PERMANENT MAGNET MOTOR RISK ASSESSMENT IN OIL & GAS OPERATIONS

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ABSTRACT

In an effort to address safety concerns, permanent magnet motor (PMM) manufacturers and operators have worked together and developed API 11S9 Recommended Practice for PMM Safety that covers many of the safety issues relative to PMM operations in Electric Submersible Pump (ESP) applications. The PMM is a very good generator due to “always on” permanent magnet rotor so it presents a risk of electric shock and potentially arc flash (AF) hazards if rotation occurs when service personnel handle the ESP cable or junction box conductors at surface. A detailed study of AF hazard suggests that the PMM in various sizes does not present an AF risk leading to a more conventional choice for the required level of PPE for service personnel. There is still a similar risk with traditional induction motors (IM) but not as severe as with the PMM. The primary method to avoid shock hazards is to shunt the ESP cable leads which forces a braking torque and to ensure an EquiPotential Zone (EPZ) is created at surface. Implementing an EPZ surface significantly reduces hazardous potential differences in the vicinity of the PMM surface ESP cable connections, thereby lowering the risk of electric shock to workers.

Other methods developed recently attempt to block flow thru the pump or to lock the motor or pump shaft. Of the 20,000+ PMM installations in the past 15 years, almost all were safely installed by shunt method and without additional devices intended to prevent inadvertently rotating the motor. Doing a thorough risk analysis can help to determine if additional engineering controls are required to mitigate risks. This analysis ensures that we don’t introduce complications on installing, operating, troubleshooting and pulling an ESP. The paper concludes with a summary risk assessment, procedures and implemented training. This advanced safety strategy can be adapted across various industries utilizing these motors.

INTRODUCTION

Evaluation of ESP workovers (WO) includes run-in-hole RIH and pull-out-of-hole POOH, or install and pull, respectively. Operation and troubleshooting when using a PMM have certain considerations. The RIH JSA has more emphasis and time taken to ensure equipment lands in operational condition. POOH is done more rapidly and has variability in risk condition based on how the unit failed. Previous paper on this topic covered procedures and how these might change when running a PMM versus an IM. The latter still has some voltage generation when auto-rotated of 30 - 80 volts due to residual magnetism and the long ESP cable capacitance, similar to the choke on alternator charging automobile 12 volt battery. This effect is basis for ESP back spin detectors in variable speed drives (VSD’s). While IM voltage generation is not inconsequential, the voltage potential with a PMM is much higher so steps needed to prevent rotation or mitigate effects if rotation happens - due to fluid flow thru pump. The main method to prevent PMM rotation is to shunt the motor leads. If PMM motor leads are not shunted, the shaft is not locked or flow to the pump is not blocked, it can and will spin up to high rpm yielding a significant voltage level that can lead to injury or death.

ARC FLASH CALCULATIONS AND METHODOLOGY

The electrical system examined consists of a utility feed at 13.8 kV transformed down to 480 V to allow connection to a variable frequency drive. A step-up transformer then brings voltage back up to 3 kV to limit voltage drop along the 7500' length down the well to the PMM and pump. The wellhead junction box is the last point above ground before the cables go down the well. This point is key, as it is the location where the maintenance personnel would disconnect the PMM from the VSD / utility source and be exposed to an arc flash hazard if the PMM were to rotate and provide current back to the system.

Power system modeling software calculated electrical properties of a PMM driven by the fluid head as the source for the system and the key point for the arc flash calculations being the wellhead junction box. The one-line diagram(s) in Figure 1, below shows the entire connection and the reduced model circled. The calculations under a number of scenarios summarized in the Table 1, include:

- Calculations were performed for each of the 5 most common motor sizes (400, 264, 250, 144 and 80 horsepower). As expected, greater horsepower translated into higher incident energy levels at the wellhead junction box.
- Calculations for the largest two motor sizes (400 and 264 horsepower) were made with both an unlimited (1000 seconds) arcing time and with the arcing time limited to 2 seconds. The unlimited arcing time examined if the arc would ever reach a point where it could melt the conductors at the motor terminals, in effect turning the conductors into a fuse. The arcing current never reached a level (greater than 2000 amps) anywhere on the system to damage the conductors.

Below are assumptions used to model the system:

- Most of the calculations assume the arcing time limited to 2 seconds, which is a recommendation of IEEE 1584. Per Section B.1.2, "if the time is longer than two seconds, consider how long a person is likely to remain in the location of the arc flash. It is likely that a person exposed to an arc flash will move away quickly if it is physically possible and two seconds is a reasonable maximum time for calculations."
- The calculations also assume that the PMM immediately applied maximum electrical energy to the system after removal of VSD power and fluid reversed through the pump.
- The ambient temperatures throughout the system is assumed to be constant.
- The model of the PMM as a source was considered to be higher than the same size (in horsepower) induction motor because of the higher efficiency and torques seen in PMM's, plus the fact that PMM's operate as synchronous due to no external excitation.

Below Figure 1 is a simple 1-line representing a workover condition where the ESP is disconnected from surface equipment for AF calculations with the PMM as the source. This is different than typical AF studies where the current source and incident energy comes from the electric utility which has a much higher incident energy than that available from a downhole ESP.

Figure 1. Electrical model of ESP completion.

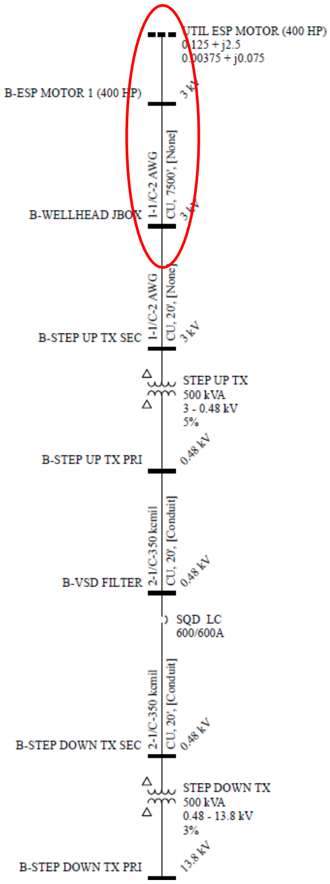


Table 1. AF results versus PMM horse power

MOTOR SIZE (HP)	ARC FLASH BOUNDARY (INCHES)	INCIDENT ENERGY (CAL./ SQ. CM)	BOLTED FAULT CURRENT (kA)	ARCING CURRENT (kA)
400	11.6	0.6	0.09	0.08
264	9.1	0.4	0.061	0.053
250	8.7	0.4	0.057	0.05
144	5.9	0.2	0.031	0.027
80	4.4	0.1	0.019	0.017

The calculated fault current at surface in Table 1 is 2 to 3 times the motor rated current. These results are very dependent on the time that it would take for the motor or cable to fail and / or service personnel to get away from hazard (2 seconds in these calculations). The data suggests the incident energy is well below 1.2 Cal/cm^2 required for CAT 1 AF rated PPE. These results should be followed with actual PMM tests which tend to be destructive so methods are being developed to safely obtain this data.

EQUIPOTENTIAL ZONE (EPZ)

The methodology centers on creating an EquiPotential Zone (EPZ) tailored for PMM cable splicing/wellhead connector operations and testing its effectiveness through actual on-site evaluation of the process.

An EPZ is a work zone in which the worker is protected from electric shock due to differences in electric potential between objects in the work area. These differences in potential can be caused by induced voltage, voltage energization, or lightning. The worker in an equipotential zone is protected from electric shock because there is a near identical state of electrical potential between any two points on the body. Now that everything around you has been brought to the same voltage as the potential voltage generated from a spinning PMM, there will not be a voltage difference between any two points that you can possibly touch. No voltage difference means no current and not current means no danger! To ensure that personal protective grounds will protect the worker from hazardous step- and touch-potential conditions, it is essential to employ recognized good engineering grounding methods.

Grounding of all electrical equipment is a critical and mandatory risk mitigation measure designed to ensure a low-impedance return of any fault current to the source, as well as to prevent development of hazardous voltages coming between electrical equipment and personnel working in near proximity.
In addition to more permanently mounted electrical equipment (VSD, transformer, etc.), electrical grounding safety practices involving PMM operations must also take into account temporary surface electrical equipment such as cable spoolers, service rigs, and any other equipment that may come in contact with the ESP power cable.

Standard practices include:

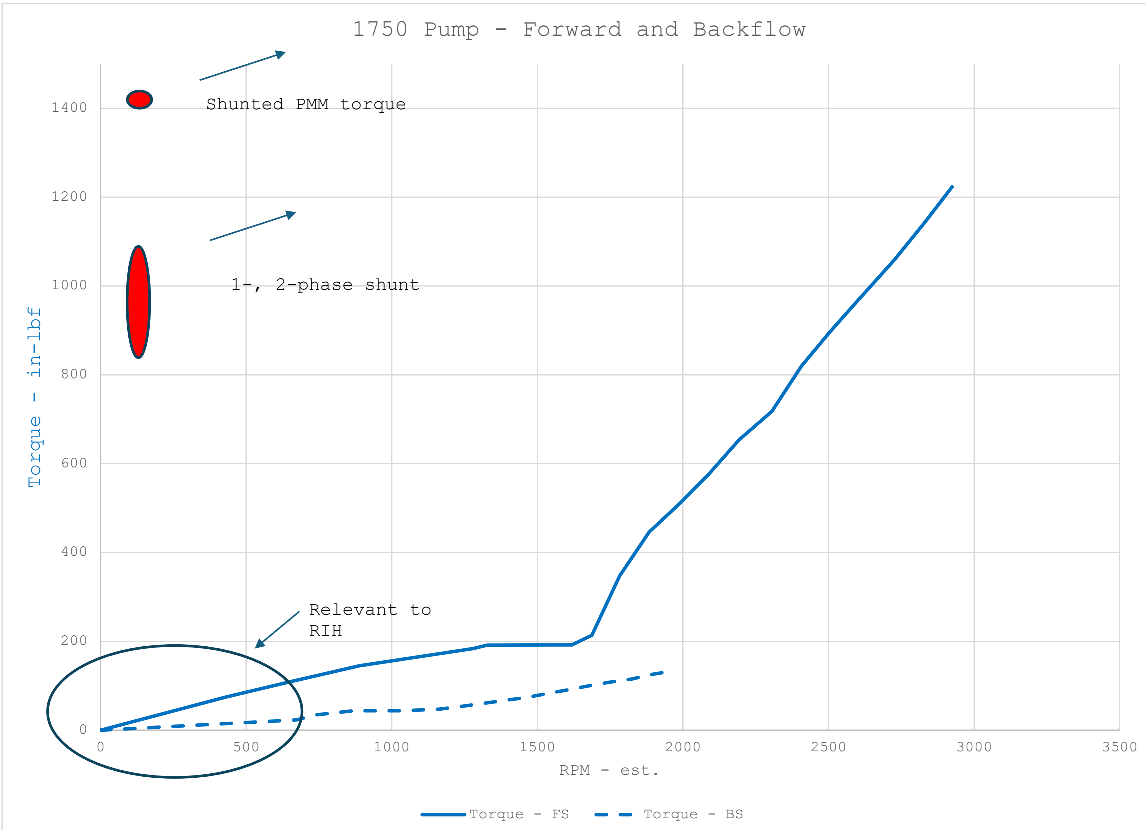
- Proper grounding of all surface electrical equipment to the wellhead or approved alternate grounding point.
- Proper grounding of the well service rig to the wellhead or approved alternate grounding point.
- Proper grounding of cable reel and spooler to the wellhead or approved alternate grounding point.
- Creating Equipotential Zone (EPZ) grounding and bonding of (conductive) splicing table (if used for cable splicing operations), including proper grounding of cable armor, to a grounding mat which is in turn bonded to the wellhead or approved grounding point.

The application of EPZ grounding specifically for PMM's addresses the electrical hazards for majority of shale ESP completions. Engineering controls should not be used just because new gadgets are available nor take the place of thorough risk analysis. The AF analysis presented for various size PMM systems helps narrow the requirements to deal with all those risks. While mechanical lock and flow blocking devices add to our toolkit for engineering controls, it is important to apply results of thorough risk assessment to see where these tools might best be used – typically in conventional, frequently not required in unconventional wells.

SHUNT SURFACE CABLE

As mentioned above, the ESP cable should be shunted, and grounded at the cable spooler with the spooler also tied to the system ground. Below in Figure 2, is a laboratory test of a PMM connected to ESP cable and forcibly rotated at different speeds. A 1- or 2- phase shunt is not as effective brake action and has an oscillating torque but is still quite high. The test shows that, while shunted, the torque required to turn the shunted PMM is quite high and unlikely to rotate during regular operation, such as RIH. Also shown on Figure 2, the torque to turn a typical shale pump (flow tested in both directions) is an order of magnitude lower than shunted PMM motor.

Figure 2 - Torque shunted PMM vs torque and forced flow thru pump



PMM RISK ASSESSMENT

Normal ESP operations include install (run-in-hole, RIH), troubleshoot, and pull (pull-out-of-hole, POOH). The latter includes "normal pull" of failed ESP, green or elective pull where the ESP is still operational and fishing operations. It is not possible to de-energize the PMM so an Energized Electrical Work Permit (EEWP) may be required under Article 110.4(B) of NFPA 70E. Note that there are other risks as part of ESP workover such as pinch, chemical, environmental (H2S), etc., and are all part of a job safety analysis, JSA, preparation to do the work safely.

RIH and POOH workover

For RIH and POOH, it is best to use a shunt or short at surface which serves as a virtual brake on the PMM. Given that pressure changes are very slow on installs, pulls and frac hits, and how that compares to potential torque on pump versus shunted motor, there is not a real need for barrier or shaft lock devices. If risk analysis shows there to be a potential for an unplanned breakthrough event with rapid pressure / flow, then it would be advantageous to have additional safety device(s) in place. The API 11S9 effort was initiated following a fatality several years ago. That event had a rapid pressure and flow condition due to simultaneous operations (SimOps) where one group removed a tubing plug that had some back pressure and did not communicate that work to service hand who was doing splice and was electrocuted.

Troubleshooting

After the ESP is installed and commissioned there may be instances where service personnel need to test the condition of the downhole equipment, isolating from the VSD at the junction box. The leads in junction box are assumed to be at high voltage and tested to insure levels are safe to proceed with checks. In addition to isolating the VSD, service personnel should also consider if there might be secondary sources of power, such as corrosion / cathodic protection devices. These would normally be isolated during a workover, RIH or POOH, but might still be active during troubleshooting. When an ESP is condemned / declared failed then the downhole leads are isolated from the surface kit in preparation for the rig to perform workover. Most wellhead providers have shunt kits available to expedite POOH process in a safe manner.

Fishing procedure

One special consideration of POOH of an ESP is when the completion is stuck and the tubing separates. If the motor is a PMM, then it is important to keep from generating power at surface as the ESP components are fished out of the well. Administrative rules are not best practice for this unusual condition as they are not always followed. A typical fishing procedure involves first cutting the tubing just above the ESP which eliminates the potential shock hazard on cable at surface. It is possible to run flow barrier and / or shaft lock devices with PMM's but these may require additional services. Wireline and other service providers may not be able to verify the device is operational at the point of ESP failure. A simpler solution would be to run a check valve on install, and wireline pulled before startup. This would prevent fluid falling through the pump. Then for the pull, the same check valve could be rerun, and a hole punched in tubing above the check valve to allow the tubing to drain while pulling.

It should be noted, however, once tubing parts in a fishing operation, any completion jewelry is no longer relevant and is just more stuff that needs to be fished. If there is still a concern with having cable burn coming out of hole with sparks flying then, as the ESP cable fault gets close to surface, the equipment POOH rate should be slowed as approaches the surface. Fortunately, most cable burns occur near the ESP so there won't be much fluid left to spin the pump and motor upon reaching the surface.

Future work

If sufficient flow / pressure is applied to ESP with shunted PMM what would be required to overcome breakaway torque? Testing would be done on representative pump and motor, and be done in both flow directions. It is important to note that rotational direction of centrifugal is not always as expected when operated as turbine. This is key to certain shaft-lock safety devices that rely on counter or counter-clockwise rotation to function properly. In a similar manner centrifugal pumps provide lift regardless of rotation direction. Any risk assessment done to consider using these devices should evaluate likelihood of that the device will still be functional at end of ESP life. Similarly, verifying device operation in both flow directions may be impossible.

Shunt tests have been done forcibly rotating the PMM in 3-, 2-, and single phase shunt condition. All previous shunt testing has been stopped upon reaching the motor current rating at 300 - 500 rpm so that motor does not burn. A worse case AF test would simulate a not-shunted PMM that spins easily up to 3500 rpm then is suddenly shorted. How quickly the motor burns/fails or the 2-second rule defines the available incident energy, thus arc flash risk and what PPE would be required for a specific task.

ESP motors, being long and skinny, have very low inertia. For an IM, the current collapses soon after surface equipment isolates a fault condition, and motor stops contributing to the fault, if inside the motor, and even if fluid column continues to spin the motor. For a PMM, however, if there is a fault and motor continues to rotate, then (similar to utility), the motor, even if isolated from surface gear, can continue to contribute fault current. The amount of current is much lower than typical utility fault conditions, hence our focus in this paper is leaning more toward shock rather than arc flash considerations for electrical safety in the risk assessment.

CONCLUSION

Use of shunting of surface cable and implementing an EPZ significantly reduces hazardous potential differences in the vicinity of the surface ESP cable, thereby lowering the risk of electric shock to workers, whether IM or PMM motor. The calculation of AF available energy on PMM's leads to better choices on procedures and protection methods for service personnel and the required level of PPE. Also described are various engineering controls, e.g. tubing flow plugs and mechanical locks, many of which introduce complications on installing, operating, troubleshooting and pulling an ESP driven by PMM. While mechanical lock and flow blocking devices add to our toolkit for engineering controls, it is important to apply results following a thorough risk assessment to see where these tools might best be used - typically in conventional, frequently not required in unconventional wells. Engineering controls should not be used just because new gadgets are available nor should they take the place of thorough risk analysis. The risk analysis presented helps narrow the requirements to deal with all ESP operation risks.

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