Allen-Bradley

Variable Frequency Drives

Variable Frequency Drives Optimize Performance and Protection of Offshore Oil Electric Submersible Pumps

Application Notes

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Offshore Oil Operations

As global demand for reclaimable petroleum reserves increases, so does the demand for technological advances in artificial lift systems, especially in the field of offshore oil operations. Such operations have the reputation of being extremely expensive with no guarantee that results will yield reserves that will justify such costs. Artificial lift systems are an essential part of offshore drilling, especially in maturing oil fields where the reserves lack sufficient pressure to easily bring the crude oil to the surface. Electric submersible pumps (ESP's) offer the highest yield of most deep-well artificial lift systems, but suffer the highest frequency of expense and repair. This profile outlines how a careful selection of technologies, specifically the use of electric submersible pumps with variable frequency drives, can optimize the performance in well extraction on offshore oil production platforms. This profile also compares ESP systems to other contemporary artificial lift techniques, discusses electromechanical, solid-state reduced voltage starting options in comparison with the benefits of continuous duty motor control using variable frequency drives. In addition, this profile outlines design considerations, with special regard to powering systems with diesel generators, that are critical for determining a solution in this given application.

Electric Submersible Pump Technology

Electric submersible pump technology in oil field operations is still in its infancy, even now in the year 2001. ESP's had been around for years in applications pumping water or other fluids of relatively low viscosity, such as fresh water wells. Up until the early 1990's, ESP's saw their first applications in offshore oil field operations exclusively used in fire fighting or well injection operations. However, adapting such motors for use in such extreme conditions as downhole operations had occurred slowly and almost exclusively by North American Companies, whose main markets were fresh water well applications. In 1994, the first practical application of downhole ESP's became moderately successful at an offshore rig in the Campos basin off the coast of Brazil. The application required the design of a production string consisting of a submersible pump driven by an electric motor, separated by a sealing section from the actual pump – to allow for expansion of gas and fluid and to allow for the installation of a gas/water separator. With the pump section positioned down the well just below the surface of the deposit, the separated crude oil is pumped to the surface via conventional sucker rods. The wellhead is capped with a valve for venting the gas. The gas is either burned off (flared) to avoid re-infusion of the gas into the reserve or retained for use in artificial lift or well injection processes. Perforations in the well casing allow the water to be forced out into the annulus of the well casing and raw crude mixture to enter.

The production string required a pump driven by a two-pole, three-phase AC induction motor redesigned to fit down a well shaft measuring 4 ½ to 6 ½ inches in inner diameter and capable of handling thick fluids mixed with abrasive materials like sand. Horsepower ratings of 750 horsepower were achievable with the inclusion of additional rotors. However, 50-250 horsepower ESP's were the most common. Production strings, including modular motor, separator, fluid coupling and pump sections could be as long as 90 feet, making the entire string extremely vulnerable to failure due to radically uneven and severe torsional stresses. The motors and pumps were required to endure extreme mechanical stresses; pumping crude oil at a viscosity greater than 10 degrees API, at temperatures ranging between 100-275 degrees F. (with poor heat dissipation capabilities within the completely sealed sections), and at depths of up to 15,000 feet. The extreme stresses and frequent, relatively high cost of repairs (due to the limitation of global suppliers) made production use of ESP's very expensive and hindered by frequent downtime. One rig operation using ESP's off the coast of Brazil reported a motor failure rate of one every 60-90 days, with alarming regularity. Many operations that were determined to use ESP's for downhole service were required to do so on a rotational basis. A platform would have several units. One motor would be put into service until it required repair, whereupon another would replace it while it was sent offsite and, at great expense, rebuilt.

However, technological advances in both motor technology and applications of stronger metal alloys and thermally durable metal plastic composites were steadily making their way into a multitude of industrial processes. These advancements were coinciding with improvements in well development techniques. By the late 1990's, ESP's were becoming not only feasible but essential. The rapidly improving designs of ESP's also included enhancements in low resistance, waterproof cable designs, ceramic long-life bearings and increased operational speeds of up to 2900 rpms on a 50 Hz. Supply, and the introduction of variable frequency drives. Although the ESP motors and pumps were run continuously, the most severe stresses were caused by across-the-line (full-voltage) starting of the motors which caused rapid deterioration of the motors insulation, amounting to frequent and very costly repairs. The motor as a result of reflective wave phenomenon was incurring these severe stresses – incidences of voltage peaks occurring at the motor terminals that cause deterioration of the moor insulation by partial discharge/corona. Although the reflective wave effect can occur in any AC motor application, regardless of cable length or inverter devices, the voltage peaks can be most severe at startup and in applications using poor output waveforms and requiring cable lengths over 500 feet.

Several motor design considerations play an important role in a given motor's ability to withstand this phenomenon. The environmental conditions are expected to perform in are severe, especially in downhole applications. Extremes in conditions such as humidity, temperature, and contaminants are primary causes in early failure of motors. Being a completely sealed motor, an ESP must also have exceptional capabilities to dissipate or withstand severe inner core temperatures – requiring high temperature insulation ratings. The application process of resin (dielectric varnish) in ESP's is likely quite rudimentary, and the potential for mechanical damage in ESP's is very high. The method of assembly and quality of the winding including the pattern are limited by the design characteristics of the motor – very narrow and lengthy rotors with limited shaft thickness'. The concentricity and thickness of the magnet wire film is limited by the required compactness of the motor design. The winding process including the type of resin used, the process in which it is applied and the steps taken to prevent voids are critical measures in constructing a motor to withstand the destructive energies of partial discharge/corona. All of these factors will determine the relative cost of an electric submersible pump and its ancillary equipment. The replacement of an entire production string, including pump, motor, separator and optional fluid coupling of high quality could run as high as US$500,000.

Artificial Lift Systems

Although they tended to be expensive, ESP systems offered a potential flow rate superior to that of conventional artificial gas-lift systems or Progressive Cavity Pumps (PCP's). In addition, ESP systems offer superior performance in gaseous and water-infused environments. Gas and water occur naturally with crude oil and in high percentages. The gas and water must be separated from the flow of crude oil in order to pump it to the surface. High percentages can cause gas locking in the pump mechanism resulting in a serious decrease in flow delivery – requiring the entire production string to be pulled from the well and re-primed. Artificial gas-lift systems that inject gas in to the crude were often used in conjunction with surface operating reciprocating pumps or horizontal centrifugal pumps. However, these systems become far less efficient in deeper, deviated wells. Using gas-lift also increases the degree of component flow constriction caused by scaling and the accumulation of paraffin crystals. These techniques also require an abundant supply of gas to e stored at the surface. Gas that is separated and vented is not easily retained for re-injection. Gas that is re-injected also quickly becomes contaminated by oxygen, carbon monoxide and hydrogen sulphide that can rapidly cause corrosion to the production string components.

The Progressive Cavity Pump (PCP), a closely related cousin to the ESP, consists of a helical bore that rotates inside a similarly helical cavity. The rotation creates cavities with negative pressure (vacuum) to open and close forcing fluid up through the pump body. The PCP offers excellent performance in extracting crude oil at high viscosity. However, the PCP's are vulnerable to damage from abrasive materials and are limited to well depths of 5,000 feet. In addition, PCP's do not perform well in deviated wells.

Power Supply and Cabling Requirements

For any process engineer required to design systems for offshore drilling rigs, the extensive mechanical considerations for downhole equipment and techniques are only the beginning. One must also spend a great deal of time configuring the desired system to run on a certain power supply and control. One common hindrance to the operation of ESP's in downhole operations deals with controlling a motor from an excessive distance from the power supply. Substantial power losses occur in conducting power across a cable that can extend as long as 15,000 feet – nearly 3 miles. This is an inherent requirement, due to the nature of offshore production, that cannot be overcome.

Proper selection of cabling can greatly enhance the overall system performance. Numerous difficulties such as common mode currents, noisy ground currents, electromagnetic interference and cable cross-talk are common in offshore operations especially when motors are controlled by high frequencies of 50-60 Hz. – mainly due to poor cable configuration. Common ESP cabling incorporates a construction consisting of three insulated current-carrying conductors, one per phase, a single, randomly wound, uninsulated copper grounding conductor, and a basic overall polymeric jacket surrounding the core. An unequalized ground potential and stray capacitances develop between the three-phase conductors and the single grounding conductor and because of this asymmetry, the magnetic fields from these phase conductors do not completely cancel. This stray flux generates common mode currents that return to the inverter causing noise and subsequent tuning problems that interfere with the inverter response time. This problem can be mediated by including three fully insulated grounding conductors, one per phase, symmetrically placed with the phase conductors, all contained within a continuous interlocking aluminum sheathing encased in a polymeric jacket. The arrangement allows for better flux cancellation between the three phases and the aluminum sheathing will reduce the incidence of stray electromagnetic interference that can still occur at higher frequencies and that can resonate across adjacently routed cables.

Diesel generators have historically provided power supplies for offshore rigs. It is very rare that offshore activity has been so extensive or been in such close proximity to an onshore power generating station that a sub-sea cable could be considered feasible. In general, generators usually supply a voltage rating of 380 or 460 V and yet the horsepower requirements of ESP's tend to require much higher voltage ratings between 950-1200 VAC. This is mainly due to the torque and horsepower required for the motor to force crude oil/gas and water mixtures from as deep as 5000 feet. Many global suppliers of ESP systems offer variable frequency drive systems as complete packages for their systems. However, these systems tend to fall into the low voltage category because they require a portable power supply fed by 380-460 VAC diesel generators. This poses an unusual challenge in selecting an appropriate power supply for ESP;s in that the motor ratings are too high for a low voltage supply and yet too low for a medium voltage one. Medium voltage solutions are intended for use in applications requiring a supply of 2400-7200 volts. The service duty of an ESP motor requires a drive system or starter with a high degree of versatility to accommodate rotational operation of several ESP motors, often with different ratings. In short, the system must be capable of being retuned or recommissioned every time a motor was removed, repaired and replaced. This demands an “ease-of-use” factor that is critical for offshore rig personnel.

Due to the prohibitive expense of procuring new equipment, it is common for rig operations to be limited to retaining existing motors and generators when trying to optimize their production. As part of the equipment selection process, limited control room space is a considerable design requirement in offshore operations for obvious reasons. The system enclosure would require as small a footprint as possible without compromising ample space for maintenance accessibility and heat dissipation, as well as additional space required for optional equipment such as transformers, line reactors or filters. This space requirement sets serious limitations as to the choice of systems especially when selection of a medium voltage solution is required. A system enclosure for use in severe environments like the North Sea, Bohai Bay (China) or Campos Basin (Brazil) would definitely require a weatherproof configuration. Weather conditions in these areas are notorious for being extreme – destructive storms, high waves and excessive ice packs. Many an offshore rig has met with disaster as a result of these severe conditions. Even under the mildest of circumstances, any power supply enclosure in these environments would be extremely vulnerable to ingress of moisture and dust.

Power Generation

Due to the location of most offshore production rigs, the nature of the power supply is rigidly dependant on a portable source, namely that of the diesel generator. Onshore, generators are used primarily as back-up sources of power and are often run continuously on standby and in parallel to a standard line supply, for institutions where total loss of power can be disastrous (such as hospitals, etc.). However, in a situation where generator-fed power is the primary supply, strict design requirements must be acknowledged in order to prevent costly ad time-consuming failure and/or redesign and retrofit. Selection of the generator itself requires careful calculation of the system(s) it is meant to power. Power consumption data needs to be gathered over an extended period of time and peak periods need to be identified to properly select a generator to meet the current and voltage demands required by a given system. The proper selection of the actual engine to generator also requires in-depth knowledge of systems requirements.

Powering electric submersible pumps from a generator implies that the power supply is essentially, non-regulated. Generators powered by diesel engines are subject to changes in performance that can objectionably affect the generator output. A deviation in frequency of +/- 1 Hz. can result in a significant rise/drop speed and an even more significant rise/drop in torque causing the motor to either overshoot (+) or stall (-) reaching locked rotor condition that can make it difficult to restart the motor. Motors that are controlled by high-frequency square-pulse inverters like VVI or VSI’s can experience serious fluctuations in frequency as a result of repeated malfunctioning of the generator’s voltage regulator. Generators that are forced to perform under severe conditions without performing regular scheduled maintenance will gradually display reduced performance in regulated electrical output.

Engines and generators must be considered individual elements especially in systems where generator supply is the primary. Engines must supply the necessary horsepower (or kilowatts kW) and control speed and frequency in order for the generator to supply the necessary kVa (kilovolt*amperes) required to start and drive a system under a given load. Engines and generators are separate elements in a given system, but generators directly influence engine performance. If, for example, a pump/motor is positioned down a well 2000 feet and begins to develop oscillations, if the current draw exceeds that of the generator output, a regenerative condition can occur causing the engine to stall. Together, engines and generators must satisfy the high magnetizing current draws (the reactive component of the equipment in terms of kVAr) of a given ESP system.

Power supplies fed by generators require the generator to be sized to deliver at least 65% of the rated voltage at motor startup to enable proper starting torque. Due to excessive cable lengths and the inherent mismatching of the surge impedance of the motor to its power supply/control a reflective or transient standing wave phenomenon can occur that can result in voltage peaks at the motor terminals two times that of the originating waveform. This causes severe voltage and frequency variations that can cause severe internal stresses to the motor and deterioration of the motor’s insulation. Severe mechanical damage can occur to the motor if the generator is not running at normal frequency levels when the motor is started, or if the generator is shutdown or is allowed to run out of fuel before the motor is shutdown. There is a high risk of damaging the motor’s thrust bearing if the generators are allowed to coast down to zero speed with the motors still connected. The ideal system for controlling motors in downhole systems powered by generators would be capable of starting and stopping the motors with greater flexibility than just by the standard across-the-line methods. In addition, a system capable of variable frequency control on a continuous-duty basis would optimize the yield of ESP systems while minimizing the potential for mechanical failure.

Starting-Duty versus Continuous-Duty

As part of any downhole application of ESP motors, it is necessary to determine the service duty of a given system. Full voltage (across-the-line) operation is without doubt the simplest method available. However, when difficulties begin to arise, it is necessary for the process engineer to examine all the available technologies in downhole equipment. One of the most common problems experienced with ESP's is the frequent incidence and high cost of downtime coupled with the obvious loss of production – namely the extraction of crude oil from a deep well. In identifying the necessary solution, it needs to be determined under what classification of service duty the ESP system falls – starting or continuous duty. The starting of ESP motors can demand from the system as much as 600% of its rated torque. This can cause serious drop in voltage and current to any other equipment running on the same generator-fed supply. High torque starting requirements in pump applications are common in onshore industrial processes. With their offshore counterparts, they share some common problems related to high torque starting requirements and solutions. The "water-hammer" effect and pressure surges are common in pump application that require fluids to be conveyed up a vertical column from a motor standstill condition and stopped without the falling fluid forcing the motor into a reverse rotation. A check valve is usually installed to prevent such occurrences. However, a split-second delay in the closing of the check valve, on systems conveying large volumes, can still result in an undesirable effect. In offshore applications, the length of this column can be substantial – several thousand feet. In onshore applications, it is a common practice to start a motor under reduced voltage – to ramp up the motor speed and torque and to ramp down when stopping the motor. This effectively overcomes these effects.

Use of fluid coupling as a hydro-kinetic linkage between motors and driven loads is fairly common in industrial processes where solid materials are being conveyed or milled. Fluid coupling is generally used to reduce mechanical stress and the frequency of repair. Fluid couplings can be very expensive to retrofit, design intensive, require a great deal of maintenance and are generally considered "over-kill" in relatively low torque applications that only handle fluids. However, the task of extracting crude oil from deep wells has seen some ESP suppliers include a specially designed fluid coupling as part of their offerings in downhole production string components. The fluid coupling provides some separation of the motor from the driven load. Since there is no rigid contact between the output of the ESP motor and input to the pump, any forces acting counter to the rotation of the pump, such as a hammer effect at motor shutdown or during a stall condition, will not adversely affect the motor.

Electrical solutions to downhole application problems are quite numerous. Devices such as Solid-State Reduced Voltage (“Soft”) Starter, Autotransformer or Reactor will all provide starting solutions with torque control, but lack the capability to independently overcome thermal limitation, cable length and line harmonic issues. As an example, Soft-Starters are limited to a certain number of starts per hour and Autotransformer, even fewer. In addition, these options may require additional control space in order to allow for ample heat dissipation. None of these options can directly overcome issues with respect to cable length or the power losses and destructive energies that can be generated. Line harmonics are generally not an issue when dealing with starting options, except when the acceleration to full load speed falls into the 30 to 120 second range, at which point the primary concern would be that of the integrity of the motor. It should be noted that Soft-Starters do generate harmonics at startup due to the switching nature of the SCR inverter devices. The duration of this distortion is brief – only until the motor reaches full load speed and achieves the transition to full voltage and the intensity is generally considered to be at acceptable levels. All options can effectively reduce the degree of voltage dip or flicker at startup, but can compromise on the starting torque of the motor, requiring greater times to reach full load speed and forcing the motor to quickly reach its thermal limitations. These options require precise design and application of motor data. Invariably, the motor data will determine whether or not one of these options could be successful or even applicable. A general rule of thumb is that if a motor cannot be started and accelerated to full load speed under full voltage, none of these reduced voltage options will be successful either. In addition, these options often require new motors of special configuration supplied with precise nameplate data. Establishing accurate nameplate data on an older ESP pump/motor cannot be done easily or cost effectively. Exact calculations are required when considering applying a Soft-Starter to an older downhole AC submersible motor. The relationship between torque and current with regards to reduced voltage starting of submersible induction motor is a considerable design requirement. When starting an ESP under reduced voltage, one also reduces the available torque to driven load by the square of the voltage. Such a condition would dictate that the total system inertia be limited to a minimal initial torque requirement (by starting unloaded) and marginal inertial load. ESP’s were designed to start under full load and any attempt to start the ESP with no load would cause the motor to overspeed, causing motor protection devices to trip and possibly causing damage to the motor.

Electromechanical devices like autotransformer and reactor are limited to starting duty only and provide no means of deceleration control. Soft-Starters are only capable of starting and stopping loads gently and limiting the amount of inrush currents to the motor. Soft-Starters are programmable gate-driven controllers that use the same SCR switching technology used in Variable Frequency Drives. They are, however, thermally limited to variable speed control at startup only. They must eventually perform a transition to full line voltage. They lack the inherent variable load-speed control that Variable Frequency Drives (VFD's) were designed for and do not possess the capability of continuous precision torque/speed rate control. Soft-Starters can be programmed with various starting and stopping profiles and can be very effective in avoiding pressure surges and the "water-hammer" effect that is common in many pump applications. These devices can deliver up to 600% full load current, 180%full load torque with a stepless transition startup of a submersible motor – which is more than ample for starting high inertia loads over excessive cable lengths. Soft-Starters differ from the other devices mentioned in that they can provide soft-starting by limiting current rather than directly reducing voltage.

All techniques have their advantages and disadvantages. Autotransformers provide the best torque per ampere of current ratio, but its size, expense, and thermal characteristics make it generally unsuitable for offshore operation. Reactor starters possess great acceleration characteristics at high speeds and with smooth transitions to full voltage, but are capable of in-rush currents just as severe as across-the-line starting, if the reactor becomes saturated due to poor application of the reactor to the motor. Solid-State soft starters are equipped with phase loss and stall protection, but it is a common misconception that these devices are capable of continuous, variable speed duty, partially due to the stepless transition to full voltage that they provide. In addition, because soft starters use the same SCR technology, as VFD's to manipulate waveforms they tend to create harmonic distortion until they transfer to line. All of these options exhibit performance that, depending on the application – well depth and conditions, quality of power supply and motor rating, may or may not be applicable to a downhole ESP application. These options do not provide the flexibility of infinite control across the entire torque and speed spectrums, with the added degree of motor protection, that VFD's do. Although a device capable of soft starting an ESP is definitely an enhancement over across-the-line starting, a device capable of continuous variable speed control would best optimize well extraction in offshore operations.

Variable Frequency Drive Topologies

When selecting a variable frequency drive system for a downhole operation there are several choices to take into consideration. All choices of VFD's offer the same advantages in varying degrees. A VFD offers ESP systems continuous-duty variable flow and pressure control, which in turn increases productivity, process control flexibility and energy savings. Having direct speed control over the pump motor amounts to maximum system efficiency and reduced maintenance when compared with across-the-line (full voltage) operation. The VFD provides the essential reduced voltage starting characteristics of a soft starter combined with continuous-duty variable frequency operation. This directly results in increased life of the mechanical equipment and reduced incidence of downtime. The requirement for a compact footprint can seriously limit the choice of drive system especially when a desired system required additional equipment (line reactors, filters, and/or transformers). Many international companies offer complete custom systems in a broad selection of topologies. The topologies of available systems fall into the following categories: Six Step VVI, VSI-PWM and CSI-PWM.

The Six Step VVI – (Variable Voltage Inverter) has been around since 1979. Being the most common topology for ESP's historically, suppliers of downhole systems have long since offered drives using the VVI topology. This is mostly due to the fact that the VVI is a relatively inexpensive compact (but rudimentary) low voltage solution. It is, however, a method that is not very motor-friendly. The VVI achieves variable performance solely by varying the frequency of the inverter, capable of 2000 Hz. typically. It employs a variable voltage inverter consisting of a silicon-controlled rectifier linked via a variable DC bus and chopper circuit to a variable voltage rectifier. Although the VVI does offer variable frequency control and improved motor performance when compared to that of full voltage, the output waveforms tend to be of poor quality. The amplification of these waveforms by a step-up transformer (to boost the voltage from the generator fed 380 or 460 V up to the standard 950-1200 VAC ESP rated voltages) would result in very high dv/dt stresses that occur as a result of reflective wave and the destructive forces that can cause deterioration in the motor insulation. The higher the frequency and the greater the surge impedance mismatch between the motor and the drive, the greater the severity of reflective wave and resulting partial discharge/corona effect on the motor. The industry mindset at the time of VVIs inception was to re-enforce the design of the downhole pump motors rather than to seek better solutions for power supply and control. The VVI would have little or no effect of alleviating the downtime of any offshore ESP system. However the VVIs relatively high degree of placement in the field is mostly due to familiarity and convenience. Process engineers engaged in such offshore activity considered it more cost-effective to send a motor off every 6 months (at best) to be repaired than to invest in a better control system. This is partially due to the high-risk nature of offshore exploration. The VVI generates a fairly high total harmonic distortion (THD) of current that causes excessive motor heating and decreased performance. This inherent THD also causes cogging of the rotors at reduced voltage, low speeds. There is very little evidence to suggest that the VVI offers any real advantages economically (beside a very limited variable frequency control) that make it a better alternative to full voltage. Global suppliers of variable frequency drive systems (non-exclusively to ESP systems) generally do not offer Six Step VVI systems for their applications, favoring instead more modern topologies in medium voltage products.

Medium voltage drives operate by converting three-phase fixed main system AC voltage to DC voltage. An identical DC voltage pattern is induced into a three-phase inverter that is electrically opposite the rectifier and is used to reconstruct the AC wave form by means of high speed switching of high current semi-conductors called silicon controlled rectifiers (SCR's sometimes called "thyristors") and gate turn-off thyristors (GTO's). The inverter reconstructs the AC waveform at frequencies typically from 5-70 Hz. Inverter frequencies of 200 Hz. are available on some medium voltage drives. This high speed switching emulates the mechanically –driven, rotor-induced bi-polar switching of magnetic fields that generate alternating current, with the added ability of modifying the output frequency.

The inverter converts the variable DC voltage back into AC (as variable three-phase) where it is supplied to the motor or pump. There are two main topologies available in medium voltage drives that vary in the manner the DC voltage is conveyed to the inverter, the manner in which the inverter converts the DC voltage back into a reconstructed variable AC waveform and the type and characteristics of the resulting waveform that is produced. Both topologies attempt to produce waveforms that are virtually sinusoidal and both have inherent advantages and disadvantages which reveal important design criteria necessary to consider when applying a medium voltage solution to any given motor application. The two main topologies available for medium voltage drives are the Voltage Source Inverter (VSI) and Current Source Inverter (CSI). These topologies are also available in 6, 12, and PWM (Pulse Width Modulation) configurations. The more sophisticated and efficient PWM configurations will be discussed due to the enhanced degree of these configurations to mediate certain application-specific design problems.

The VSI-PWM – (Variable Source Inverter – Pulse Width Modulation) topology utilizes a rectifier and inverter section that includes a large capacitor between them and an inverter device known as an integrated gate bi-polar thyristor (IGBT). This arrangement generates a high switching frequency that enables the capacitor to quickly supply, with little impedance, instantaneous currents to the inverter when rapid changes in the motor performance are requested. The VSI-PWMs inverter output response time is 3-5 times (greater than 30 radians per second) that of the CSI-PWM, however, the VSI-PWM requires exact matching of the motor to the inverter. Due to the difficulty in determining accurate nameplate data on existing motors and anticipating the performance under certain conditions for derating, procurement of new motors is usually recommended when selecting the VSI-PWM topology for a drive system. The requirement or retain existing motors due to the prohibitively high cost and extraordinarily long lead times, usually rules out VSI as an option. In terms of actual performance, the VSI-PWM generates fairly high dv/dt thermal stresses and total harmonic conditions, which can seriously affect the performance and longevity of the motor without the aid of some additional line filtering equipment.

The high frequency switching nature and square-pulse waveforms of the VSI-PWMs inverter IGBT's generate numerous problems in downhole applications, which are difficult to mediate. These problems are both mechanical and electrical in nature and can seriously affect the longevity and performance of the motor. The fast fall and rise times of the inverter devices and the varying widths of modulated pulses do not allow for instantaneous and complete cancellation of the voltage waveforms like a balanced 60 HZ. three-phase application would. The result of this being the generation of a common mode voltage that occurs between the inverter and the ground. This common mode voltage in turn generates induced shaft voltages in the motor. These voltage transients (dv/dt) also interact with the circuit impedance of the inverter, the three-phase power supply cables and the relative impedance of the motor to generate high frequency common mode currents (CMC's). These common mode currents increase with the degree of dv/dt and the inverter frequency. In keeping with basic laws of electrical theory, these common mode currents seek the path of least impedance to ground while returning to the inverter. In many cases, these paths can become the shafts and bearings of the motor and all of its connected equipment. At high frequencies, the mechanical equipment itself can become conductors of capacitive reactance. If the CMC's become sufficient enough in magnitude, early deterioration of the bearings can result causing premature mechanical failure to the motor and connected equipment. In addition to CMC generation, the VSI-PWM also generates waveforms that become seriously distorted by the reflective or standing wave phenomenon. Similar to the behavior of wave motion in water when an object interrupts a wave, the wave changes its direction and "reflects" back onto the originating wave. Thus, its amplitude peaks become the sum of the originating wave and the reflected wave. Therefore, in the reflective wave phenomenon, voltage peaks at the motor terminals can be two times that of the output waveform. These peaks can be particularly detrimental to the motor at startup. The source of the reflective wave is a mismatching of the surge impedance's of the motor and inverter, as well as the capacitance of the motor at startup and is further aggravated by excessive cable length (and/or improper selection of cable). The voltage peaks at the motor terminals are most severe at startup and because they occur with every inverter switching incident they can continue to occur, depending on the inverter frequency, albeit at acceptable levels. Two by-products of the reflective wave effect are partial discharge/corona – these two terms are often used interchangeably. These two effects have serious destructive potential that can damage the motor insulation. Partial discharge/corona occurs when a localized portion of the motor insulation begins to break down and is directly related to the excessive voltage peak that is generated by the high frequency square-pulse waveforms. It occurs as a result of electrostatic fields surrounding oppositely polarized conductors that begin to strip electrons from the surrounding air gap leaving molecules with a positive electrical charge (ionization). These ionized particles bombard the insulated surface of the motor windings gradually causing loss of material and deterioration. In addition, the insulation is also attacked chemically by ozone, which is a by-product of ionization. The ozone combines with nitrogen from the air to produce forms of nitrous oxides, which corrosively attack the insulation causing embrittlement and eventual fracture. In addition, the partial discharge/corona also creates hot spots in the windings caused by voids or air bubbles that were formed in the insulation as the dielectric resin was being applied during manufacture. As both partial discharge and corona effects continue to attack the insulation, eventually they will expose bare wire causing arcing to occur from phase to phase or phase to ground.

The waveforms generated by the VSI-PWM are, however, considerably less stressful on the motor than any low voltage drive topology like the Variable Voltage Inverter (VVI). The VSI topology is best optimized in applications that convey, crush or separate solid raw materials that vary in consistency, weight or density, where instantaneous response can be required from the inverter and where cable length between the drive and the motor is not excessive. However, due to the high speed switching nature of the VSI-PWM and resulting common mode currents and reflective wave effect, severe oscillations can occur at startup and power losses and surges can be excessive enough to interfere with inverter response time. For this reason a more continuous, smoother inverter operation for a downhole electric submersible pump system is preferred. This can best be achieved by selecting a topology that generates waveforms that are virtually sinusoidal. Such a waveform would mediate most of the problems incurred and/or aggravated by the use of high frequency square-pulse inverters.

The CSI-PWM – (Current Source Inverter – Pulse Width Modulation) topology offers a list of features to a medium voltage solution that make it the ultimate system for productivity, flexibility, and motor protection. This topology incorporates an inverter that demands all current required through a large DC link reactor. This places high impedance on the circuit between the inverter and the rectifier and results in a decreased response time to that of the VSI-PWM. The inverter converts the DC link current back into variable frequency alternating current that is supplied to the pump or moor. The switching of the GTO's transfer the DC link current to the AC output terminals in an output waveform that is dependent on the timing of the switching. The CSI provides tighter, smoother control over fluctuations in motor performance where quick responses are not an issue, such as fan or pump applications. The CSI-PWM is a less complicated and less expensive alternative. The CSI-PWM generates motor-friendly output waveforms at all loads and speeds, because it operates at frequencies closer to that of the actual motor specifications and incorporates the use of a motor filter capacitor and inductive components of the motor load cables and stator windings, to create a balanced 60 Hz. three-phase variable speed motor application. This arrangement efficiently converts variable duty-width square pulses into pulses that are virtually sinusoidal and that exhibit a Total Harmonic Distortion (THD) of less than 5%. Due to the refinement of the waveform, an AC motor under the control of the CSI-PWM does not suffer the same degree of waveform distortion and destructive energies such as reflective wave, common mode currents, induced shaft voltages or partial discharge/corona. These effects are almost completely mediated with a sinusoidal waveform. The remaining 1-5% of incidences remaining are well within acceptable limits and can easily be eliminated by the use of additional equipment.

In terms of overall system features, the CSI-PWM brings to medium voltage drive technology inherent over-current protection, regeneration capability, fuseless power structure, low component count and the capability of operating motors on cable lengths up to 15 km with only marginal power losses when tuned correctly to a given motor. In addition, modern interfaces for CSI-PWM's allow for the operator to easily auto-tune or manually tune a drive system to a given motor. This greatly facilitates the rotational use of ESP's on offshore operations, thus minimizing downtime. The CSI-PWM in its 6, 12 and PWM configurations have all been proven to reduce operating costs and mechanical failures wile extending motor longevity. With the additional use of an isolation transformer, the CSI-PWM can be used on existing motors including ESP's without the added requirement of modifying them or replacing windings. Harmonics are generally not an issue in offshore applications with respect to compliance with regulations because they are powered by generator and not by a governing utility and are, therefore, unofficially exempt. However, in applications where new drive installations must comply with regulator guidelines regarding line harmonics, an isolation transformer will provide cancellation of the principle 5th, 7th, 11th and 13th harmonics by using phase shifting of the secondary voltages. To further enhance the attributes of the CSI-PWM drive topology, all of these features are applicable to both induction and synchronous motors, old or new.

Conclusion

In conclusion, the design requirements for ESP systems require extensive and careful consideration when trying to mediate specific application problems. When trying to reduce downtime and increase production, identifying the system duty of the motors is the first step in selecting a proper starter or variable frequency drive solution. It can be seen that some solutions present as many functional disadvantages as they do mediate. It is the difficult task of the process engineer to gather all the information, weigh all the evidence and properly apply the chosen technologies to their existing systems. Selecting a good solution provider that offers the same attention to quality technical support as they do manufacturing cost effective top of the line motor controls products is critical in achieving one's objectives in such projects. Such a provider is Rockwell Automation, who offers an extensive line up of Allen-Bradley medium voltage starters and variable frequency drives. The Allen-Bradley Bulletin 1557 MV drive has been a mainstay for years in every industry utilizing AC motors for industrial processes. The Bulletin 1557 offers a CSI-PWM topology that is unprecedented in improving motor control and mediating process control problems. The smaller Bulletin 1557M Mini-Drive offers the same superior technology of the CSI-PWM into a drive system enclosure that requires less than 20 square feet of valuable control room space. To this impressive technology and improved component design that allows for application in the most severe environments. Allen-Bradley drives and starters are also backed by the extensive network of Rockwell Automation Global Technical Services, who provide fast, courteous response from trained service engineers anywhere, anytime – 24/7. In addition, all systems can be interfaced to allow centralized control and remote monitoring through a motor control center. All systems are available in NEMA enclosures that are ideal for the severe environment of offshore operations. The increased output and reduced operating costs of using Allen-Bradley products can also be greatly enhanced by the increased efficiency in overall system performance as well as making the compilation of process control, duty cycle and machine performance data much easier to manage. This in turn enables effective service and maintenance scheduling. In the field of offshore oil operations, incidences of downtime are very expensive. With ESP systems under the control of Allen-Bradley medium voltage drives and starters, instances of downtime can be greatly reduced, if not eliminated.

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