ENGINEERING FUNDAMENTALS OF MULTI-MW VARIABLE FREQUENCY DRIVES— HOW THEY WORK, BASIC TYPES, AND APPLICATION CONSIDERATIONS

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ABSTRACT

A brief historical overview of the conversion from mechanical systems to electrical systems at low power levels is presented to gain an understanding of what is occurring at multiple megawatt (MW) power levels in industry. An overview of drive technologies as they apply to multiple MW power levels is presented to assist an application engineer in applying an electrical system. The benefits of applying a variable frequency drive (VFD) system, such as greater reliability, smaller size, lower production costs, better performance, and increased automation potential are available with existing technology. A total cost of ownership (TCO) process is discussed and it defines the steps and tradeoffs required in determining an optimum system solution. The transition in the

multiple MW market from mechanical systems to VFD systems is in process, and the rate of transition will accelerate over the next 10 years as the enabling drive technologies continue to be developed.

INTRODUCTION

Industries, such as the petrochemical industry, that utilize multi-megawatt (multi-MW) mechanically driven systems are dominated by gas turbines. These large mechanical systems are reminiscent of the power systems used in the early 1900s; single-shaft systems operating at a single speed. Within these industries electrical systems are a new and emerging technology. The authors hope to provide an understanding of the most likely evolution to occur in multi-MW industrial systems as they convert from mechanically driven systems to electrically driven systems by starting with a brief recap of the historical evolution of low-power electrically driven systems.

For the sequence of converting multi-MW mechanically driven systems to electrically driven systems to begin, requires the industries that utilize these multi-MW mechanically driven systems to be familiar with and to understand the advantages and disadvantages of the alternative electrically driven systems. The focus of this paper is to provide members of those industries a brief understanding of what a VFD can provide at multi-MW power levels. Following the brief historical overview, a review of the technology and functions of the most common low-power VFD will be covered. Once the fundamentals of the low-power VFD have been presented, those same ideas and concepts will be expanded to cover the multi-MW power levels. This discussion will include some existing drive topologies already operating in the high power levels and some new topologies that are just starting to be used at the high power levels.

Understanding how a VFD functions will not in itself cause industry to start applying the technology to the multi-MW power range. Ultimately these industries must recognize the benefits that a VFD can bring to the industry such as improved reliability, greater cost savings, and improved overall process benefits. This paper presents what are believed to be the major benefits to applying a VFD at multi-MW power levels. However, the benefits are dependent on the specific application. What may be a benefit for one application may have little or no effect on another application. To support the benefits presented, two actual installations of a multi-MW drive are mentioned, focusing on the justification for the installation cited by the authors of past papers presented to this audience. To gain a complete understanding of the benefits a VFD can bring to a specific application, one should contact and work with a VFD manufacturer or system integrator directly during the justification process.

The primary driver for converting to an electrically driven system, higher profits through lower operating costs, has to be justified. An application guideline and a TCO process are presented to help guide the critical cost analysis. This process requires the participation and cooperation of a qualified electrical system integrator.

HISTORICAL PERSPECTIVE OF ELECTRIC POWER CONVERSION

Industries, such as the petrochemical industry, which currently utilize multi-MW power systems, are not unlike the general manufacturing industry's situation in the early 1900s with low-power applications. The evolution from a mechanically powered system to a fully controlled electrical system is shown in Figure 1. By considering this evolution it is possible to gain an understanding of what may occur as these multi-MW systems undergo a similar conversion process, or phases of implementation.

Referring to Figure 1, over the last 100 plus years low-power industrial energy conversion has transitioned from systems powered by water, steam, oil, or gas engines to systems powered by electric motors in an intelligently controlled plant.

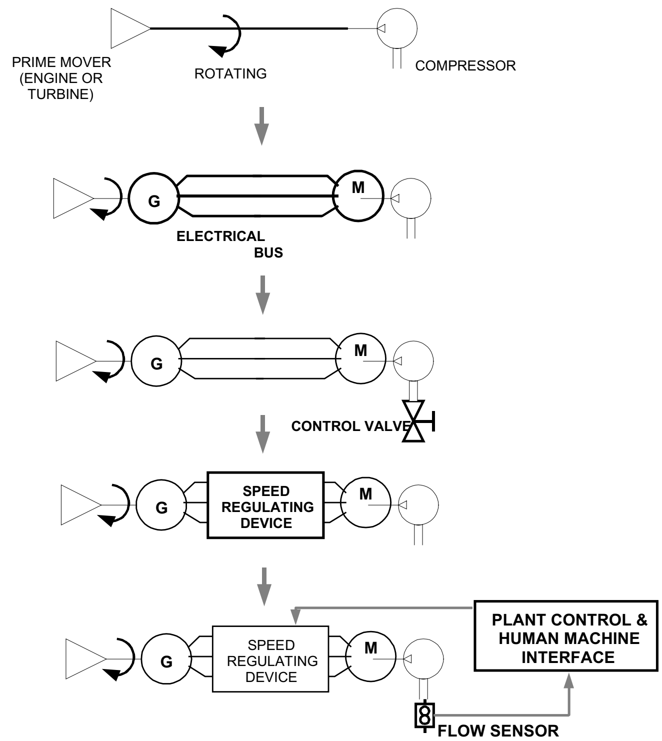

Figure 1. Historical Evolution of Industrial Energy Conversion.

In the 1800s and early 1900s the primary means of power distribution in a factory was a single shaft powered by a water wheel or steam powered reciprocating engine or turbine. The power to control the speed and torque of a process was tapped from the single shaft directly or via gears, belts, and pulleys. Complexities inherent in converting primary power to the desired speed and torque for the specific subprocesses, plus the need to manage power interruption using mechanical switches, brought high maintenance and serious downtime cost penalties. For example, one can quickly recognize a situation when the prime mover or the single shaft has a problem and the entire production facility would need to be shut down during the maintenance or repair activity. To overcome these downtime costs, the production facilities needed to either increase equipment reliability so the interruptions would never occur, increase the cost of the product to cover downtime costs, or to remove the dependence of the process on a single prime mover and shaft.

Conversion to Fully Controlled Electrical Systems

Removal of the production process dependency on a single prime mover and shaft could not be realized until the availability of an electric power utility infrastructure and the invention of the electric motor. With this conversion from discrete mechanical prime movers to a single distributed electrical power source, it became possible for the industrial world to transition to multiple electrical motors being fed from a single utility power grid. Since the power grid operates at a single frequency in a given geographic area, motors on this power grid all operate at essentially the same speed. Therefore, fluid, gas, and airflow processes could only be controlled through the use of mechanical devices, such as control valves, dampers, gears, and pulleys. Since operating multiple systems off a single power grid (with a high degree of availability and reliability) could now minimize costs associated with production downtime, the next big issues of efficiency and production process control became the prime focus of development efforts. Mechanical methods of process control are slow in reaction time and present poor efficiency when operated at points other than at the designed system flow point.

The next major step came with the insertion of a "speed-regulating device" between the utility power grid and the motor. One of the first devices appeared on March 16, 1897, when Frank R. Bacon, founding president of Cutler-Hammer, was issued a patent for a "Controlling Mechanism for Electric Motors." Bacon's invention provided the production facilities with the option for controlling discrete production processes by controlling the speed of the motor directly without shutting down the entire operation. Now motors could be operated at any speed in order to make repairs or adjust the process flow for higher quality or efficient operation. The "speed-regulating device" controls the conversion of electric power, from one form to another, in order to control the electromechanical power delivered by the motor. Further evolutions in "speed-regulating device" technology, combined with the more recent development of computer controls, have resulted in the development of the variable frequency drive or VFD, which allows for continuous control of motor speed and torque and opens the door toward continual improvement of process efficiency and flexibility.

Today, a single process flow can be sensed and fed back to a central plant controller. This communicates with other processes in the plant, receives inputs from an operator, via the human machine interface (HMI), and then commands the VFD or some other type of "speed-regulating device" to maintain optimum performance with coordinated, appropriate instructions. More recently, systems have been developed where remote personnel can monitor, diagnose, and command changes within a single facility or multiple facilities to maintain peak production performance, minimizing onsite personnel and associated costs. This final phase of the conversion to a fully controlled electrical system represents the integration of the best technologies in power conversion, computers, digital and analog control, process control, diagnostics, and information management.

As presented here, the conversion of a mechanically powered plant to a fully controlled electrical system can be viewed as having three phases. Phase one begins with replacing a single mechanically powered shaft with multiple motors connected to a power grid. Phase two starts with using simple methods of speed control at discrete points in the process that are critical to efficiency, reliability, quality, or cost of production and progresses to a continuously-variable speed control over a wide range by utilizing a VFD. The third phase is integration and control of multiple discrete process steps for overall process coordination and automation. The ultimate objective is process optimization allowing for lower operating costs through the production of consistent, high quality product at any speed of the process.

Electric Conversion at Low Power

The conversion from mechanical to electrical in the low-power industrial market has matured and is in the final or third phase. The conversion has proceeded at a rapid rate, which is evident in the VFD compounded annual average market growth (CAGR) of 9.5 percent over the last five years (Automated Research Corporation, 1999). This change has matured in the low-power market to the extent that not only is electric conversion the only solution, but the drive and motor products are viewed as commodity components. Process control integration using VFD products is being facilitated by growth in both the computer and communications industries. High reliability, performance, and quality are standard, and price has become the primary purchasing factor.

Conversion to Multi-MW Power Levels

The conversion to electrical systems at the multi-MW ranges in the petrochemical market is presently in transition to phase two. VFD/motor systems are being used to provide adjustable speed control at discrete process points in a few applications. At power levels of 5 MW and below, the technology is very mature and readily available. By using load commutated inverter (LCI) drives, cascaded, or multilevel inverter topology (discussed later), an electrically driven system over 10 MW can be realized.

Above 10 MW, the technology options available are limited, and most installations are still predominately mechanically powered. There are applications, however, as high as 100 MW, successfully implemented in the petrochemical industries today (Kleiner, et al., 1989). LCI drives and cycloconverters in combination with wound field synchronous and induction motors enabled these multi-MW conversions more than 15 years ago. These installations have established a record of reliability and ruggedness over the years, both in commercial and industrial applications. Their selection is generally limited to low-speed, high-torque applications by the inherent features of the technology.

The future trend of high MW rating installations might be anticipated by examining the phases of implementation and the history from the early 1900s. This historical model predicts rapid high MW rating conversion will occur when the common power shaft of the large gas turbines can be reliably replaced with electric motors and drives and demonstrated benefits to the bottom line accrue. The reason for this conversion will be the same as those that history recorded in the manufacturing industry—namely profits flowing from reduced labor, decreased energy usage, and process improvements.

There has been a delay in the more rapid conversion of multi-MW rated systems. The lack of available suitable technology and limited knowledge of process requirements by the electrical system suppliers has contributed to the delay. Detailed knowledge of available technology and intimate familiarity with system/process requirements for each application is necessary to identify superior solutions and validate the predicted benefits of an electrical conversion. The limitations of the early power electronic drive technologies at higher MW ratings are being overcome with maturing technology applied to the low-power VFD and solid-state power switching device technology. The newer device technologies and VFD topologies developed in the last 10 years are more flexible and adaptable. For example, high-power systems at rotational speeds greater than 3600 rpm will require that power be delivered at frequencies above 60 Hz, the standard in the United States, from the commercial power grid. The new technologies available in the lower-power VFD readily supports supplying power at several hundred Hertz, even to thousands of Hertz (Graham and Graham, 1993). With suitable motor designs being developed from lower power rating experience, it is now technically feasible to drive up to 40 MW or greater, directly, without the use of speed increasing gear sets (Kleiner, et al., 1999). It is apparent as these technologies continue to demonstrate reliable service they will take over the high-power process functions just as they did at the lower power applications.

This transition to wider applications of VFDs and electric motors in industries where higher power ratings and higher rotational speeds are needed will require close collaboration between the operators and equipment suppliers to achieve the desired bottom line benefits. Industry application engineers and electrical system integrators need to carefully apply multi-MW VFD/motor systems to ensure the potential benefits of the technologies are thoroughly exploited for each application.

VFD TECHNOLOGY OVERVIEW

The basic function of a VFD is to synthesize the voltages and frequency applied to a motor so that effective speed and/or torque control can be achieved. In order to understand how controlling motor voltage and frequency leads to motor speed and/or torque control for various motor types, refer to APPENDIX A.

Fundamentally, the principles of operation applied to a low-power VFD are the same as the principles of operation applied to a multi-MW VFD. The major reason low-power VFD technology cannot be applied directly to a multi-MW VFD is the limited power ratings of the semiconductor devices used in the drive. This section addresses the principle of how a low-power VFD operates. Expanding those principles for use at the multi-MW power range is the topic of the next section.

A top-level schematic of a low-power VFD is shown in Figure 2. The system can be subdivided into two major subsystems, one providing a "brain" function and another providing a "brawn" function.

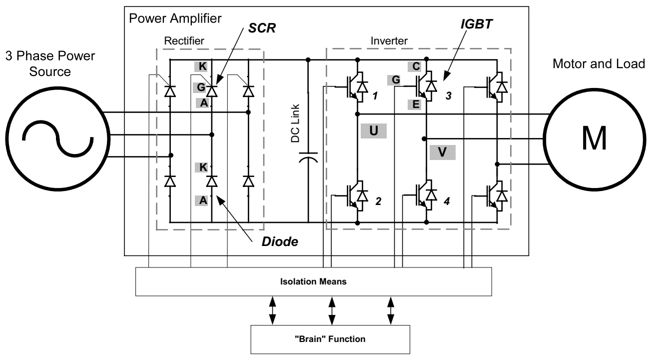

Figure 2. VFD Functional Block Diagram for a Low-Power Inverter Topology.

VFD "Brain" Function

The "brain" of the VFD performs four very critical functions for proper operation of the VFD.

- A communication interface function to communicate with an external process controller or a local control keypad over a standard communication bus to receive reference signals and commands and to transmit the status of the drive.
- A speed control function that calculates both the voltage and frequency necessary to maintain the motor speed at either the reference torque or speed set-point and to maintain the desired machine flux (or V/Hz).
- Basic power conversion logic determination function that effectively converts the analog reference voltage and frequency to a three-phase "digital" representation of the required power semiconductor states ("on" or "off") that will synthesize the reference three-phase AC voltages.
- A protection function that monitors such parameters as voltage across power semiconductor devices, motor current feedback, and VFD internal temperatures to determine whether it is safe for the VFD power semiconductors to turn on or off.

All these functions are powered by an internal power supply derived from the input AC power.

In most VFD products on the market, all elements of the "brain" function are implemented by a combination of a microprocessor (µP) or digital signal processor (DSP) with supporting circuitry, a programmable logic device (PLD) or an application specific integrated circuit (ASIC), and analog sensing circuitry. Advances in other industries such as telecommunications and computers have enabled the implementation of powerful functionality at a reasonable cost. Due to the tremendous growth in volume for low-power applications, suppliers have emerged with low-cost solutions using the same hardware (with the exception of the protection function, sensing circuitry, and the internal power supply) for the "brain" function across multiple platforms from low power to multi-MW.

The VFD offers the possibility of a highly dynamic and accurate control of the motor load if desired. Limitations in obtaining the desired accuracy or performance lie in both the time and amplitude resolution required to synthesize the three different phase voltages, given the processing speed demands on the speed control function. These limitations are a result of both the "brain" function and the "brawn" function. From the standpoint of the "brain" function the limitation is in the speed and accuracy of the µP, PLD, and sensing hardware, and increasing this speed and accuracy corresponds to an increase in cost; not a limitation in the available technology. For all but a few special applications the speed and accuracy of the low-cost solution hardware are adequate.

VFD "Brawn" Function

Achieving the desired performance of a VFD/motor application is more significantly affected by the "brawn" function than the "brain" function. The real limitation is in the capability of the power semiconductors that are used in the power amplifier block of Figure 2 to synthesize the required three-phase voltage applied to the motor with the required time and amplitude resolution.

The "brawn" refers to all the components within the drive that aid in the transfer of real or apparent power from the source to the load. Again referring to Figure 2, the principal elements of the VFD "brawn" function are:

- An isolation means, which provides electrical isolation between the power conversion logic and the main power circuit, shifts the digital-logic-level voltages to voltages high enough to switch a power semiconductor from a full on-state to a full off-state.
- A power amplifier that effectively connects the input power lines to the motor through specific power semiconductors as dictated at any instant of time by the power conversion logic.

The key components of the power amplifier are the rectifier, DC link, and inverter. The function of the rectifier is to receive AC power and convert it to a DC voltage, more commonly referred to as the DC link. The DC link in most implementations consists of a bank of electrolytic capacitors. The purpose of the DC link is to provide a reservoir of electrical energy (stiff DC voltage) against which the inverter can draw energy to perform work. The inverter converts the DC link voltage from DC to variable-frequency, variable-voltage AC suitable for controlling the motor and load.

Power Conversion Fundamentals

The inverter topology of Figure 2 is the topology of choice for the vast majority of low-power applications. Understanding why this is and how the inverter operates are key to understanding how usage of the VFD has proliferated in the low-power market and how the VFD will find greater application in the multi-MW market in the future. This understanding begins with the power semiconductors. For the inverter topology shown in Figure 2, the principal power semiconductors are the diode, silicon-controlled rectifier (SCR), and insulated gate bipolar transistor (IGBT).

Power semiconductor devices control the flow of power within the power circuit. The function that they perform is identical to that of a switch. The "ideal" switch would incur no losses, thus generate no heat, while either conducting or switching between conduction states ("on" and "off"). In the off-state, the ideal switch would withstand infinite voltage and remain in the off-state regardless of the polarity of voltage applied. In the on-state, the ideal switch would allow current flow in either direction. The transitions between on-to-off, and off-to-on would occur instantaneously and could occur at will (through digital control) and at whatever rate desired.

With the ideal switch it would be possible to connect the input voltages of a VFD to the motor through a controllable matrix of switches. The switches within this matrix would change states through active control at a very fast rate as the input AC voltages vary with time in order to construct whatever voltage amplitudes, phases, shapes, etc., are necessary at the motor terminals using "pieces" of the input voltages. The resulting average voltage across and the actual current through the motor would be whatever is required to achieve the desired motor torque, flux, and, ultimately, speed.

Unfortunately, the ideal switch does not exist—the power semiconductor device is the closest approximation. Power circuit topologies have evolved around the available power semiconductor technology of the time.

Diode

The diode is the simplest power semiconductor device. A diode conducts current in only one direction and cannot be turned on or off at will: diode "commutation" (transition between on- or off-states) is a function of the voltage "across" or the current "through" the device. Referring to Figure 2, the label *A* designates the anode while the label *K* designates the cathode of the diode, respectively. When the voltage from anode-to-cathode is positive, the diode conducts current (on-state), otherwise the diode does not conduct current (off-state). Once in the on-state the diode continues to conduct current from the anode-to-cathode until the current switches direction to some negative peak (the diode recovers), and the diode then ceases to conduct current with the exception of a very small amount of negative leakage current.

While the diode is conducting, there is a small amount of voltage drop from anode-to-cathode, so the diode will incur a "conduction loss." In addition, there is a pulse of energy that occurs each time the diode recovers that contributes a small amount of "switching loss." If the diode's anode-to-cathode current or the diode's cathode-to-anode voltage exceeds a certain level, the device will fail; thus there is a safe operating area (SOA) within which a diode—or any power semiconductor device for that matter—can operate. The method used for removing the heat generated by the conduction and switching losses away from the power semiconductor and the need to operate within the SOA dictates the selection of a device for a particular power level of an application. For all low-power applications, diode devices are readily available for the inverter topology of Figure 2.

SCR

The SCR functions in the same way as a diode when a positive voltage is applied to the SCR gate, designated as G in Figure 2. The fundamental difference between a diode and a SCR is that the "turn-on" process of the SCR is controllable. The SCR will block positive voltage (prevent current from flowing) as long as the gate voltage is very low or at zero potential. In this way the SCR is one step closer to an ideal switch than the diode. However, the "turn-off" process is not controllable, and like the diode the SCR requires that the conducting current is negative, plus the gate voltage is taken high in order to turn off. The purpose for the SCR in the inverter topology of Figure 2 is to control the rate of increase of DC voltage across the DC link capacitors while starting the VFD. If a large positive voltage were suddenly applied to the DC link, an excessive amount of inrush current would occur. Therefore, the SCR and its control are effectively an inrush current limiter. Once the DC link capacitor is charged to its full voltage, a positive voltage is applied to the SCR gate and the SCR then operates essentially as a diode.

From the above descriptions of the SCR and diode it is understood that the rectifier circuit of Figure 2 is perfectly suited for AC-to-DC power conversion. The SCR/diode begins to conduct current in one direction when the anode-to-cathode voltage is positive, and the occurrence of negative currents ensures that the SCR/diode will switch off. Positive current flows into the VFD DC link and positive voltage is applied across the DC link to create a unidirectional DC source against which the inverter can draw power to create a variable frequency and voltage for the motor.

IGBT

A commercially purchased IGBT module consists of an IGBT wafer in parallel with a reverse diode wafer. In this configuration the IGBT module more nearly approaches the ideal switch over the range of low-power VFD applications than any other power semiconductor device available today. The device can be turned on by applying a positive voltage to the IGBT module gate, designated by the label *G* in Figure 2, and similarly turned off by applying a negative voltage to the IGBT module gate. The device will block a positive voltage (prevent current flow) that is applied from collector-to-emitter of the IGBT module, labels *C* and *E* in Figure 2, but it will be forced to conduct if a negative voltage is applied because of the reverse diode connected from emitter to collector. Because of this reverse diode, the IGBT module is ideal for use in converting a DC voltage to an AC current. The reverse diode allows for current to flow through the device in the negative direction (from emitter to collector) while the IGBT wafer allows current to flow in the positive direction.

During commutation (switching), the IGBT module does not switch from an on-state to an off-state instantaneously because the current through the device ramps down to zero while the voltage across the device ramps up to the DC link voltage. This transition occurs at a finite rate. During switching from an off-to-on-state the reverse occurs, the current through the device ramps up to the current demanded by the motor while the voltage across the device ramps down to the IGBT module's turn-on conduction voltage. This turn-on transition also occurs at a finite rate, but is typically faster than the turn-off rate. The result is a limitation in how quickly and often the device can be switched. Also, a pulse of energy occurs each time the device switches that causes turn-on and turn-off power losses. These switching losses, as well as conduction losses, contribute significantly to heat that must be conducted away from the device in order to avoid a failure, and also have a significant effect on the size of the device selected. With proper application of the IGBT module size, rating, and cooling system, the IGBT-based VFD can be switched up to 25,000 times a second ("switching frequency" of 25 kHz) and higher in specific cases, where required.

The SOA of an IGBT module dictates the voltage that can be applied and the amount of current that flows from collector-to-emitter. A commercial IGBT module is designed so that the SOA is the same for the reverse diode and the IGBT wafer. For an IGBT module, if a voltage higher than the SOA voltage (device's maximum voltage) is applied, even for an instant, the device will fail. The maximum current rating is typically up to 10 times the device current rating. IGBT modules on the market today have voltage ratings at 600 V, 1200 V, 1700 V, 3300 V, and 6500 V and current ratings up to 3000 A.

DC-to-AC Power Conversion

Conversion from the DC link voltage to the AC voltages applied to the motor can best be understood by considering the voltage that occurs across points *U* and *V* in Figure 2. In the simplest terms DC-to-AC conversion is accomplished as follows:

- When IGBT module 1 and IGBT module 4 are commanded on by the power conversion logic while IGBT module 2 and IGBT module 3 are commanded off, the DC link voltage is applied to the terminals of the motor. If positive current flows from the positive DC link to the motor, the IGBT wafer of IGBT 1 is conducting and the reverse diode of IGBT module 4 is conducting. If negative current is flowing, the reverse diode of IGBT module 1 is conducting and the IGBT wafer of IGBT module 4 is conducting.

- When IGBT module 1 and IGBT module 3 are on, zero voltage is applied to the motor and current flows, or freewheels, between the IGBT wafer and reverse diode of the upper pairs. Whether the reverse diode or IGBT wafer conducts, depends on the initial direction of current in the motor. Similar operation occurs when IGBT module 2 and IGBT module 4 are commanded on.

- When IGBT module 2 and IGBT module 3 are commanded on by the power conversion logic while IGBT module 1 and IGBT module 4 are commanded off, negative DC link voltage is applied to the terminals of the motor.

The power conversion logic is responsible for determining the AC voltage waveform that will be applied to the motor. There are a variety of ways in which this may be accomplished. But if the switching frequency of the IGBT modules is at least 10 times greater than the desired fundamental frequency to be applied to the motor, then the method that will give the best reproduction of the desired AC waveform is pulse width modulation (PWM).

One popular PWM control technique is called sine-triangle PWM. The switching patterns for a single phase utilizing this PWM strategy are shown in Figure 3. In this PWM approach, a reference sine wave (*V ref* +) is generated and compared with a triangle wave. The frequency of the triangle wave is the same as the switching frequency of the IGBT devices. Referring to both Figure 2 and Figure 3, when the reference wave is greater than the triangle wave, IGBT module 1 is turned on and IGBT module 2 is turned off. The resulting voltage waveform from node *U* to the negative side of the DC link is *Vun*. An inverted reference sine wave (*V ref* −) is also generated and compared to the same triangle waveform. The same type of logic comparison is made, but the resulting waveform is delayed by 180 degrees and used to commutate IGBT module 3 and IGBT module 4. The resulting voltage waveform from node *V* to the negative side of the DC link is *Vvn*. The difference between these voltages is the PWM voltage that results across nodes *U* and *V* or the line-to-line voltage applied to the motor (*Vun* – *Vvn*). The PWM waveform has a voltage characteristic at the desired fundamental frequency shown as *Vout*, *fundamental*. Similar balanced voltages, each offset by 120 degrees, are applied to all three phases of the motor. Since the motor load is inductive and acts as a filter, the output current is continuous and sinusoidal.

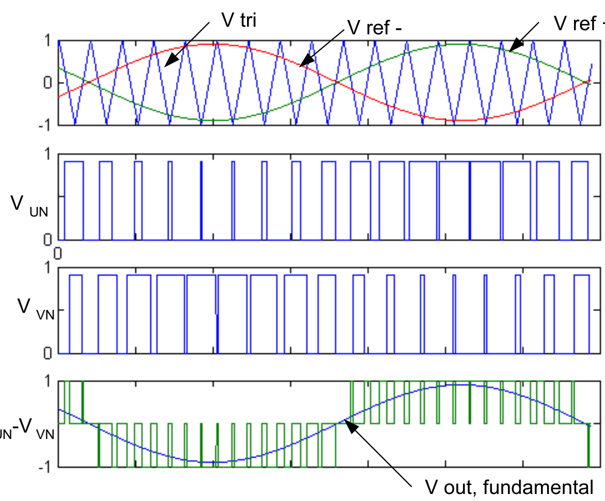

Figure 3. Sine-Triangle PWM AC Voltage Waveform Synthesis for a Single Phase.

The explanation presented above aids in understanding how the power semiconductors limit the performance of a VFD. The faster the IGBT devices can be switched on and off, the closer the voltage applied to the motor is to the commanded voltage whenever the commanded voltage changes in amplitude or increases in frequency. This means better dynamic response, higher achievable motor speeds and reduced motor torque ripple and heating. The larger the voltage and current demand of the motor, the larger the voltage and current rating of the IGBT required and, thus, the slower the achievable switching frequency in order to avoid considerable voltage distortion due to switching (slew) rate limits on the devices or device overheating.

EVOLUTION OF VFD TECHNOLOGY FOR MULTI-MW APPLICATIONS

Clearly, the challenge for VFD technology as the power increases is in achieving the desired performance given the SOA and switching frequency limitations of the power semiconductor devices. Historically, the power requirement of the application has driven the type of power semiconductor used. Until the advent of IGBT modules with voltage ratings higher than 1700 V, for applications beyond 5000 kW, IGBT modules have not been the device of choice, but instead devices that behave less like an ideal switch, like the SCR, have been used. The use of such "naturally commutated" devices prohibits the use of the PWM control scheme. As discussed earlier, the PWM control scheme requires high-power devices that can be turned on and off on demand and at very fast rates. Using the SCR as the power switch requires a control scheme that waits for the power device to turn off due to naturally occurring events at the load, which may limit the types of loads a SCR-based drive can operate. Historically, multi-MW VFD/motor implementations were based on topologies that allow for the use of SCR devices, like the cycloconverter and load commutated inverter (LCI).

With the advent of new inverter topologies and the continuing development of power semiconductor devices, such as IGBT modules, with simultaneous higher voltage ratings and better switching characteristics, the trend for multi-MW VFDs is to use topologies similar to Figure 2 and utilize the PWM control technique described above and pictorially represented in Figure 3. The result is that multi-MW VFD/motor implementations will now allow more flexibility in motor types used and, in addition, provide better performance at lower cost than previously achieved. For the purposes of this paper the four most common topologies will be briefly described. They are the cycloconverter, the load commuted inverter, the cascaded H-bridge topology, and the multilevel inverter topology.

Cycloconverter

The first implementations of multi-MW VFD/motor systems primarily used the cycloconverter. A block diagram of the cycloconverter is shown in Figure 4. This topology uses the SCR as the power semiconductor device. The SCR is very limited in the rate at which it can be turned on or off (switching frequency), but SCR devices are available with voltage ratings up to 4500 V. In addition, multiple SCR devices can be connected in series and share the total blocking voltage so that early implementations of the cycloconverter could interface to a 4160 V supply using the more commonly available 1200 V and 2200 V devices. The cycloconverter works on the principle of converting AC voltages of one voltage and frequency to AC voltages of another voltage and frequency. Due to limitations in the device switching frequency and the need to force a commutation to the off-state with the load, it is not practical to produce an output frequency of greater than 20 Hz without causing excessive motor current ripple, which results in motor heating with an assumed input frequency of 60 Hz.

In addition, in order to guarantee that the SCR will turn off, the load must have a slightly leading power factor (power factor is explained in the section discussing the advantages of a VFD). This requirement drives the choice and/or configuration of the motor load. As an example, consider a cycloconverter powering an induction motor. Since the induction motor has a lagging power factor, capacitors must be connected across each line of the induction motor. These capacitors can lead to stability problems and often limit the range of speed control even further. Another solution is to use a wound field synchronous motor with field current control. The field current can be varied to keep the input power factor leading.

Some of the drawbacks of the cycloconverter implementation can be overcome if the device can be "force commutated" off, in the same manner as an IGBT. Since the 1980s the gate turn-off

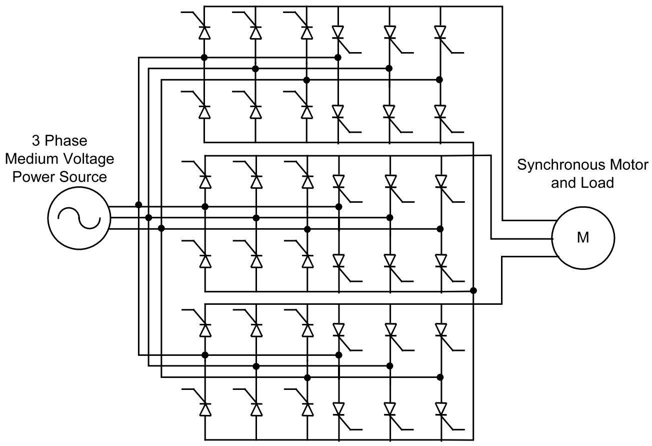

Figure 4. Cycloconverter Block Diagram.

thyristor (GTO) has been available. This device allows the same SCR device to be turned off on demand. However, the GTO switching frequency is limited to below 1 kHz, so the PWM control scheme cannot be implemented on a cycloconverter with good results. Other GTO devices are in development with the promise of higher switching frequencies, such as the emitter turn-off thyristor (ETO) and integrated gate-commutated thyristor (IGCT).

Load Commutated Inverter

The most common drive topology implemented in a multi-MW VFD is the LCI topology shown in Figure 5. Like the cycloconverter, the LCI topology is based on the SCR device and is typically used with synchronous machines at very high power ratings (up to 100 MW). The efficiency and reliability are much better because this topology has one-third the number of power devices as the cycloconverter. Efficiencies of 95 percent are achievable, which is on a par with a low-power VFD. However, the drive is still limited to a low switching frequency, thus limiting the overall performance of the drive.

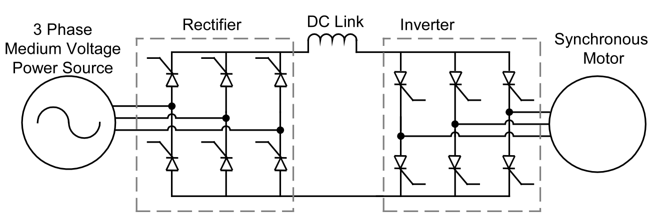

Figure 5. Load Commutated Inverter Block Diagram.

The structure of the LCI is similar to the low-power inverter topology of Figure 2. There is a rectifier, a DC link, and an inverter. However, there are three major differences.

- The rectifier converts the input AC voltage to a DC link current instead of a voltage, therefore requiring six fully controlled SCR devices on the input power.
- The DC link is a large inductor rather than a bank of capacitors.
- The inverter converts DC link current to three-phase AC voltages with a leading power factor load required.

Just as for the cycloconverter, a wound field synchronous motor is the best choice for the load. A typical LCI drive supplies power to the motor from about 10 Hz up to a frequency of up to 60 Hz allowing for full control of a two-pole motor up to 3600 rpm. Near zero Hz, and zero rpm, an LCI drive has to be supplemented with means to start the motor, as the load motor at low rpm cannot develop the necessary back EMF (voltage) to commutate the SCRs.

Cascaded H-Bridge

IGBT-based PWM controlled inverters have been penetrating into medium voltage and multi-MW markets for some time now for two major reasons. First, higher voltage IGBT devices, 3300 V and more recently 6500 V ratings, are becoming readily available on the market. Second, cascaded and multilevel inverter topologies have been developed and are increasingly being deployed in industrial applications that are built upon the IGBT-based PWM inverter topology.

Figure 6 shows the cascaded H-bridge topology. The idea is to create a single-phase converter module, made up of a low voltage rectifier and IGBT-based PWM controlled inverter and then appropriately connect them together to provide medium voltage capability. Referring to the inside view of the single-phase converter module shown in Figure 6, the rectifier and DC link are the same as shown in Figure 2, but the inverter only has two IGBT legs. The voltage on the output corresponds to the voltage of a single-phase and is the same as the phase voltage shown in Figure 3.

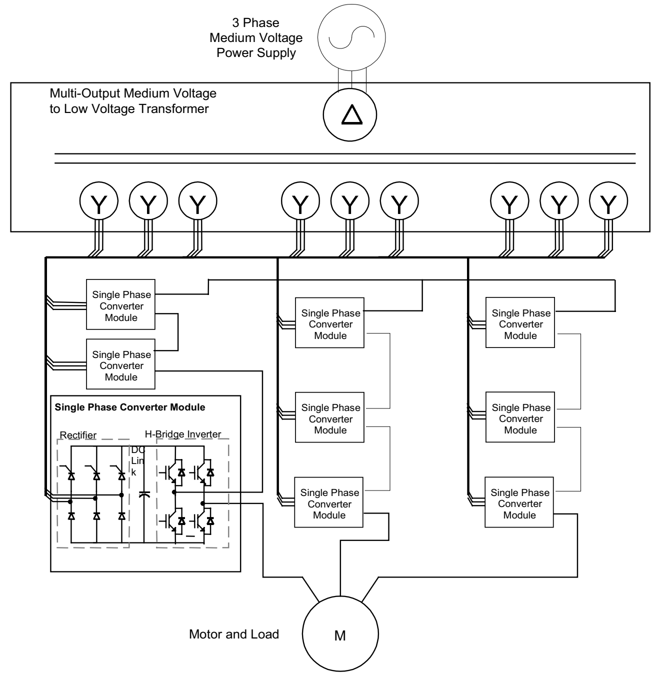

Figure 6. Cascaded H-Bridge Inverter Block Diagram.

The single-phase converter modules are connected in series and each is powered by a set of three-phase, isolated secondary windings on a transformer. The input to the multisecondary transformer is from a medium voltage supply (i.e., 4160 V or 13.8 kV). The three-phase secondary voltages are selected so as not to exceed the rating of the H-bridge inverter IGBT devices. The IGBT voltage ratings and the desired output voltage of a motor phase determine the number of series connected (cascaded) H-bridges. For example, with 1700 V devices, which are readily available, a DC link of 1100 VDC is achievable. Each H-bridge inverter can accurately produce a 600 VAC output and four modules connected in series add up to 2400 V. If three single-phase stacks of four modules each are connected in a wye arrangement (as shown in Figure 6), the line-to-line voltage applied to the motor is 4160 V. The motor voltage can be increased either by adding more stacks in series or by going to IGBT devices with higher voltage ratings. For example, with 3300 V IGBT devices, the motor voltage can be easily increased to 6.5 kV with the same number of cascaded levels. Alternatively, the number of levels can be reduced from four to two if 3300 V devices are used for the 4160 V motor. Cascaded H-bridge inverter VFD products are available commercially that stack up to five H-bridge modules in series and produce upward of 10 MW.

The cascaded H-bridge inverter has another significant advantage from the standpoint of performance. For each H-bridge inverter, the triangle references in the sine-triangle PWM scheme can be phase shifted from each other to achieve a higher composite switching frequency on the output to the motor. For example, if every IGBT is switching at 2 kHz, the switching frequency of a single H-bridge inverter is 4 kHz, since the triangle references are shifted by 180 degrees (Figure 3). If there are four modules in a stack and the two triangle references in each stack are phase shifted by one-fourth of a full 180 degree period (45 degrees), the composite switching frequency of a single-phase series stack is 16 kHz. The voltage produced by a single phase of the cascaded H-bridge inverter is shown in Figure 7.

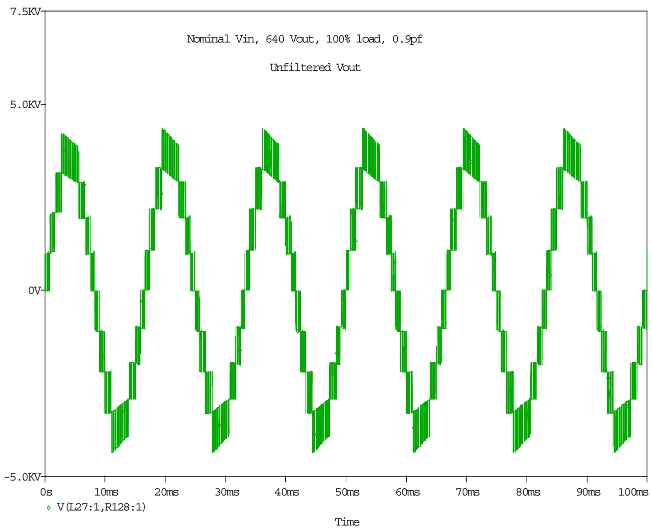

Figure 7. Output Voltage of a Single Phase of the Cascaded H-Bridge Inverter Drive Topology.

From the standpoint of torque ripple and heating on the motor, as well as dynamic performance, the cascaded H-bridge inverter VFD/motor drive can achieve a level of performance equal to that of a low-power VFD/motor drive. Unlike the cycloconverter and LCI VFD implementations, the motor load can be any motor type, from an induction motor to a permanent magnet motor. In addition, the output frequency can exceed 60 Hz, allowing a multipole motor to be used for applications requiring a speed greater than 1800 rpm. For example, with an output frequency of 120 Hz applied to a four-pole motor, the speed will be 3600 rpm. The main advantage is that the diameter of a four-pole motor is smaller than that of a two-pole motor with the same torque rating and when operated at the same power rating.

Multilevel Inverter

Another IGBT-based implementation is the multilevel inverter. Like the cascaded H-bridge inverter, the multilevel inverter topology divides the voltage output to a medium-voltage load among several IGBT devices to accomplish an IGBT-based PWM controlled inverter. However, instead of isolating the DC link voltage of a series of inverters, the topology divides the DC link voltage that each IGBT must block down to a level suitably below the IGBT voltage rating through a matrix of diode connections. The simplest form of the multilevel inverter topology is a three-level inverter, or more commonly referred to as a neutral-point clamp inverter shown in Figure 8.

The neutral-point clamp inverter is the most popular of multilevel inverter topologies and is implemented in many industrial, transportation, and commercial applications, especially in Japan and Europe. The form of this topology is one step away from that of Figure 2 where multiple IGBT devices are simply

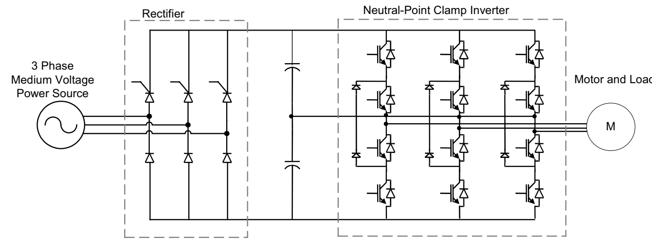

Figure 8. Neutral-Point Clamped Inverter Topology.

connected in series for higher voltage applications. Although some series connected IGBT implementations have been attempted, it is difficult to force the IGBT to share the DC link voltage during the commutation to an off-state. On the other hand, the diode connections to the DC link midpoint in Figure 8, along with active control of the switching states between IGBT devices, ensure voltage sharing across devices.

Each device in the neutral-point clamp will see one-half the total DC link voltage. If, for example, 1700 V IGBT devices are used, a 2200 VDC link can be achieved and 1500 V can be applied from line-to-line at the motor. If 3300 V IGBT devices are used, a 5000 VDC link can be achieved and 3300 V line-to-line voltage can be applied to the motor. If 6500 V IGBT devices are used, a 10 kVDC link can be achieved and upward of 4160 V line-to-line voltage can be applied.

The industry trend with the multilevel inverter is to increase the voltage rating of the IGBT devices used in the neutral-point clamp topology rather than increase to more levels. The reason to limit the number of levels is because voltage sharing becomes difficult with only a rectifier between the input power and the DC link as the levels increase beyond three (Peng and Lai, 1994). Present-day solutions with levels greater than three propose that, for each leg of the inverter, there is a corresponding actively controlled leg that interfaces to the AC power source (Menzies, et al., 1993). An example of an inverter phase leg of a five-level inverter, with multilevel structures on source and load sides of the DC link, is shown in Figure 9. Research continues into control approaches that will allow for more than three-levels and a single passively fed DC link (Peng, 2000).

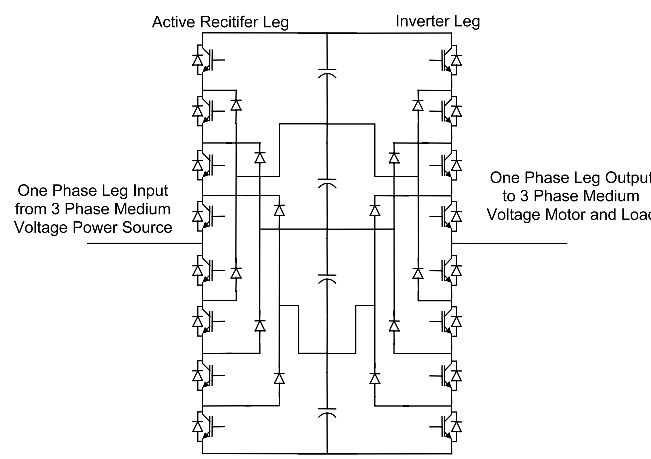

Figure 9. Five Level Neutral-Point Clamped Inverter Topology for a Single Phase.

A multilevel inverter topology has two advantages worth mentioning when compared to the cascaded H-bridge inverter topology. First, there is no need for a large isolation transformer. Second, for the same number of IGBT devices as contained in the cascaded H-bridge inverter, the voltage across each device in a multilevel inverter topology is one-half that of the voltage across each device in the cascaded H-bridge inverter topology. However, one key disadvantage to the multilevel inverter topology when compared to the cascaded H-bridge topology is the need for a more complex control system, especially when the number of levels increases above three. With more than three levels it is necessary to impose a requirement that the rectifier be actively controlled.

In summary, Table 1 compares the major advantages and disadvantages of the multi-MW VFD topologies described above. The actual selection of a topology for an application can be made with the help of a VFD system integrator. Typically a VFD supplier will specialize in one type of topology, so discussions with different VFD suppliers may be warranted.

Table 1. Comparison of Multi-MW VFD Topologies.

VFD Topology	Advantages	Disadvantages
Cycloconverter	• Simple Architecture • Can operate at low speeds	• Poor Input and output Harmonics. • Cannot achieve nominal motor speeds with present device technology. • Complex circuit design • Poor Power Factor at low speed • Requires leading power factor load
Load Commutated Inverter (LCI)	• Inherent Regenerative capability • Good torque control • Speed regulation to 1% • Up to 100 MW	• Poor Input and Output Harmonics • Motor speeds limited to 3600rpm • Poor Power Factor at low speed • Requires leading power factor load
Cascaded H Bridge	• Can be used for motor speeds beyond 3600rpm • Can use low voltage IGBT devices • Scaleable power levels • Simple PWM control • Simple voltage sharing • Good output voltage harmonic performance • Low DV/DT • Good input current harmonic performance	• Multiple isolated secondaries • Transformer front-end required
Multi-Level Inverter	• Can be used for motor speeds beyond 3600rpm • Works with simple Rectifier front-end • Low DV/DT • Good harmonic performance	• System Complexity • Requires active front-end for levels beyond three • Poor input current harmonic performance, unless active front-end is used

ADVANTAGES OF VARIABLE FREQUENCY DRIVES

A survey of the available literature indicates that once a TCO study has been performed, justifying an electric system for a specific application comes down to a few key advantages that a VFD has over a more conventional mechanical system (Kleiner, et al., 1989; Kleiner, et al., 1999; Kleiner, 2000; Kuemmlee, et al., 2000). The following list summarizes those advantages and each will be discussed in greater detail in the subsequent text.

- Lower cost of energy
- Compliance with environmental regulations
- Improved process flexibility and control
- Reduced size
- High reliability

Lower Cost of Energy

As one would expect, a reduction in the energy cost, whether electrical or fuel, required to operate a process is a major objective when considering the electrification of a process. A VFD can reduce the cost of energy in several ways. For this paper, the authors will focus on three specific ways. First, the very nature of how certain processes are controlled can greatly reduce energy cost if a VFD is utilized. Second, a VFD can improve the overall efficiency of a system. Last, a VFD can be used to obtain the maximum utilization of the electrical power supplied from the utility by maximizing something referred to as the power factor.

Process Control

The best method to explain how controlling a process with a VFD can reduce energy cost is to use an example from the petrochemical industry—the design of a pump. When selecting a pump, the first issue is the determination of the maximum flow for the process. The most common method of flow control is to throttle the flow on the discharge side of the pump via a valve.

Figure 10 shows the total energy, due to speed control and efficiency combined, which can be saved by using a VFD to control the pump speed, as opposed to a valve in a centrifugal pump. There are three key relationships that help understand energy usage when performing pump design (*Engineering Cookbook, A Handbook for the Mechanical Designer*, 1999):

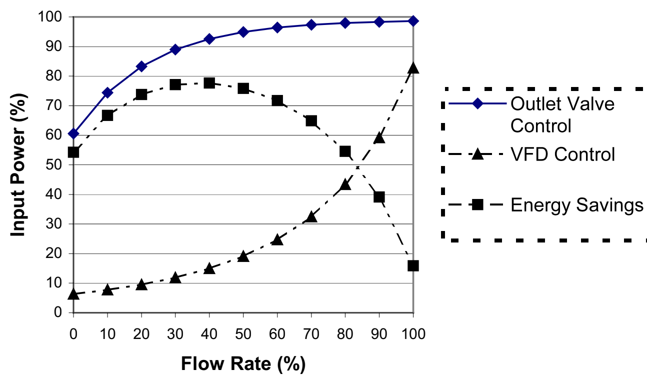

Figure 10. Energy Saved with a VFD Speed-Controlled Pump Versus Mechanical Control Valve.

- Flow *is proportional to* speed
- Pressure *is proportional to* speed ^{2}
- Power *is proportional to* flow ^{3}

For this example, consider the motor is powered across the utility supply line at a fixed speed and a valve is used to control the process flow. At 80 percent flow, the control valve implementation will require nearly 100 percent of the input power. For the VFD implementation, where the motor speed is controlled, at 80 percent flow, the power required is $(0.8)^3$ or 51 percent. If the pump is to operate at this reduced flow or at any lower flow rate, then a significant energy savings will result with the utilization of a VFD. With the VFD controlled pump, a small flow or speed change can result in a significant energy savings (Carlson, 2000). In addition, with the pump operating at 100 percent, the insertion losses of the system will require an additional 30 percent of energy above that required by the process (Irvine and Gibson, 2000). In comparison, the insertion loss of the VFD approach will typically require less than 5 percent of energy above that required by the process. Therefore, even at 100 percent speed, the VFD approach is more advantageous in terms of energy consumption over the control valve approach than is indicated in Figure 10.

In low-power pump applications, this example illustrates the reason why the VFD technology has made significant market penetration. With the costs increasing both in the production of energy and the use of energy, these savings can provide a competitive edge. The added pressure of increasing oil prices, cost of extraction, and utility deregulation has not only forced users, but also utilities, to consider these savings. The savings are so significant at the low horsepower range that the added cost for the initial installation of a VFD is typically recovered in less than a year. Since, the basic physics is the same whether it is a multi-MW application or a low horsepower application, the reduction in energy cost required by similar processes can be very significant at multi-MW power levels.

Efficiency

The efficiency of energy conversion in a VFD and motor are important energy cost considerations. As described above, the ability to electrically control the speed of the motor with a speed-regulating device, such as a VFD, will significantly reduce the energy draw of a pump or compressor system. In addition to the savings gained by controlling the speed of the pump, energy is saved due to the improved overall system efficiency of the VFD and motor installation. This increased efficiency can be understood when considering the components that make up a typical petrochemical industry installation. In the example discussed above with the centrifugal pump using a single speed motor with a mechanical valve control, the efficiency can be less than 70 percent when operating under 80 percent of rated speed, assuming a motor efficiency of 94 percent and the valve insertion loss. A system using speed control with a VFD and motor, however, will be about 90 percent efficient taking into account both the motor and drive efficiency. Efficiency of a typical VFD and motor system, without a pump, is high throughout the speed range until below 50 percent, as indicated by Figure 11. The change in efficiency is due primarily to the motor. The VFD efficiency itself is relatively flat over a wide speed range.

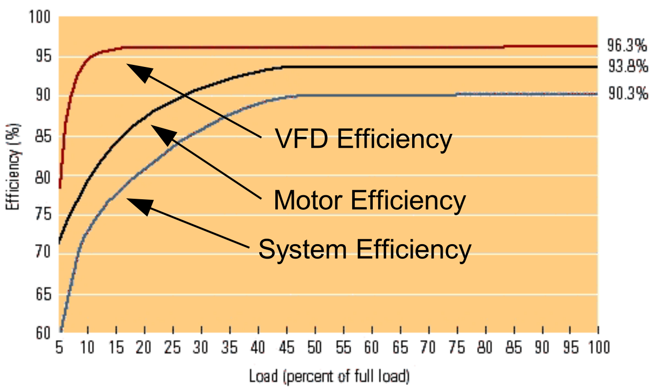

Figure 11. VFD/Motor System Efficiency Versus Load. (Courtesy Howe, 1996, E Source)

Power Factor

The use of a VFD and motor in a process to provide energy savings and process control does not eliminate all losses, but the amount of energy lost can be significantly reduced. Power factor is a measure of energy that is not being used to produce real work (i.e., torque), yet costs the utility money to deliver. The utilities monitor power factor and will charge significant penalties if the user's power factor demand is out of specification.

There are two components to power factor:

- The amount of displacement or phase angle of the fundamental current from the fundamental applied voltage, and
- The amount of distortion or difference in the shape of the current waveform from the voltage.

Both components together affect the amount of root mean square (RMS) current that a VFD/motor load draws, which is the basis for the power factor measurement by the utility. If a typical induction motor load is connected directly across the line, without a VFD, the power factor is mostly due to displacement and will be from 70 percent to 80 percent. With a VFD/motor combination, the power factor is mostly due to input current or voltage distortion and can be as low as 50 percent under certain operating conditions. It would seem that improved power factor is not an advantage with a VFD/motor system. However, the input power factor can be increased to as high as 97 percent either by modifications made to the installation or by additional control means within the VFD. This aspect of the input power factor of a VFD is discussed in detail in the section on "*Input Power Quality and Electric System Compatibility*."

Achieving a high power factor with a VFD/motor system is another example where the application engineer and the VFD system integrator must work together to achieve the minimum total cost of ownership. The power factor a system attains depends primarily on the impedance of the power source, topology of the drive, range of operating speed, control modulation methodology, the type of motor used, and start/stopping requirements.

Compliance with Environmental Regulations

As international environmental concerns for greenhouse gas and other emissions from industrial processes mounts, the pressure from regulating agencies and public opinion is driving industry to develop low-emission solutions. Electrically driven systems have demonstrated the ability to virtually eliminate onsite emissions of greenhouse and other air quality degrading matter. In some cases where local air quality regulations budget each industrial installation's allowable emissions, growth or expansion is no longer feasible using onsite fossil fuel consuming energy conversion equipment, such as internal combustion engines, gas turbines, or coal/oil fired steam plants. In these situations the most practical solution is an electrically driven process, if the local power grid can feed the added demand.

In addition to the near zero onsite harmful atmospheric emissions, electrically driven systems offer the benefit of limited acoustic energy emissions, and much simpler structural enclosures necessary to house the equipment as a result.

Improved Process Flexibility and Control

Energy saving is a major decision factor in the process to convert to VFDs and motors, but another, just as important, advantage is process flexibility and control. The ability to run a particular subprocess at the desired speed can be critical. With modern speed control and the use of feedback sensing, the subprocess can run at the exact speed or flow required to obtain optimal output or performance of the subprocess.

A block diagram of a VFD with the various levels of control is shown in Figure 12. The modern VFD can communicate with an external process controller over a standard communication bus. This same communication bus also interfaces with process sensors, such as flow sensors, temperature sensors, etc., and other VFD/motor systems. The process controller collects the information it needs over the communication bus and then determines what speed commands to send out to the VFD/motor systems. The process controller also communicates with a programmable logic controller (PLC) and human machine interface. The PLC is used to open and close breakers, switches, relays, etc. and collect additional data over external digital and analog inputs and outputs (I/O) as necessary. The process controller may also receive commands from a user over the HMI as well as describe processes in real time, monitor data, and report process component health and status.

Using variable frequency drives at the multi-MW level, provides more flexibility by giving the operators more options to accommodate changes in production needs. For example, the VFD has a certain amount of inherent energy storage capability in its DC link, so that it can keep the motor moving during short interruptions in the input power. In addition, with special control measures, the VFD can help the motor ride through much longer interruptions by utilizing some energy from the motor load at the expense of a reduction in motor speed. Slowing the process down, instead of stopping it, allows for adjustments or repairs to be made without shutting down the system. In addition, the ability of the VFD/motor system to avoid a complete stop, in a process that requires continuous flow due to the nature of the material, saves lost material and downtime. For example, glass, silicon, and paper manufacturing are processes that demand a continuous flow.

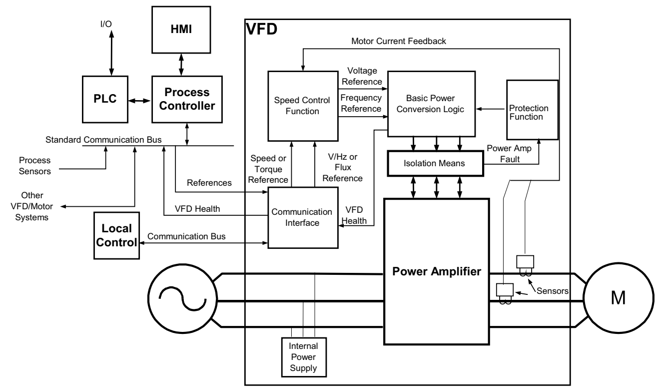

Figure 12. VFD Control Block Diagram with Interface to External Process Controller.

Also, at multi-MW levels the starting and stopping of the system can cause input power line disturbances, which should be avoided. Starting a MV system draws large inrush currents, but a VFD limits the current by providing a soft start capability. The motor is stressed during starts and stops due to the internal rotor heating. Proper application of the VFD and motor allows proper start/stops and low-speed operation without thermal stress. It is particularly important to consider start/stop situations since the time to cool a MV motor can limit cycle times, and this affects production capacity. The other consideration in start/stops is the power source. In some locations, such as an offshore facility or developing countries, the power grid is too weak and cannot support the demand on startup, so a controlled start and stop is essential.

Reduced Size

Other considerations and potential benefits in using a VFD solution are size and weight. The advances in technology have allowed the power density of electric conversion systems to be very competitive with a gas turbine compressor. Using a smaller and lighter VFD/motor combination is a key enabler to the conversion of a multi-MW mechanically driven system to an electrically driven system. For example, in a 7.1 MW VFD installation, the weight of the VFD/motor solution was three times less than the weight of the mechanical system (Fulton, et al., 2001).

When the VFD system integrator is also the VFD OEM, the VFD/motor system components can be tailored to the needs of the industry. For example, a multi-MW VFD system can be designed with a significant amount of modularity and repeatability of the drive components. This allows for easier shipping and installation. The size advantage can be further improved when cooling fluid is readily available at the application site. Liquid cooling technology is particularly applicable at higher MW levels due to the size improvement and relative low cost of cooling the VFD components. High-power density capability is available in sizes exceeding 10 MW. An example of a liquid cooled, modular power module for a multi-MW VFD is shown in Figure 13. The entire VFD system is shown in Figure 14.

In addition, the combination of a VFD with a permanent magnet (PM) motor in a multi-MW system will lead to additional reduction in size and weight. This trend is occurring in the conversion from mechanical to electrical propulsion for marine propulsion applications for the Navy (Walsh, 2002), which parallels the conversion to multi-MW VFD/motor systems in industrial applications.

High Reliability

Reliability issues of motor control and the power system are well understood and have been addressed in low voltage designs years ago. Reliability has also improved by getting better feedback on failures and using root cause analysis techniques. Feeding the

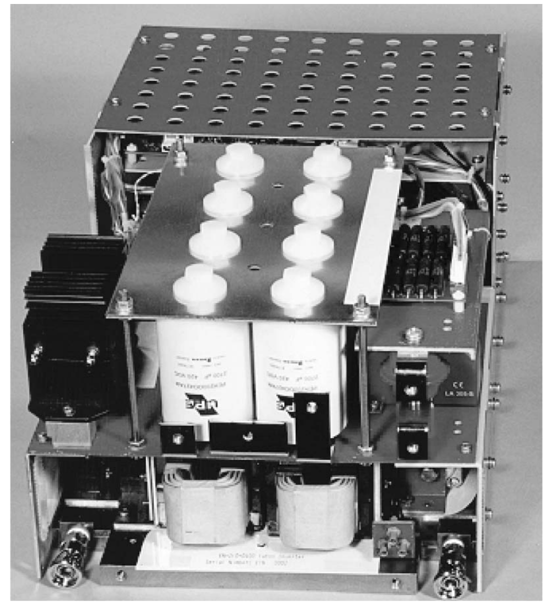

Figure 13. Medium Voltage, Multi-MW VFD Modular Power Cube.

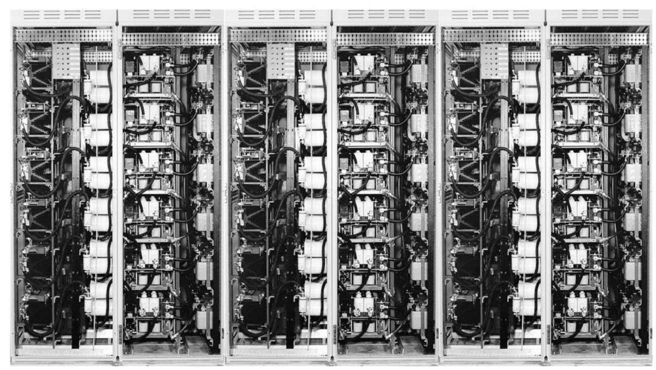

Figure 14. Multi-MW VFD System Made Up of Modular Building Blocks.

failure reports back to the designers resulted in better reliability through what manufacturers called reliability growth programs. Implementing these improvements in the design of MW drives, "…indicated that the overall reliability would be at least as good as with the gas turbine option" (Kuemmlee, et al., 2000, p. 67).

As stated earlier, multi-MW rated industrial electrical systems are not new to the market; in fact, there are several multi-MW installations (Fulton, et al., 2001) that have been put into operation over the last few years. There are larger special medium-voltage drives such as load–commutated inverters and cycloconverters that go up to the 100 MW range (Graham and Graham, 1993). These installations demonstrate that the conversion to an electrically powered plant is real and will continue. Companies looking for a competitive edge will be pushing for the conversion.

The reliability of multi-MW rated industrial process electric systems continues to improve with the maturing of power semiconductor devices and better VFD topologies (Uchida and Yamada, 2000). Power device manufacturers are continuing to increase the range of voltages that the power devices can withstand. In some VFD topologies, the power devices used at MW levels are the same ones used in low-power applications. This allows for considerable leverage in the volume (cost) and quality of the components that make up the VFD. The high reliability achievable today is increasing the proliferation of VFD technology into industrial, commercial, and military markets.

The power density of silicon devices is rapidly increasing. This trend allows for the integration of the entire subassemblies of a VFD into a single "power module." In this spirit, the power module of Figure 13 may actually be purchased, a component building block, which the OEM VFD supplier/VFD integrator puts together into a multi-MW system (Kehl and Beihoff, 1999). Today's power semiconductor devices are made on robotic manufacturing lines with automated techniques of mounting and soldering silicon wafers onto the ceramic plates. The result is a very high-power density and high reliability device (Kerkman, et al., 1999).

A failure of a VFD is more likely to occur due to misapplication than from aging of the VFD system. In fact, the mean time between failure (MTBF) of the VFD system can be extended indefinitely by enclosing or "cocooning" the VFD system to isolate it from environmental effects and by intelligent monitoring and cooling techniques that enable condition-based maintenance (Murdock, et al., 2002).

Other Advantages

Some benefits, if considered alone, may not typically justify the use of an electrically driven system, but are nonetheless additional benefits provided by the new technology. As the cost and power level of electrically driven systems improve, these additional benefits will allow overall process control to be more efficient. These "additional" benefits are the primary justification in the low-power systems due to the maturity of the technology and applications. These added benefits listed below will be recognized in multi-MW applications as the technologies mature.

- Diagnostic capability of drive software for system analysis
- Drive software flexibility to filter resonant frequencies
- Reduced maintenance of heating, ventilation, and air-conditioning (HVAC) systems
- Coordinated communications between drives and system controller
- Input power quality and electric system compatibility
- Output power quality to the motor and motor compatibility

Most of these items are self-explanatory, but the last two items, input power quality and output power quality, are very important when interfacing an electrically driven system with the rest of the facility and will be briefly discussed.

Input Power Quality and Electric System Compatibility

Input power quality deals mainly with voltage and current distortion that occurs on the AC power lines in a plant installation. The electric system compatibility encompasses interactions between the VFD and other system components that share the electrical AC bus. To prevent other equipment from experiencing operational problems, a facility wants any equipment attached to the distribution system to induce the minimum amount of distortion possible. A VFD can provide individual harmonic distortions on the input power lines that are less than 1 percent of the fundamental.

For a typical topology with a rectifier front end, the input current waveform will have a distortion as shown in Figure 15. The harmonic currents that result are nontriplen (not a multiple of three) odd harmonics of the fundamental with the highest harmonic, fifth, being at 20 percent of the nominal fundamental current. For plants in many locations other than the United States, there are specifications, such as CN 61800-3, that limit the harmonic currents to below 5 percent of the fundamental. The VFD can be brought into compliance with these specifications by making modifications to the VFD. For low-power VFD systems, one way to accomplish this is to replace the rectifier with another inverter, which actively controls the input current to regulate the DC link voltage and keep the input power factor to unity. The result can be individual harmonic distortion less than 1 percent.

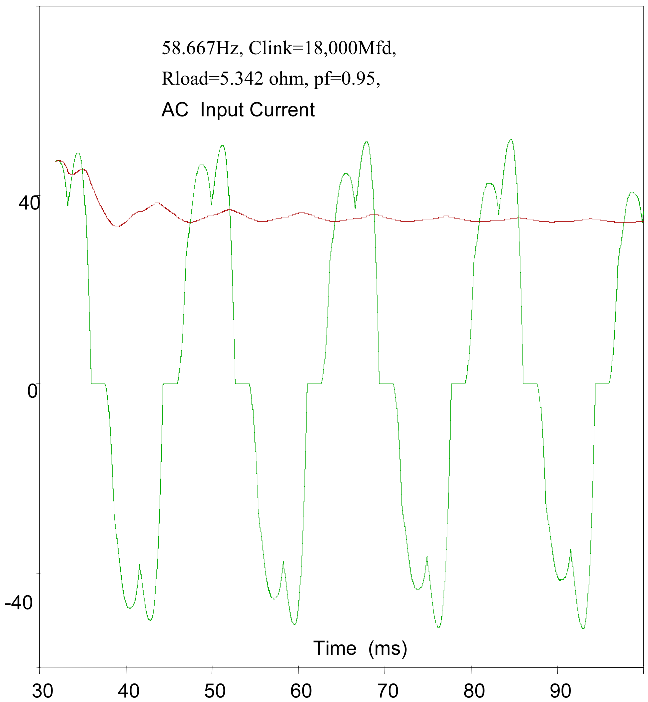

Figure 15. Input Current for a VFD with Six-Pulse Rectifier Front End.

A multi-MW VFD using the cascaded H-bridge inverter approach of Figure 6 has an inherent advantage from the standpoint of reducing input current harmonics. This reduction can be accomplished with minimal additional cost if the electrical output of the multiple secondary windings is displaced by equal angular increments over a 60 degree span. For example, for a four-level cascaded H-bridge with four secondary three-phase windings per single phase, the phasing would be 22.5 degrees, 7.5 degrees, −7.5 degrees, −22.5 degrees. The resulting individual current harmonics will be less than 1 percent. As levels are increased, the input current harmonics can be reduced even further.

The three-level VFD of Figure 8 will have the same input current harmonic distortion as the low voltage VFD of Figure 15. The input current harmonics can be reduced to less than 1 percent by replacing the rectifier front end with another three-level inverter interfacing between the input source and the DC link capacitors.

Output Power Quality to the Motor and Motor Compatibility

For some applications, minimization of torque ripple on the motor load is important. The PM motor has the inherent benefit of very low torque ripple, when compared to an induction motor, because of the lack of electrical conductors on the rotor. In addition, the combination of a VFD/PM motor will typically have more than two poles, which further reduces the torque ripple. In such cases it is important that the output voltage waveform from the VFD does not introduce torque ripple. The increased switching frequency of the cascaded H-bridge and multilevel inverter structures help to accomplish this (refer to Figure 7).

It may be necessary to add additional filtering to make the typical staircase voltage waveform of Figure 7 look more like a sine-wave. An actual 6 MW, three-level, cascaded H-bridge inverter VFD/PM motor system was built with the requirement of minimizing torque ripple. By combining high frequency, staggered switching with a filter network, the resulting output voltage spectrum applied to the motor is shown in Figure 16. The resulting output voltage harmonics were less than 1 percent, leading to a significant reduction in the VFD-induced torque ripple.

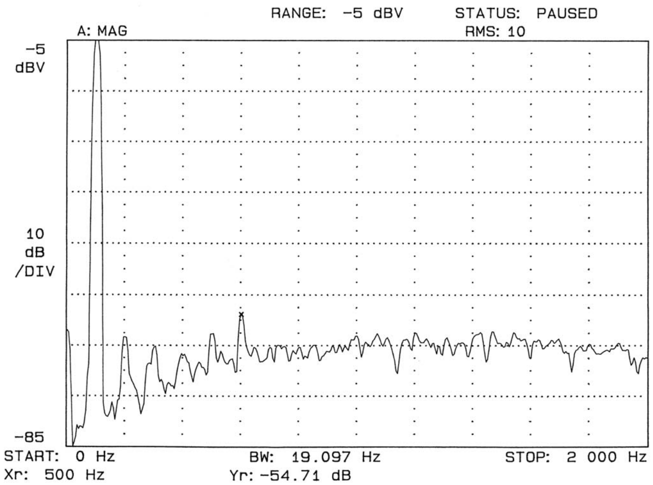

Figure 16. Output Voltage Spectrum for High Performance Cascaded H-Bridge PM Motor VFD.

Cable type and length between the motor and VFD are important from a couple of standpoints. The cable size and type need to consider the load current, voltage drop over the length, capacitance to ground, environment, and length. Cable length directly impacts reflected wave amplitudes and thereby motor insulation life. The addition of filter networks can allow for significantly longer cables without introducing voltage stresses on the motor insulation. There are good articles defining the problem, but the key is an integrator with knowledge of these issues (Skibinski, et al., 1998).

FIELD EXPERIENCE WITH MULTI-MW DRIVES

The number of installations of multi-MW VFD/motor solutions is increasing for reasons discussed above. Figure 17 shows the expanding power range of electric drives. While there are many applications in the low-power range up through 5 MW, the trend into the multi-MW is moving to high-speed applications as more IGBT-based PWM inverter solutions are implemented.

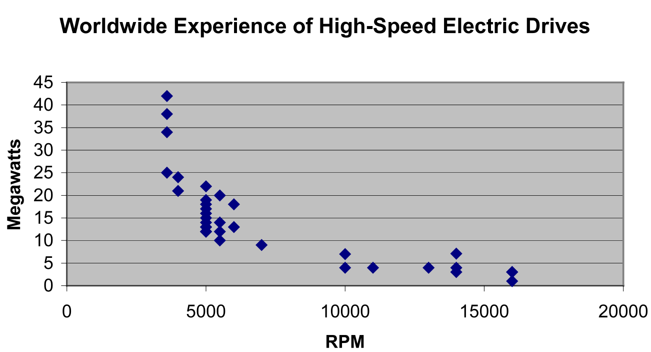

Figure 17. High-Speed Electric Drives. (Courtesy, Fulton, et al., 2001, Turbomachinery Laboratory)

In this section, a summary of two actual installations and their documented conclusions are cited for reference.

One installation cited in the references was a natural gas reservoir depletion compressor in the Netherlands at 23 MW at 5400 rpm. This conversion from an otherwise mechanical system to an electrical system using VFD/motor demonstrated the potential benefits of lowering production costs and increasing profits:

> "The present generation of gas turbines in the 23 MW range features a peak conversion efficiency on the order of 37 percent. However, by use of the present generation of large commercial combined cycle power stations to supply an electric drive, an overall conversion efficiency as high as 52 percent can be achieved. This includes all the transmission losses, i.e., natural gas to power at the compressor shaft." (Kuemmlee, et al., 2000, p. 67)

The production costs were also reduced through decreased downtime and maintenance.

Another application was an underground gas storage injection in the Netherlands at 38 MW, 4200 rpm. In this case the conversion from a mechanical to electrical VFD/motor system was driven by reasons other than cost:

> "Restrictions on harmonics imposed by the utility, special network conditions, pressure by ecological political groups and life-cycle economics were decisive in the choice of drive systems." (Kleiner, et al., 1999, p. 1)

While only two installations have been noted, the intent of citing these two examples was to highlight the variety of justifications that a multi-MW electrically driven system can satisfy. While the justification for each system is widely different, both have reaped all the benefits an electrically driven system provides. While the first example's main intent was to lower production costs and increase profits, the system also provided the company a more ecologically friendly system although it was not one of the selection criteria.

APPLICATION GUIDELINE FOR VARIABLE-FREQUENCY DRIVES

To determine if a VFD is indeed a good solution, the application engineer starts with the application and determines the output load profile of the system. For example, if the flow of the process is charted over its operating range, one should get a measure of the minimum and maximum flow requirements. Once the range of flow rates is known, the demand with respect to time is important. What type of duty cycle is demanded? What are the rates of change needed in the flow?

In general, if the output profile demands a change in flow and runs below 90 percent peak levels for significant amounts of time, or it has significant start/stop cycles, the application will profit from the installation of a VFD. Figure 10 shows that significant savings occur when operation at levels below 90 percent is required. Savings in energy usage can exceed 50 percent along with providing process regulation and control to improve the quality of the product delivered (Howe, 1996).

The VFD can successfully operate with the following types of loads:

- Constant torque regardless of speed, such as conveyors or positive-displacement pumps
- Torque increases with speed, such as centrifugal pumps, fans, blowers, and most compressors
- Torque decreases with speed, such as high inertia loads

Once the load profile is quantified and a VFD system is considered the proper solution, the next decision in the process is selecting the motor. The load defines the torque requirements of the motor and the current needed by the motor. Once the continuous, peak, and duty cycle torque are known, the VFD can be sized.

After the application engineer has determined a VFD will meet and satisfy the operational requirements, other issues must be considered for the installation to be successful and the full benefits and potential of the VFD to be realized. Implementation of a VFD/motor installation requires careful system integration. The best approach is to have the application engineer work with a single VFD/motor system integrator to address all the system interface issues that may arise. The main issues to be reckoned with are:

- Input power quality and electric system compatibility
- Output power quality to the motor and motor compatibility
- System grounding and electromagnetic interference (EMI)

An experienced VFD/motor system integrator is critical to the success of the implementation, because of the knowledge provided and the simulation tools at his disposal.

Prediction and prevention of harmonics on either the input power or the output power requires a complete electrical system analysis and requires a knowledgeable VFD system integrator. Harmonics are created and affected by the input power system, length of cabling, input transformers, drive power topology, converter power switching techniques, inverter switching technique, motor cabling, motor design, and grounding. When the applications engineer and VFD system integrator can accurately define each of the system elements and run simulations to assure system stability and high efficiency, then the VFD/motor and installation can be adequately designed.

System grounding is critical for reliable operation of the electrical installation. Proper grounding not only is required for safety reasons, but it controls common mode currents, which can contribute to electrical noise and intermittent operation (Skibinski, et al., 1998).

For the multi-MW system, grounding can be of particular concern. The reason for the concern is that the most effective means of cooling the VFD power semiconductor devices is through liquid cooling. This is accomplished by mounting the devices on a liquid-cooled coldplate that will be at ground potential unless the cooling water is deionized or some other cooling liquid, such as oil, is used. Figure 18 shows the power module capacitive couplings that are created for a cascaded H-bridge inverter on one level. The result is that even though the voltage across the device is kept within safe levels for a medium voltage system, the voltage from the device case to ground can be at any potential, from the DC link voltage to the entire line-to-ground voltage. For a 4160 V system, the isolation capability of the power semiconductors will be stressed beyond their limits. This problem can be mitigated at the VFD design level by adding layers of electrical isolation protection between the device and the coldplate (at the expense of increasing device heating) or by using resistive grounding techniques and different circuit arrangements for the entire VFD/motor system.

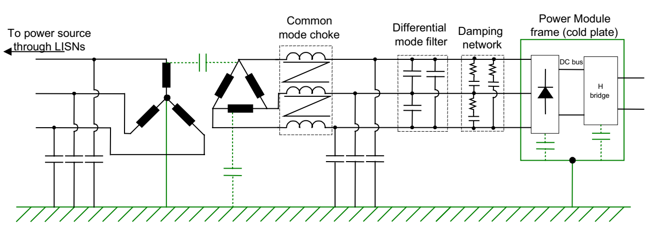

Figure 18. Cascaded H-Bridge Inverter Single-Phase Converter with EMI Filters and Capacitive Coupling (Dotted Capacitors).

Electromagnetic interference (EMI) is a growing concern in the global economy. For example, Europe has specific CE requirements that limit the radiated and conducted emissions of a system. Drives can be large transmitters of EMI if not properly installed. The grounding, topology, isolation method, and filtering all affect the system's EMI status. Figure 18 also shows the EMI filtering that can be applied to the system to help mitigate the effects of conducted EMI.

An illustration of how the system integrator, having a knowledge of the system along with valid simulation modeling, can develop a VFD/motor system for a cascaded H-bridge topology follows. The actual conducted emissions were measured on a single H-bridge to a given EMI standard. The required limits are superimposed on the measured line-to-ground voltage (Figure 19). Using a simulation model, developed and validated for a line of VFD products, the same conducted emissions were simulated in Figure 20 with good accuracy. Then an EMI filter was designed having the structure represented in Figure 18, and the appropriate filter component values were selected so that the conducted emissions were brought into compliance with the conducted emissions requirement. The simulated results are shown in Figure 21. Once the conducted emissions are validated at a single level, a full scale model of the cascaded H-bridge inverter can be built. Similar modeling techniques can then be used to determine the filtering required to bring the entire system into conducted emissions compliance.

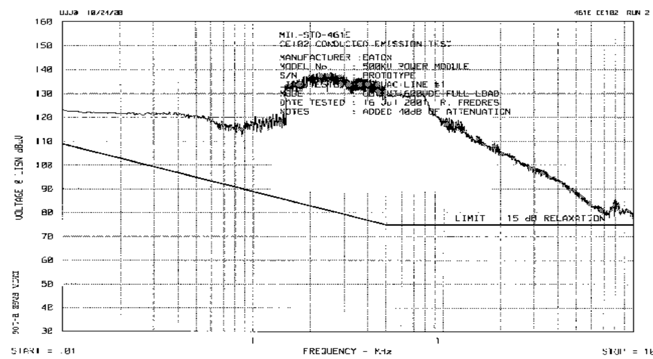

Figure 19. Conducted Emissions Measurements at Full Load Plotted Versus CE 102 Limits.

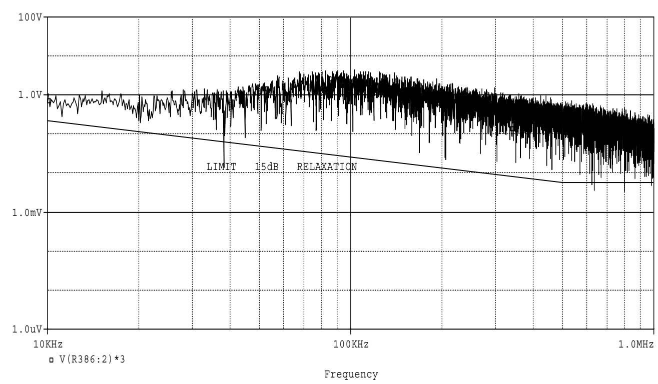

Figure 20. Simulated Conducted Emissions, Plotted Versus CE 102 Limits.

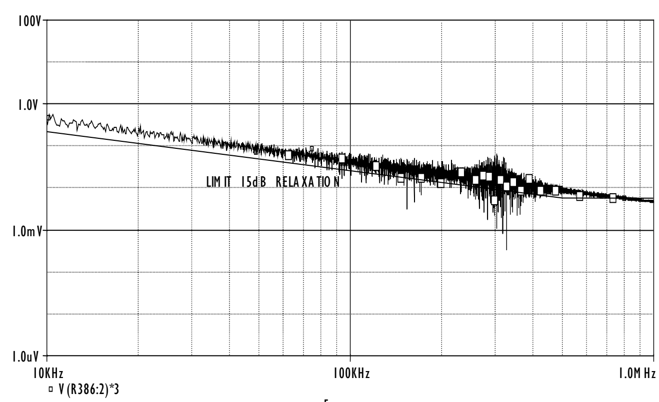

Figure 21. Simulated Conducted Emissions with EMI Filter Added, Plotted Versus CE 102 Limits.

TOTAL COST OF OWNERSHIP

The determining factor driving the conversion process from mechanical systems to electric motors and VFDs in multi-MW rated industrial drive systems is the same as that which drove the change at the lower end of the power range—greater profits. This was attained through energy cost savings, as discussed earlier, and also by selecting applications where the new performance capability offered by the electric motor enabled an improvement in the process. Consequently, improved profits justified the change to the electrical power conversion technology.

In order to identify the reasons for converting to an electric system, it is beneficial to look at TCO. The TCO assessment is a process for placing a value on different configurations of the electrically powered system and determining the true profitability over the life of the program. By presenting the key factors in the TCO, it is hoped that not only will a process guide be outlined, but it will also identify some of the critical cost and performance issues to be considered by the application team. It is important not only to consider the upfront capital costs, but also include commissioning, operation, support, and either disposal or upgrade potential for different implementation scenarios. It is important to note that this process of analysis is improved if the implementation team looks at several scenarios before selecting the final solution.

Many factors affect the total life-cycle cost or TCO in an electric conversion program (Bryant, et al., 2001). Table 2 lists some key factors the integration team should consider.

Table 2. Total Cost of Ownership.

Concept, Specification, ROI analysis & award	**Commissioning & start up costs**	**Operating Costs**	**Maintenance Costs**	**Production Costs**	**Disposal Cost and or upgrade potential**
Identify team members	Installation costs estimates (include utility substation if needed, harmonic filters)	Production direct labor	Labor required	Unscheduled downtime	Waste disposal
Performance Goals	Freight	Supervision requirements	Supervision Requirements	Reduced or increased capacity	Demolition
ROI objectives	Schedule	Overhead costs	Management and Engineering	Yield estimates	Restoration
Financial Analysis	Risk assessment document	Spare and repair needs	Spare and repair needs	ROI and risk assessment	Upgrade potential-cost estimate
Management Representation	Spare Parts stock	Cost of Power (gas or electric)	Building & shops		Capital cost estimate
Value Engineering Analysis	Permits and land requirements –purchase if needed	Support staff and training level	Inventory (parts & materials)		Install cost
Program Timeline	Compliance test plan	Waste disposal	Monitoring		
Final Performance Requirements Specification	Contingency funding	Profit goals	Repair		
Compliance agreement	Support Staff training	Raw material cost	Preventative Maintenance		
Design Specification Documents	Environmental and legislative (emissions and noise)	QA required	Turnaround		

Concept, Specification, Return on Investment, and Award

This stage is critical for overall success. There needs to be a seamless collaboration between the application engineers, program managers, and the electrical and mechanical equipment integrators. Together they can analyze and, if necessary, develop technical solutions that will ultimately achieve the highest possible profits. There are a number of steps in determining the TCO, with the first being a generation of the performance requirement document. This document guides the entire process and is critical for a focused team effort. The critical performance goals must be defined and understood. Application issues, such as those discussed earlier in this paper, must be defined in the performance requirements. Once the system integration team understands the performance requirements, it is necessary to create the design specification documents. Design documents, generated by each supplier, are a response to the performance requirement document. They state exactly how the system will be designed to meet the performance requirement document.

During this process, different methods for meeting the application requirements should be explored. High risk or development efforts need to be defined in terms of how they contribute to achieving the performance requirements, and what kind of alternate approaches need to be considered or carried as backup solutions. Sometimes customization is required to meet the specific application performance requirement. If the success or profitability is dependent on a "development" program, then it is critical to further define this effort and schedule and fund it such that it does not present problems later in the commissioning or production stage. A remote location, for example, is a factor, and the prudent program manager might require appropriate early demonstration tests to verify compliance to specification. Defining risks requires skilled, experienced integrators and directly affects the profitability and success of the program.

Value engineering is important at this stage and involves reviewing what is actually required in terms of performance. In all projects there must be a clear differentiation of wants and needs (Bryant, et al., 2001). For example, redundancy needs to be evaluated. If additional cost is being added to avoid an improbable or one-time failure it may not be justified. But, due to a remote location or the cost of downtime (identified in the TCO model), the cost of a specific feature, like redundancy, may be justified to achieve production uptime. Redundancy in the power electronic equipment can be implemented so that performance degrades relatively "gracefully" as individual failures of the equipment occur. New designs are modular and lend themselves to increasing process uptime. Reliability can be greatly improved, when downtimes are not acceptable, by scheduled replacement programs. High reliability and availability are "value-added" features in this situation.

Another consideration is design margin. There are several power system requirements that need to work within certain defined limits or standards. The amount of margin required directly reflects on the reliability and robustness of the system over the range of operating conditions. Again the application and cost of downtime must be defined in order to design in, upfront, the margin desired to obtain the desired goal. Understanding utility requirements, load cycles, and production goals are all factors in this equation. The customer will define the final performance requirements once the cost tradeoffs are known.

Finally, using experienced and capable integrators is critical. The range of skills an integrator requires is:

- Application analysis and simulation capability
- System design (hardware and software) and specification capability
- Supplier of all critical system components and taking system responsibility
- Ability to manufacture and pretest the system as required
- Global field support capability and spare stock
- Project management capability

The application program manager needs to have experts at his side to pull off a conversion to electrically driven processes, particularly the first time. Experience and know-how are critical to success. Finding an integrator with prior experience in the application is prudent. Bidding a job for the best price at multi-MW power ratings is not likely to result in the lowest overall life-cycle cost. A TCO assessment is needed to identify real expectations for the measure of improved profitability of any system. It is important to keep all suppliers accountable from the beginning for their part in the integration. The final design specification gives all parties the confidence needed for a successful implementation.

Commissioning and Startup Costs

The physical size of the system components can dramatically impact the cost of installation. The ability to have small modules, shippable by truck versus a barge or rail car, reduce shipping costs and increase options for delivery schedules (Fulton, et al., 2001).

The key factors to consider include; distance to site, size and weight of equipment, permits and restrictions, available and practical shipment modes, cost of insurance, and duties. Installation costs must be defined and contingency funds made available.

If the customization required to meet specific performance needs has significant risk, test schedules and cost estimates need to be scrutinized to ensure these risks have been appropriately addressed. Also, if the equipment is to be tied together for the first time at the work site, then pretesting must be considered. Today there are excellent techniques for minimizing the risks with thorough computer simulation of critical operating modes. A qualification test that validates the computer models should be defined before the first installation is commissioned. Skilled integrators are capable of running a simulation analysis as required.

Spare Parts

The cost of stocking parts needs to be considered and must include the cost of stocking, storage area, remote location, skill level of personnel, time to get parts, and time needed for routine maintenance and repairs. Current technology lends itself to standardized modular components that drastically reduce spare part cost and stocking requirements.

CONCLUSIONS

The conversion to electrical systems using a motor with a speed controlling device has been going on for nearly 100 years. Low-power applications are in the final phase of conversion that optimizes the process through coordinated communications and higher-level control functions. The evolution of low-power conversions is a good reference for planning MW transitions. Technology development, in both the power devices and VFD topologies, is rapidly allowing the high-power MW applications to be seriously considered for electrical conversion. The application advantages include lower costs of energy and process flexibility. These advantages can be quantified by working in a collaborate team of application engineers and electrical integrators. As in any critical technology transition, the justification must be detailed, precise, and practical while meeting the customer's application needs. The TCO is a process of identifying these important elements. The conversion to electrical systems at MW levels is underway, and the rate will increase due to the advantages and profits VFD and motor solutions can provide.

APPENDIX A— MOTOR TECHNOLOGY OVERVIEW

Before the invention of the speed-regulating device and ultimately the VFD, the electric motor itself was invented and, as conversion to electric systems became more prevalent, the electric motor evolved into various forms.

DC Motor

The DC motor has various configurations including wound field, series-shunt, permanent magnet (PM), etc. The DC motor has historically been the preferred choice when very high torque and precision control of the motor torque and position are required. The speed of a DC motor is controlled through the control of its field and control of the armature voltage applied. Therefore, some type of speed-regulating device is required, as well as an AC-to-DC power conversion unit, since the utility power grid infrastructure is based on three-phase AC power.

Induction Motor

The "squirrel cage" induction motor has become the industrial workhorse because its construction is very simple and mechanically robust. Its rotor has no brushes, consisting of a smooth cylinder with a series of longitudinal conductors (bars) embedded in slots in stacked, laminated steel rings, which are shorted together at the rotor ends by a plate brazed to the bars.

The induction motor finds wide application because of an inherent feature of self-regulating and stabilizing the speed of the machine by balancing the torque demand of the load with the output of the motor. When a three-phase AC voltage is applied to its stator windings, a rotating magnetic field is set up in the air gap between the stator and rotor, which induces currents in its shorted rotor bars that, in reaction to the rotating magnetic field, develop torque to set the rotor in motion. If there is no load on the motor shaft, the rotor will turn at a speed that slightly lags a synchronous mechanical speed that results from the following relationship to the applied electrical frequency:

$$Synchronous\ Speed\ (rpm) = \frac{120}{Poles} * Electrical\ Frequency\ (Hz) \quad \text{(A-1)}$$

As the rotor shaft is loaded, the difference between the applied synchronous speed and rotor speed, the slip speed, increases, and, as the rotor current flow increases, the stronger the rotor magnetic poles become, resulting in higher torque. The attractive feature is that a degree of speed (at a single frequency) and torque regulation is achieved without the need for a speed-regulating device. If variable speed control is required, the induction motor speed can be controlled in different ways:

- Varying the input voltage of the motor
- Changing the motor winding pole number
- Varying the input frequency of the motor
- Varying the input frequency and voltage to achieve a constant volts per Hz (V/Hz)

Two-speed control is commonly achieved by winding the motor so that it can be configured in two different pole arrangements by a mechanical switch. For example, the synchronous frequency of Equation (A-1) can be changed from 1800 rpm to 3600 rpm by switching the stator winding pole number from four to two.

The least desirable method is voltage control, since the achievable speed range is very limited, and the efficiency of the motor is considerably reduced as the motor voltage is reduced from its nominal value without changing the frequency. The motor speed can also be varied by varying its frequency as indicated by Equation (A-1); however, this will also result in inefficient operation of the motor and overheating just as is the case with varying voltage.

The most effective way to control motor speed is to vary the voltage and frequency without changing the ratio of its nominal voltage and frequency (keeping a constant V/Hz ratio). Speed can then be varied from zero to rated speed without causing overheating or significant loss of efficiency. The VFD is designed to operate on this basic principle to take advantage of the induction motor's inherent principles of operation.

If higher precision control is required, the motor speed can be controlled by controlling the slip speed. This control requires knowledge of the motor parameters applied to a sophisticated controller within the VFD. With the advent of the VFD, modern control techniques, and the low cost of the VFD system, the VFD and AC induction motor are replacing the DC motor solution in precision control applications. For these precision control applications, knowledge of the motor shaft position is required (either by measurement or estimation) and the induction motor torque is directly controlled.

Wound Field/Rotor Synchronous Motors

The synchronous motor has a rotor with two or more pairs of wound field poles on either a round or salient structure. The rotor field windings are typically energized by a DC power source that is external to the motor, requiring the use of brushes and slip rings.

The synchronous motor's speed is controlled in the same manner as the induction motor, with an additional means of speed control that controls the rotor field by controlling the field current. A significant difference between the synchronous motor and the induction motor is that the rotor rotates in synchronism with the stator's magnetic field (no slip). Therefore, the synchronous speed of Equation (A-1) is identical to the rotor mechanical speed. Unlike the induction motor, the synchronous motor is not "self stabilizing" and cannot be run directly from an AC power line without additional features to address stability problems. In addition, at startup, the placement of the rotor electrical poles, with respect to the applied stator field, is fixed by the mechanical construction—whereas the induction motor rotor field is a reflection of the applied stator field. Therefore, before the advent of the VFD, startup and stabilization of the synchronous motor could only be addressed by adding an additional squirrel cage to the rotor at the expense of reduced efficiency and increased heating. Once the synchronous motor is started and rotating at synchronous speed, as the load varies, the angular displacement changes, which affects the motor input power factor and torque output. Control of the rotor field current can be used to control the motor input power factor.

The VFD can be used in the same way as with the induction motor to control the speed from zero to rated speed. Speeds above rated speed can be achieved by controlling the rotor field. A significant difference is that speed or current feedback control means must be added to stabilize the motor speed as speed and load change. Position feedback is required for precision control at low speeds or startup. The volts per Hertz applied to the synchronous motor is typically modified to maintain the input power factor close to unity, in order to reduce stresses on the VFD system.

Permanent Magnet Synchronous Motor

In the case of the permanent magnet motor, the magnetization energy is provided by permanent magnets mounted on the rotor without the current flow and the associated losses of either the rotor bars ("squirrel cage" induction motor) or wound field excitation (wound field synchronous motor). The result is a substantial improvement in torque density (achievable torque for a given size and weight), reduced cooling requirements, and improved efficiency. In order to achieve these benefits with the PM motor, the use of a VFD with advanced embedded control is an absolute requirement.

For low-power applications, the benefits of improved torque density, cooling system effectiveness, and increased efficiency are typically not significant enough to justify the additional cost. Therefore, VFD/PM motor systems are usually applied to low-power applications only where precision (servo) control and high torque near zero speed are requirements. However, from a TCO view of multi-MW systems, the reduction in size and weight and increased efficiency will lead to greater reductions in operating costs that may justify the additional installation cost of the PM motor solution.

Motor Type Overview

Table A-1 compares the key features between the various AC motor types discussed.

Table A-1. Comparison of Various Motor Types.

Motor Type	Typical Applications	Advantages	Disadvantages
Wound Field DC Motor	• High Torque Applications	• Higher torque capability than AC motor solutions.	• Controlled AC to DC power converter required • Maintenance costs due to brush and commutator maintenance. • Cooling rotor winding drives cost/weight and limits achievable torque density.
AC "Squirrel Cage" Induction Motor	• Workhorse of the industry • Better for high speed applications since no brushes • Power Range: 0.75-200KW Typically and up to 2000KW installed	• Inherent speed and torque stabilization when connected directly to AC line. • Robust, reliable, low cost. • Low Maintenance • Special enclosure available for wet, corrosive, or explosive environments • Efficiency > 90% achievable. • Across the line operation if the VFD fails	• Poor input power factor leads to higher operating cost (without VFD) and higher installation costs (with VFD).
AC Wound Field/Rotor Synchronous Motor	• Large MW applications	• Controllable input Power Factor through field control	• Additional costs of both VFD and controlled AC to DC power conversion. • Maintenance costs due to brush and commutator maintenance. • Cooling rotor winding drives cost/weight and limits achievable torque density.
AC Permanent Magnet Motor	• Servo and precision low power applications • High torque, low speed applications. • Applications with controlled and high acceleration rates • High torque at high speeds	• High Torque to weight ratio • Low rotor inertia • No Brushes, low maintenance • High dynamic speed and torque response with appropriate VFD and controls	• VFD required for stable start up and speed/torque control. • Demagnetization potential under extreme faults and over-heating conditions

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