox for constant lubrication, the minimum speed is once again restricted by the motor cooling limitation, or 10% of full speed operation.

Variable torque VFDs must be used when controlling fans. A constant torque VFD may damage a gear driveshaft, as the VFD attempts to maintain a constant torque regardless of the magnitude of the load.

VFDs also introduce the potential for operating the motor at the cooling tower system’s resonant frequency, so it is recommended that frequency ranges where heavy vibrations occur be locked out. Locking out frequency ranges is a common feature in VFD soft-
ware. A vibration specialist can provide an acceptable method for determining the frequency ranges that should be locked out.

**Motor Arrangement:**

As VFD pricing has become more competitive, two-speed motors are used less than they had been in the past. However, pony-motor configurations are still utilized for motor redundancy. This configuration includes a main motor for full-capacity requirements and a pony motor, which is typically designed for 2/3 full speed but consumes only 1/3 power of the main motor. For example, a cooling tower with a 30 HP main motor may have a 10 HP pony motor.

When two motors are used for redundancy, the main motor is typically controlled by an across-the-line starter while the pony motor is controlled by a VFD. This configuration reduces the total equipment first cost due to a VFD that is sized for approximately 1/3 full power. For 85% of the operating time, systems often require no more than 70% full capacity from the cooling tower. A VFD on the pony motor controls the fan speed from approximately 10% to 70% full capacity, and the main motor will be available for full capacity or in the case of pony motor failure. If a specific load profile shows a significant number of operating hours in the 70-100% capacity range, it may be more cost effective to place a VFD on the main motor.

Table 1 compares the costs of operating a cooling tower using a standard pony motor configuration to using a VFD on the pony motor. Costs are based on weather data for Baltimore, MD and energy consumption at nominal conditions. Figure 2 shows the energy savings of the VFD on pony motor arrangement compared to the standard pony motor configuration. The table identifies temperature ranges and the average number of hours per year that temperatures lie within those bins, while the energy cost is based on a typical rate of $0.10/kW. Tower load (tons) is based on the amount of energy required to remove the building heat load generated during the total number of hours within each temperature range:

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Tons = \frac{(Flow) \times (Range) \times 500}{BTUH}
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In Table 1, the leaving water temperature from the cooling tower remains constant at 85 °F and the flow rate is constant at 1500 GPM, while the temperature range (difference between entering and leaving fluid temperatures), cooling tower load, and entering wet bulb temperature change.

This example links energy consumption to a 30HP main motor and a 7.5HP pony motor. The energy costs for the pony motor across-the-line configuration are based on fan cycling on and off in order to maintain a leaving water temperature of 85°F. It can be assumed that the total amount of time that the fan remains on is based on required fan speed, which is proportional to cooling tower capacity. It is recommended that a payback analysis be performed when determining how to apply the VFD.

Another motor configuration option is to control more than one motor with only one VFD. At the expense of redundancy, using only one VFD may be more cost effective than matching one VFD to each motor, based on unit and field installation costs. Engineers and owners must ensure that the following three requirements are met when controlling multiple motors with a single VFD:

1) The VFD should be sized to supply the total amperage of all motors and must not be designed by merely summing the horsepower of each motor.
2) Line-side wiring and short-circuit protection must be rated for maximum VFD amperage draw regardless of the total motor draw on the load side.
3) Each motor on the load side must be individually protected for short circuit and overcurrent conditions.

The National Electrical Code (NEC) contains information regarding the minimum requirements for sizing protection, and most VFD manufacturers can determine the required component sizes.

**Additional VFD Benefits**

VFDs offer additional operating benefits, such as maintenance and sound reduction. An adjustable acceleration time results in a soft start rather than full load starts, which place heavy stresses on mechanical components. Soft starts enable the VFD to gradually ramp the motor speed, preventing high stresses on belts, bearings, and fans. In addition to smoother cooling tower operation, VFDs prevent other system components, like the chiller, from overshooting and undershooting. Therefore, smooth system operation improves total system efficiency.

Cooling tower fan sound levels can be very important when the equipment is installed near residential and commercial buildings. The cooling tower fan sound level increases with increasing tip speed, so by reducing the fan speed to the current heat load, the
VFD will reduce sound levels compared to those generated at full speed. Soft starts and fluent accelerations also eliminate extreme startup noise, especially during periods of relatively low wet bulb temperatures that lead to frequent fan cycling.

**Summary:**
When selected appropriately for cooling tower applications, variable frequency drives (VFDs) produce many benefits. The most obvious benefits include energy consumption reduction and lower sound levels produced by a slower fan tip speed. Additional benefits include reduced maintenance due to the extended life of drive components.

For indoor applications, engineers should select a NEMA Type 1 or 12 enclosure, while a NEMA 3R or 4 enclosure should be selected for outdoor installation. Cooling tower VFDs should include a 3% line reactor, at a minimum to impede overcurrents created by switching frequencies. The design engineer must also ensure that the VFD is suitable for the harmonics generated on the electrical grid; refer to IEEE-519 for details. It is also recommended that an across-the-line bypass be included for performance testing, VFD maintenance, and operation in case of VFD failure.

Cooling tower VFDs typically control the fan motor based on an analog input signal from either a temperature sensor, which senses the leaving water temperature, or a Building Management System (BMS). Various protocol cards are available for communication between the VFD and BAS, allowing remote control and monitoring capabilities.

When operating multiple cooling tower fans with multiple VFDs, it is more energy efficient and cost effective to ramp all motors simultaneously rather than cycling them on and off. All cooling tower fan motors must be driven by a variable torque VFD, and the resonant frequency ranges or ranges of heavy vibration should be locked out.

If motor redundancy is implemented, a VFD can be installed on the pony motor, which typically operates as much as 85% of the time, and the owner saves on first cost while maximizing energy efficiency. One VFD can control multiple motors when sized according to combined current draw from all installed motors.

VFDs offer energy efficiency that, when coupled with VFD cost reduction over the past few years, significantly reduces operating and maintenance costs.