CONSIDERATIONS FOR APPLICATION OF ELECTRICAL SUBMERSIBLE PUMPS FOR UNDERGROUND COAL MINE DEWATERING

Michael L. Nave P.E. Member
Consolidation Coal Company
P.O. Box 1314
Morgantown, WV. 26554

Abstract - At mining depths beyond 800 feet, electrical submersible pumps become an economic alternative for coal mine dewatering. Pump Configurations differ from Fresh Water or Petroleum applications. Coal Mines are regulated by the Mining Safety and Health Administration. Power supplies are resistance grounded. Controls are implemented by a combination of commercial and custom techniques. Pump reliability is affected by downhole conditions, logical controls, and clear operator interface. Successful pump application is dependent on the site specific requirements addressed by the mine operator.

INTRODUCTION

Electrical Submersible Pumps have been utilized for many years in lieu of line shaft driven vertical turbine impeller pumps when depths exceed 500 feet. [1] Common applications include fresh water aquifer pumping and petroleum well production. In the classic configuration the electric motor driver is on the bottom and the multiple stage pump close coupled on the top of the Electric Submersible Pump (ESP). The fluid flows up the well to the pump suction past the motor.

Traditionally, mine pumps have been close coupled or line shaft driven vertical turbine impeller pumps for high discharge heads. Modern Longwall mining techniques have made the recovery of deep seams economically feasible. Longwall Mining creates large areas of "gob", or waste seam blocks up to 1,000 feet wide by 10,000 long. Caving creates strata breakage from the seam to the surface which promote water inflows. Seam depths commonly exceed 800 feet. Geologic conditions and strata subsidence make it difficult to drill a pump hole with casing of sufficient vertical straightness to house a line shaft driven pump assembly. If water is allowed to rise in the gob area behind the longwall face, it can possibly block bleeder ventilation of dangerous gases, primarily methane, to the discharge bleeder fan on the downdip seam rear of the longwall panel. In Coal Mine applications, the ESP is positioned below the coal seam. Water flows from the horizontal seam into the well casing perforations above the ESP and down to the pump inlet. Pumps are operated in a pump down, or cycling manner.

The severe conditions and service requirements demand a high reliability pumping system. The ESP requires some special considerations for successful application to coal mine dewatering.

PUMP CONFIGURATIONS

Mine water varies from neutral to very acid, PH from 7 to 1.5. Almost all mine water is abrasive, due to suspended solids.[2] Consequently, many pumps and motors are constructed of corrosive resistant materials such as stainless steel. For high solids pumping, pumps are constructed of wear resistant materials.

With the ESP positioned below the coal seam in a flooded casing, cooling of the electric motor on the bottom is of concern. Normally, a shroud is placed around the motor up to the pump inlet that forces the water to flow down the well casing around the shroud lip and up to the pump inlet as shown in Fig. 1. Velocity must be at least 1 foot per second, but no more than 8 fps, to insure turbulent flow for adequate cooling [3]. Since the hole is below seam, it accumulates solids that can block the shroud inlet.

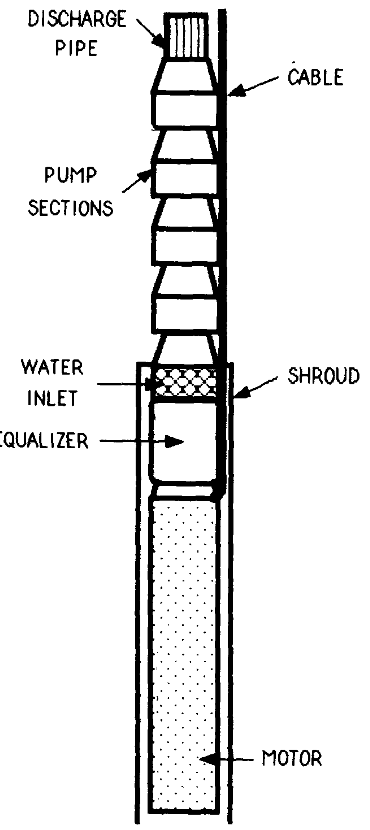

Fig. 1. ESP Configuration

Recently, certain prototypes have been developed for mine applications with the motor on the top and the pump on the bottom of the configuration [4]. This Upside-Down design is shown is Fig. 2. This places the motor up out of the mud debris in a full flow cooling stream. It does subject the motor seals to the high pressure of the pump outlet.

ESP motors are designed for a small diameter borehole. The two pole stators are continuous coils. Rotors are made of small sections that stack for higher horsepower. Air gaps are as small as .014 inch [5]. Motors designed for fresh water service are water filled. Stator temperature rises are limited to 180 degrees Fahrenheit. Motors designed for oil wells are often mineral oil filled, with maximum stator temperature rises limited to 300 degrees Fahrenheit. Mining applications can benefit from higher motor withstand temperatures since cooling paths along motors become coated with interferents such as iron sulfates. Motor voltages vary from 440 to 3000 volts AC. Motor amperages are as large as 400 amps at 440 volts in fresh water style pumps, and limited to 100 amps in higher voltage oil well style motors.

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ESP supply cables for freshwater wells are usually PVC insulation in a triplexed three conductor assembly. ESP cables for oil wells are usually three conductor high temperature insulations with an overall armored jacket [6]. Oil well cables are designed to operate in high ambient temperatures with low gas infusion into cables. Cables for mining applications are usually flat cable assemblies of a G-GC construction with EPR or Hypalon jacketing. Mining requires a ground wire to the pump assembly with a dedicated pilot ground check wire. For cables applied at voltages above 600 volts, the individual phase conductors are shielded with a copper or stainless overbraid shield. This precludes phase to phase faults downhole without involving phase to ground first. The power supply is resistance grounded to a low amperage ground current and protected by a sensitive ground fault protection relay. For larger cables than #2 awg, in order to reduce well string diameter, individual phase conductors with a separate ground are arranged in a side by side pattern attached to the pipe string with banding clamps at specified intervals. When the ESP is handling acid discharges, fiberglass type discharge pipe is used to support the pump string. Since this type of pipe has limited thread strength, the cable supply must be limited in total hanging weight. Pumps are being specified in higher motor voltages to reduce cable sizes.

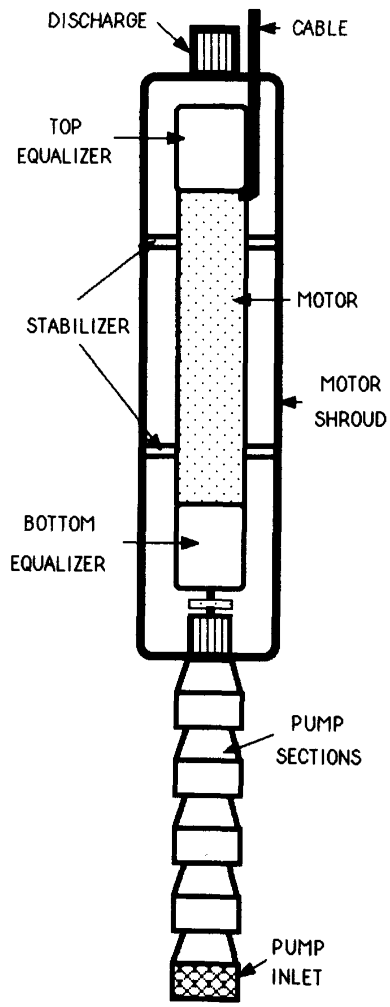

Fig. 2. ESP Inverted Configuration

CODE REQUIREMENTS

Coal Mines are regulated by the Federal Mine Safety, and Health Administration, and by individual State Departments of Mines. The applicable Regulations are listed under the Code of Federal Regulations, Title 30 [7]. Parts that are of particular interest electrically include Part 75, "Mandatory Safety Standards - Underground Coal Mines", and Part 77, "Mandatory Safety Standards, Surface Coal Mines and Surface Work Areas of Underground Coal Mines". The National Electrical Code applies on the surface, but exempts underground mining under Article 90-2 [8].

The portion of the pump circuit that extends underground through and into the coal seam must comply with Part 75. This requires the power supply to be low resistance grounded to a separate ground bed. The pump must be grounded by a continuous ground wire extended from the ground bed to the pump motor. To ensure that the ground wire is continuous, Part 75 require a fail safe ground wire continuity monitor.

The surface portion of the circuit can be treated as a permanent circuit or a portable circuit under Part 77. Usually, due to the nature of the cable exit from the pump hole, it is handled as a portable circuit. The surface portion is also regulated by the National Electrical Code. This determines ampacity requirements for the pump circuit supply cables.

If the ESP circuit is over 1000 volts, then the requirements of Part 75 and Part 77 that refer to High Voltage apply. Most high voltage ESP circuits extending underground can be considered permanent equipment since the ESP and cable assembly are housed inside a metallic borehole casing. The designer must confirm that the borehole casing that is removed in the coal seam is replaced by an equivalent metallic casing shroud.

ESP CONTROLS

Circuit Breaker

The ESP power circuit is provided with a three phase circuit breaker. CFR Part 75 and Part 77 require the circuit breaker to provide protection against undervoltage, grounded phase, short circuit, and overcurrent. Depending on ESP voltages, circuit breakers range from molded case, to systems power breakers, to vacuum breakers at higher voltages. The circuit breaker is equipped with thermal and magnetic trip elements. The other protections dictated are provided by separate devices that trip the circuit breaker through a shunt trip or undervoltage trip element. When the breaker trips on instantaneous current trip, the breaker must be locked out and annunciated to prevent reclosing automatically or manually on a downhole phase to phase fault. ESP circuit breakers that are located in remote locations are often equipped with electrical closing operators to enable reclosure after a loss of site power provided all other safety devices are normal.

Motor Starter

A full voltage non-reversing motor starter is the most common ESP starter. With larger sizes and higher voltages, vacuum starters are preferred. Since the ESP motor is designed to fit in a small diameter borehole, it has a low rotor inertia. Thus, the mechanical and electrical forces on the motor during starting are severe [9]. Shaft and seal problems are common. Suppliers and users recommend avoiding repeated starting and pump- off [10]. On mining ESP's, no check valve is used in the discharge piping to allow backflushing of the lower sump hole. Start-up with an empty pipe causes severe upthrust on the pump impeller bowl sections [3]. To reduce these stresses, the ESP can be started with a reduced voltage starter. This is most effectively executed by a six SCR phase controlled time ramp starter with an initial current of at least 250 percent of full load current and a ramp to synchronous speed time of no more than 3 seconds to avoid sub-synchronous mechanical harmonics [11].

Overload

The ESP motor thermal time-overcurrent withstand curve is not similar to standard Nema T frame type motors. Thus, a standard bimetallic or eutectic Nema Class 10 or 20 overload is a poor duplication of the motor winding temperature. A programmable motor protector can model the exact time-overcurrent withstand curve of each ESP. The effects of ESP motor current imbalance can accelerate motor heating. Since the ESP motor is long, narrow, and wound for 3600 rpm with unequal winding parameters, the motor can present an unbalanced load. Motors should be test run on a balanced voltage supply before being sent downhole. Flat pump cables or single conductors arranged side by side around pump tubing present an unsymmetrical impedance to the voltage supply [12]. Mine power systems, constructed in rural and difficult terrain, can present incoming voltage imbalances. The ESP overload must be equipped with a sensitive current imbalance algorithm that accelerates overload trip times.

Surge Arrestors

ESP's at mine sites are often located at the end of long bare overhead distribution feeders. Large mining loads are distributed radial along the feeders. Lightning surges and system switching transients can damage ESP motor windings. No minimum Basic Impulse Level standard exists for ESP motor construction. A recommended surge protection system include an incoming line station class silicon oxide lightning arrestor, a series air core inductor, and parallel metal oxide varistors and surge capacitors between the motor starter and the borehole cable [13].

Motor Safety Disconnect

For low voltage (0-600 vac) ESP's, a local non-fused safety disconnect is placed near the top of the pump borehole to provide a local lockout station with visual disconnect for service work. For medium (600-1000 vac) and high (> 1000 vac) voltage ESP's, a starter three phase disconnect with a positive load side grounding feature and visible viewing window is provided.

Ground Fault

Mining ESP's are commonly supplied by resistance grounded power supplies. Traditionally, line to ground currents are limited to 15 amps. Modern sensitive ground fault zero sequence sensing devices allow for lowering line to ground currents to as low as .5 amperes depending on system capacitive charging currents and zero sequence current transformer common mode errors on pump starting. ESP cables are configured with individual conductor overbraided shields to force insulation failures in cable to be line to ground faults. The ground fault sensing device trips the ESP circuit breaker and provides a latching annunciation to warn service staff from reclosing circuit breaker on downhole fault.

Ground Wire Monitor

The ground wire monitor continually checks for the continuity integrity of the ground wire from the ESP to the safety resistance ground bed. A low ground wire impedance limits the exposed touch potential during machine line to ground faults. CFR limits this touch potential to 40 volts for low and medium voltage machines and 100 volts for high voltage machines. Ground wire monitors pass a low voltage current to the machine on a dedicated pilot wire, or send a unique tone at 3000 Hz on the three phase wires coupled and decoupled through tuned filters.

Undercurrent

For a vertical turbine pump, the driven horsepower is a function of the pumped head multiplied by the pump flow multiplied by the specific gravity of the pumped material divided by constants and the pump efficiency. Undercurrent, or current below a specific setpoint, is a reliable indicator of a low pump flow or no flow condition which occurs if the ESP "pumps off" [14]. To avoid shutdowns on spurious hydraulic or power system upsets, a 3-5 second time delay off is configured into the undercurrent algorithm. When an ESP in a deep hole pumps off, the flow tends to surge prior to loss of pool. This causes the current to oscillate below and above the shutdown setpoint, reseting the off delay timer. An undercurrent counter is configured that effects a shutdown when this cycling occurs a set number of times within a periodic sliding window. Undercurrent is a normal shutdown on small ESP's, and a back-up to level control fault shutdown on larger ESP's.

Flush Back Timer

Mining ESP's installed with no check valve in the discharge piping allow reverse flows after shutdown to enter the lower ESP hole at high velocities to flush out sediments. Since most ESP holes intake outside air to mine workings, this practice also prevents winter freezing of the discharge column. A flush back timer is configured to prevent pump re-start during pump backdriven reverse rotation.

ESP Temperature

The ESP is sensitive to downhole motor temperature. Mine water deposits iron sulfates on the motor surface, impeding the cooling efficiency of the water flow. Repeated starts raise motor temperatures. A thermocouple or RTD is inserted in the stator water or oil cooling bath. This temperature is conveyed to the surface as a 4-20 ma instrumentation current loop in a twisted, shielded cable to a readout with shutdown setpoint alarm. The highest temperatures for each motor run cycle are recorded. Any upward trend indicates gradual loss of the motor cooling path.

Level Control of Pool

To extend ESP life, it is important to minimize the number of pump cycles where "pump off" shutdowns occur. This requires downhole sensing of the pool level within the pumped mine seam. A common sensing device is fixed location resistivity or capacitance probes. These perform adequately where suspended solids and silt build-up is low. Downhole level can also be sensed by inserting a submersible pressure transducer to at least the bottom of the seam. Since the measured pressure is proportional to the water depth multiplied by the water density, pool depth can be calculated. Most mine discharge water has a specific gravity below 1.1. A fixed submersible pressure transducer, however, can be covered or blocked by solids. In severe conditions, a downhole bubbler pressure sensing system is used. Here, a constant regulated air pressure source provides a small sensing flow directed down a sensing stainless or Teflon tubing to the bottom of the seam where it is allowed to escape at a sense hole. When water rises over the sense hole, the resulting back pressure is measured at the supply end at the surface. This pressure is the sum of the pressure proportional to water depth plus the pressure drop from the air flow in the tubing from surface to seam minus the negative seam air pressure resulting from the mine ventilation fan. The tubing pressure drop and seam pressure can be measured by pumping water level to below the sense hole. To prevent silt from blocking the sense hole, high pressure 100 psig purge air is blown through the tubing periodically. The purge period and duration is adjusted for conditions. The ESP level control system is operated in a pump down operation with fixed start and stop points in seam. The ESP control system records and displays the average time from high level to low level for pump down. A change in average cycle time indicates an alteration of pool inflow in seam or ESP pump wearout. Total pump run time is recorded.

Interlocking

The pumped water is discharged to a water treatment plant at a rate from 200-2000 gpm. This plant corrects PH, aerates, and removes suspended solids. The ESP must be interlocked to plant control schemes that confirm that the plant is prepared to treat water.

The mine seam is ventilated with outside air to dilute methane and airborne coal dust produced at the mining face. Within 15 minutes of any loss of positive ventilation flow from any fan, all electrical power must be removed from the mine seam and ESP. The ESP can not be re-energized again until an examination by a certified mine foreman of the mine area is made after restoration of normal ventilation.

Automation Controller and Annunciation Display

To effectively execute control logic, fault response, and annunciation, a programmable controller is provided for ESP control. Programming languages are a form of ladder logic. Programmable controller memory requirements for ESP control vary from 1 to 3 K of 16 bit words. RAM memory is lithium battery backed with EEPROM storage for program transport. Input/Output requirements vary from 32 to 128. Most I/O is digital "on/off". Analog I/O include ESP amperage, temperature, and pressures. The programmable controller is hardened for the mine environment for temperature, dust, and vibration.

Operator annunciation is provided by indicator lights on small ESP installations. Lights have four indication states; On, Fast Flash, Slow Flash, and Off. On larger installations, a 2 line by 20 character text display provides English message prompting of all alarms and operator directions. The message unit has from 8K to 32K of RAM memory. At unattended locations, the data display can also store an alarm list for later review .

NEED FOR DEVELOPMENTS

Mining ESP installations will require some design improvements in order to achieve high reliability. The following problems and items need new development work:

- ESP motor coating by insulating solids;
- Pump plugging and wearout by borehole solids;
- Material deterioration by acids and abrasion;
- Motor stator temperature limits are too low;
- Flat cables with high voltage insulation and shielded phase conductors;
- Molded cable attachments to mount cable to discharge pipe;
- Downhole sensors for pressure, level, and temperature;
- Serial communication package to send sensor information from pump to surface via instrumentation cable or the power conductors;
- Molded case circuit breakers with improved electrical reclosers;
- ESP reduced voltage starters with ramp up, ramp down, and automatic phase voltage balancing;
- A combination programmable overload with temperature input and sensitive ground fault protection;
- Fiber Optic downhole level sensors for use in methane atmospheres;
- Pump performance monitoring hardware and software that can predict motor or pump wear;
- Non-Electrical powered submersible borehole powered pumps for hazardous locations.

CONCLUSIONS

Deep coal seams require mine dewatering pumps of high capacity, high head, and high reliability. Mining ESP's are a physical adaptation of a fresh water or an oil well ESP. In order to pump from a horizontal coal seam, special pump configurations are required. Downhole conditions are severe. Mine water is acid and carries suspended solids. Electrics on Mining ESP's are regulated by Federal and State laws. Safety requirements are extensive. Surface located ESP electrical controls are a major factor in pump reliability. The electrical designer must examine the particular mine requirements in order to apply effective ESP controls.

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