PERFORMANCE IMPROVEMENTS OF ESPS USING 500 AND 700 SERIES PMM IN HIGH DEMAND (HIGH FLOW & HIGH HP) APPLICATIONS

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ABSTRACT

Oil wells utilizing Electric Submersible Pump (ESP) systems require substantial electrical power for continuous operation leading to large operation electrical expenses and inefficiencies in traditional induction motor (IM) setups. This paper presents a comprehensive analysis of integrating Permanent Magnet Motors (PMMs) into ESP configurations to achieve superior power densities and operational efficiencies. By leveraging unique motor construction and advanced variable speed drive (VSD) controls, PMM-powered ESPs demonstrate up to 95% energy conversion efficiency which can significantly outperform IMs through minimized rotor slippage, reduced excitation losses, and precise torque delivery under variable downhole conditions. Field trials across multiple wells in the Permian Basin demonstrate real power savings of 10-25% due to lower losses and optimized load matching, while total input power (real + reactive) reductions of 20-30% stem from power factor improvements exceeding 0.95 eliminating the need for larger surface equipment typically required for IM applications. For larger ESP applications in 7-inch and 9-5/8-inch casing sizes that can accommodate larger 500 and 700 series motor selections, this paper provides a comprehensive review of ESP design analysis, surface equipment selection and optimization, and fundamental design challenges and integration covering the uniqueness of PMM driven ESPs.

Introduction

While previous short-term field studies have confirmed efficiency gains from permanent magnet motors (PMMs) over induction motors (IMs) in Electric Submersible Pump (ESP) systems, most analyses capture only snapshots in time. This paper extends that work to larger 500- and 700-series PMMs suitable for 7-inch and 9-5/8-inch casing applications. Field trials demonstrate up to 95% energy conversion efficiency, 10–25% real-power savings from reduced losses and optimized load matching, and 20–30% reductions in total input power driven by power factor improvements exceeding 0.95, enabling smaller surface equipment.

Electric submersible pump (ESP) systems are widely used in the oil and gas industry to provide artificial lift in high-production wells. As production rates increase and wells become deeper, ESP installations must operate at higher horsepower levels, increasing electrical current demand and cable losses. In a 400-horsepower consuming ESP application the monthly electricity operating expense could exceed $25,000.

Permanent magnet motors (PMMs) offer a high-efficiency alternative with improved power density and reduced rotor losses. When combined with high-voltage power transmission systems, PMM technology significantly reduces motor current, cable voltage drop, electrical losses, and system operating costs. Case studies over the years have published ESP system savings attributable to the PMM averaging ~20%, so for the 400HP application this $5000 per month for one well.

Conventional ESP systems employ both permanent magnet and induction motors operating at moderate voltages between 4 and 5 kV. These systems may require higher current levels, resulting in increased resistive losses in the power cable and reduced overall system efficiency for large horsepower applications.

This paper presents the design and performance analysis of permanent magnet motors compared with induction motors through key motor characteristics that define their fundamentals.

A high-voltage PMM ESP system intended for high-horsepower applications ranging from 1600 to 2800 HP is also described to highlight lower current motors at elevated voltages to further increase system efficiencies for high demand applications. The system architecture consists of a 480-V surface power supply, variable frequency drive (VFD), pad-mounted step-up transformer rated 480/7200 V, and a high-voltage ESP cable delivering power to the downhole permanent magnet motor.

Permanent Magnet Vs Induction Motor Characteristics

Permanent magnet motors operate through interaction between the stator magnetic field and permanent magnets located within or on the rotor. PMM motors eliminate rotor copper losses present in induction motors, leading to higher efficiency and reduced heating.

The efficiency gains arise from the permanent magnetic field created by the magnets that replaced the copper bars of the squirrel cage design of an induction motor. This eliminates rotor copper losses, magnetizing current from the stator, and slip, yielding much higher power/torque density. For the same output power or torque at same speed, a PMM typically requires 30–60% smaller volume resulting in much shorter axial length L for the same outer diameter of an induction motor. This is due to much higher air gap flux density of 0.7–1.2T vs. 0.4–0.6T, higher effective electric loading, near-unity power factor of 0.95–1 vs. 0.8–0.85, and peak efficiencies capable of greater than 95%.

For downhole well applications the dominating constraint is the motor outer diameter per casing size. The slenderness requirement furthers the performance divide of PM vs. IM. As the diameter is constrained, the only method to getting more horsepower is to add additional motor length for IM which can add more cost and complexity to the installation. This occurs since the IM is limited in producing larger air gap flux densities due to the space constraint of the wellbore. To raise this characteristic for IM's, a motor designer would need to increase the magnetizing current (mostly non-torque creating component) at the potential expense of stator iron saturation, lower power factor, and additional losses. For PM motors the air gap flux density is fixed by the magnetic material and design. The flux is stronger than what can be created in wellbore form factors.

For 7 inch and larger casing applications, readily available equipment is critical to efficient ESP operations for timely installs. The table below shows a comparison between large commercial induction motors and equivalent PM motor to highlight the performance differences.

Table 1 highlights the power density differences of greater than 3X for a PMM which adds in significant weight and length savings for the same horsepower output.

Table 1 - Sample Motor Specifications

Motor	Motor OD	HP	Voltage, V	Current, A	kVA	Efficiency	Length, ft.	Weight, lbs
IM	5.62	1100	4350	157	1182	82%	69	5080
PMM	5.62	1100	4430	120	920	94%	16	930
IM	7.38	1500	3700	206	1319	89%	57	7196
PMM	7.38	1500	4400	167	1271	94%	13	1600

Performance Analysis – 500 Series for 7 Inch Casing

Conventional 7-inch casing ESP applications use induction motors in mainly two sizes – 456 and 562. 456 series induction motors are used in heavier wall applications where fishing or scaling risks push this smaller size like in 7-inch 32# casing. Where more clearance is present in thinner wall casing, 562 inductions motors are used to either limit the overall length of equipment for similar horsepower to 456 series or maximize downhole horsepower by running tandem 562 motors.

Detailed below is an ESP well design for 7-inch 32# casing targeting 10,000 bpd production.

Table 2 - Well Parameters

Setting Depth	8300	ft
Intake Pressure	2650	psi
Flow Rate	10000	bpd
Gas Rate	600	Mscfd
Frequency	100	Hz
Surface Power	607	kVA
Motor Current	89	A

Based on the specific well parameters, the 538-pump selected for this ESP is modeled below showing the various operating curves at select rotation rates. This unit is expected to operate at 100Hz or 3,000 RPM and produce 10,000 bpd at 8,300 ft. set depth.

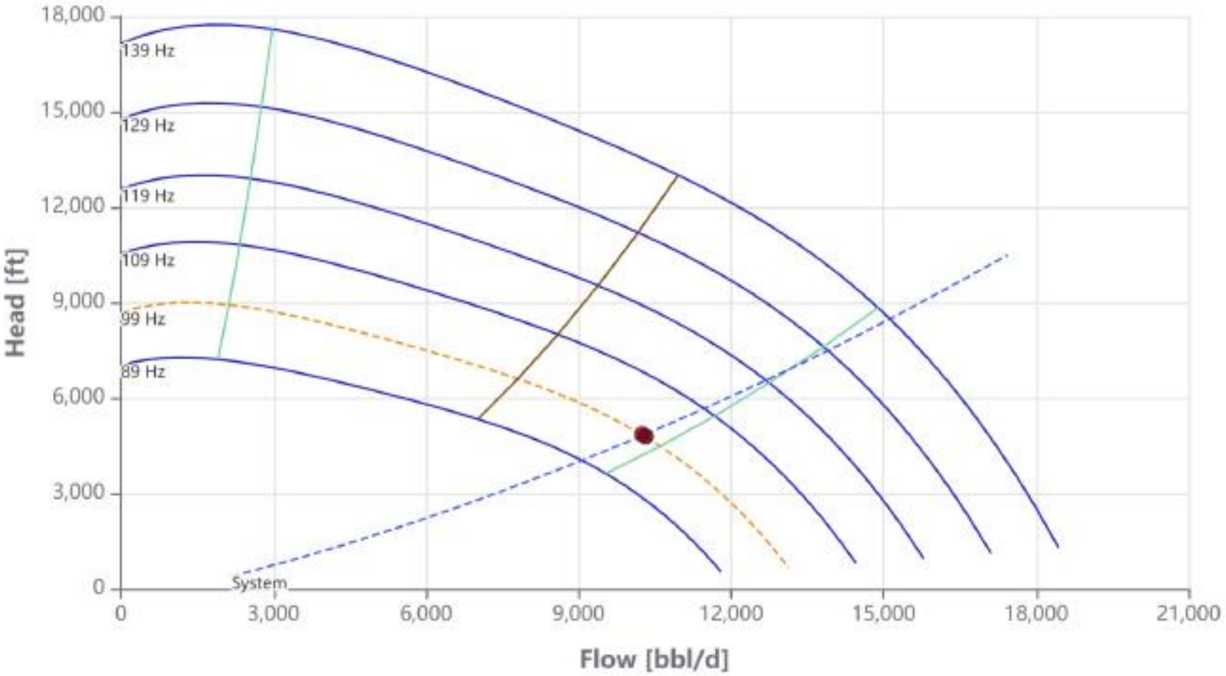

Figure 1 - 538 Pump Operating Curves

Motor	Motor OD	HP	Voltage, V	Current, A
PMM	5.19	1000	4431	125

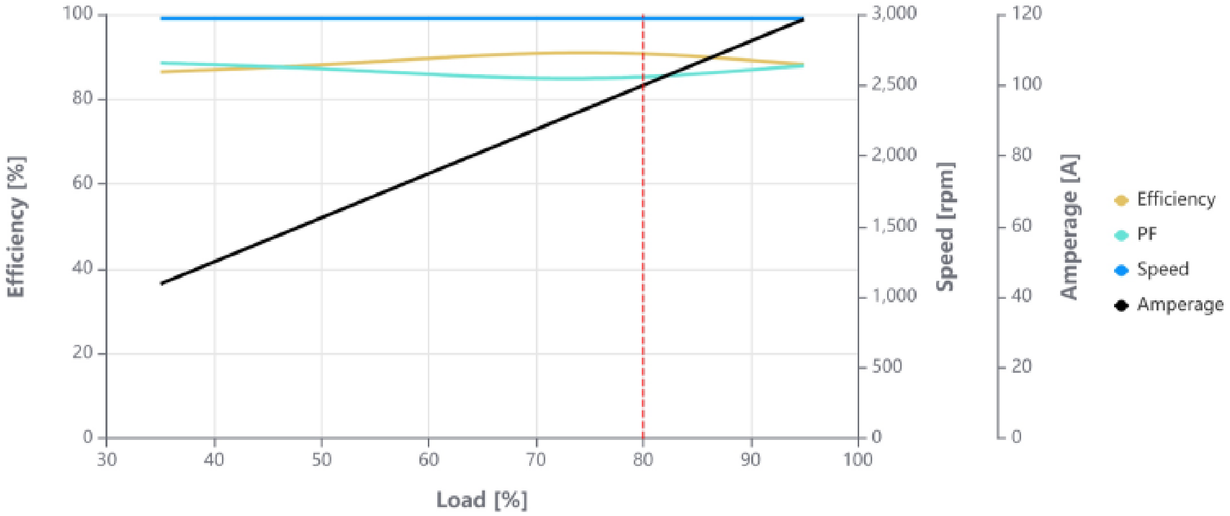

Figure 2 – PMM Specifications and Operating Plot

The PMM selected for this application is rated at 1000HP and will operate at ~80% motor load to achieve the desired production rate. This puts motor efficiency at ~91%.

Operating electricity expense is expected to be around $44,000 per month at a $0.10 per kWh rate. Comparing this with an equivalent IM design, this is around $11,000 per month savings in electricity consumption.

Table 3 - Electrical Operating Expenses

Elec OPEX	$44,000	per month
Efficiency Gain	20%	psi
Elec. Savings	$11,000	per month

Through careful front end engineering design of the ESP system, its possible to implement PMM technology to maximize both production rates and electricity savings to enable more economical solutions.

Efficiency Analysis – 700 Series for 9-5/8 Inch Casing

9-5/8-inch casing offers substantial clearances for nearly all commercially available motor offerings. With such a wide range to choose from, there can be challenges to assess which is best to specify.

This example explores a purpose built PMM for 2000HP, 700 series, and flanging up to pumps targeting 15kbpd up to 30kbpd. These are conventional, waterflood-like wells that will have stable operating conditions with little to no gas production. This operating environment allows more precise ESP designs focusing specifically on system efficiency and electrical operating expense.

Table 4 - Basic Well Parameters

Setting Depth	8000	ft
Intake Pressure	1000	psi
Flow Rate	30000	bpd
Pump Efficiency	64%	
Hydraulic Power	1262	HHP
Pump Mechanical Power	1971	HP

The table above shows an example application where the mechanical shaft power needed by the pump is nearly 2000HP. Pump efficiency is a dominating factor when considering pump selection, so care must be taken. This analysis is focused on delivering 2000HP to the pump shaft.

Design considerations for a bespoke PMM for this application begins with identifying how large of a diameter the motor can be for the given casing size. Using this diameter, the flow velocity across the motor needs to be determined in order to assess cooling potential. Assuming a ~95% motor efficiency and 2000HP output, this results in a simple 100HP heat rejection into the wellbore fluid. From the figure below, a 7.69-inch OD motor is shown at various flow rates and a minimum of 15000 bpd where the velocity over the motor in 9-5/8 47# casing is ~10 ft/sec which is more than adequate to dissipate this heat into the wellbore fluid.

Casing OD	Weight	ID	Drift	ID Area
9.625	47	8.681	8.525	59.2

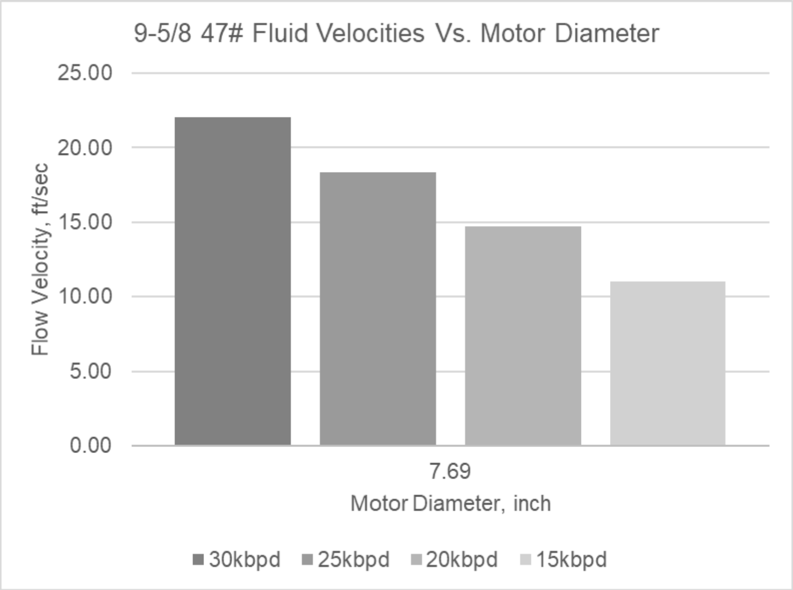

Figure 3 - Flow Velocities and Casing Details

Motor design features allow for maximizing air gap flux density by maximizing the one-piece shaft diameter for mounting the magnets This critical design step ensures maximum power output, density, and efficiency.

Starting with a fresh design sheet, a motor designer can work through many iterations of lengths, winding configurations, magnetic materials, lamination materials, etc. to arrive at a tailored solution purpose built for the application.

A brief snapshot of a motor analysis involving stator length, voltage, and current for a few winding configurations is below. In the plot, the designer can see how changes in stator length affect both the operating voltage and current for multiple winding configurations. This plot shows an example in red at a stator length of 48 inches where the amperage is >130A and the voltage is ~2700V. In this high horsepower application the goal is to maximize the efficiency, so increasing the voltage is desirable up until it reaches the limit of the surface equipment, power cable, and MLE. Exceeding those voltage ratings will have a negative effect on the operating run life which is highly undesirable.

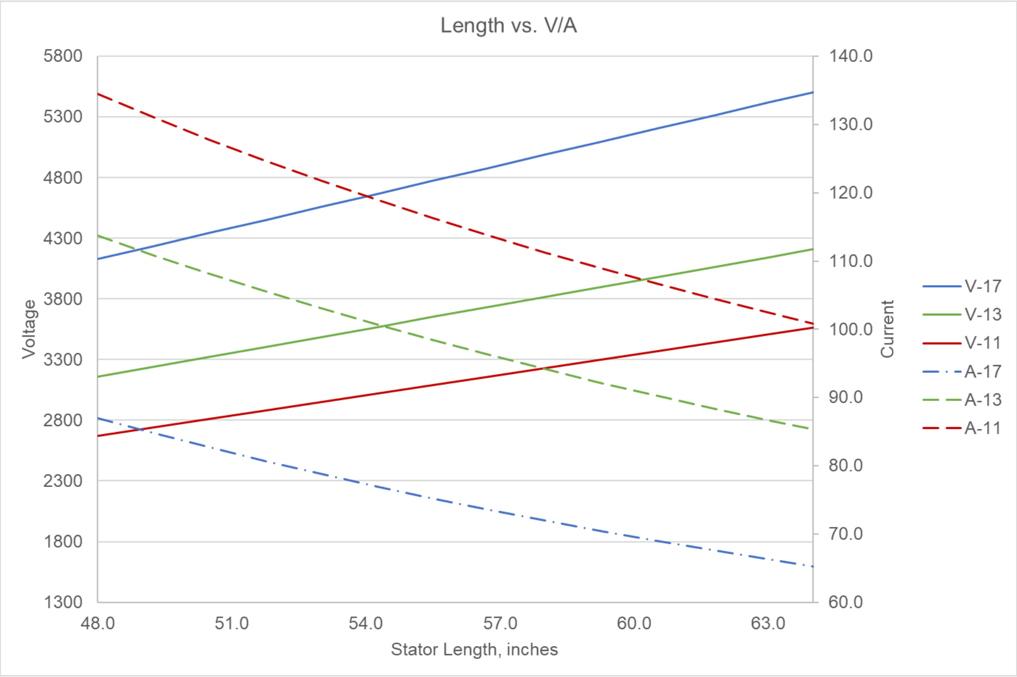

Figure 4 - PMM Voltage/Amperage Vs. Length

From the detailed motor design, the preliminary specification for this 30,000 bpd per day well, the 7.69 PMM specification is in the table below. Operating within the 5kV limits of the surface equipment and cabling, this requires the amperage rating to increase to 211A which will require a large power cable conductor size to limit voltage loss.

Table 5 - 7.69 PMM Preliminary Specifications

Motor	Motor OD	HP	Voltage, V	Current, A	kVA
PMM	7.69	2000	4550	211	1661

Using this new PMM specification, the electricity cost savings can be extrapolated. The figure below plots multiple system efficiency gains from 10% all the way to a maximum of 27%.

When looking at deployments of 25 units operating at 2000HP, the savings potential from switching to PMM may range from ~\$3MM per year up to ~\$9MM per year. This assumes electricity cost of \$0.10 per kWh. Areas with increased rates, more savings potential can be realized.

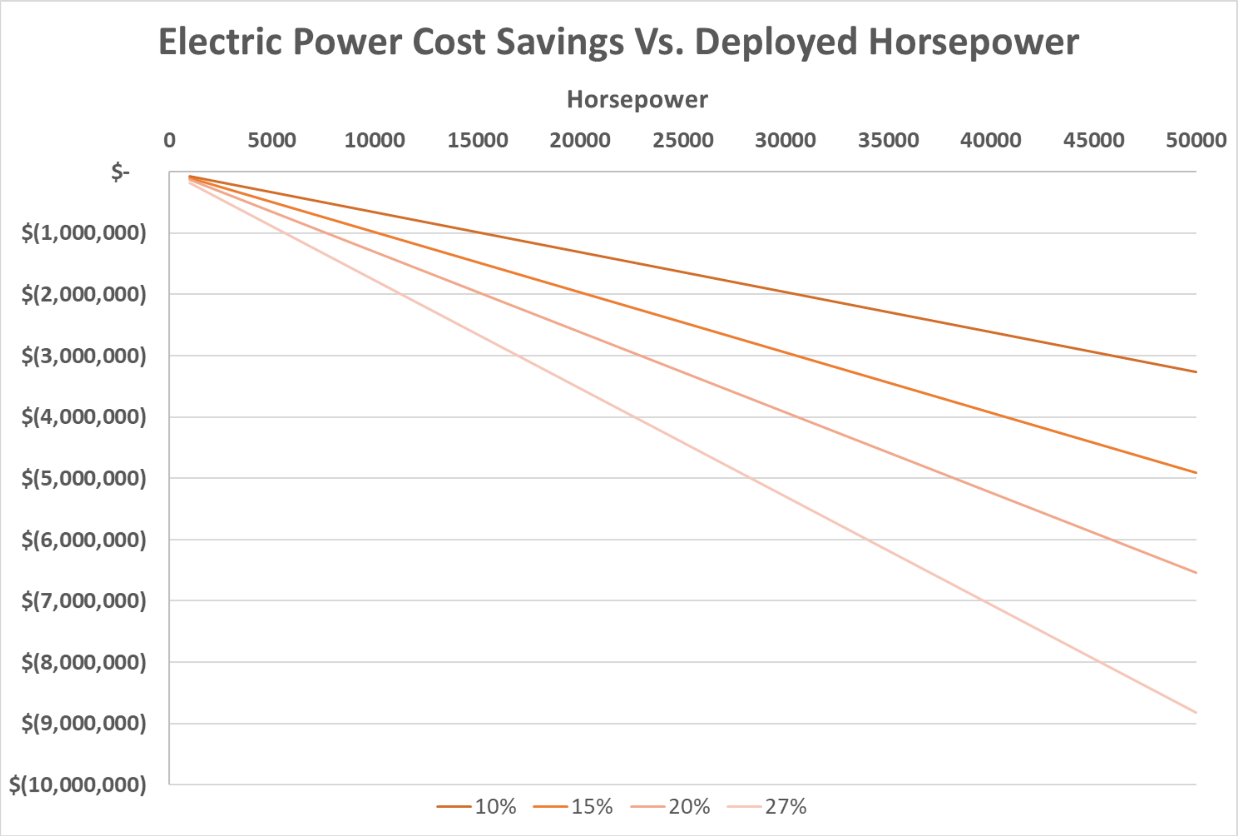

Figure 5 - Electricity Savings Estimate Vs. Total HP Deployed

Medium Voltage ESP System Architecture

From the previous examples, it's clear that an increase in motor terminal voltage will be advantageous in lowering overall operating current which can lead to better system efficiencies and costs. By lowering the current, smaller cables sizes can be used which will also lend themselves to better packaging of higher voltage rated materials as will be outlined. The voltage classes below are useful for identifying voltage ratings.

Table 6 - Voltage Classes

Voltage Class	Voltage Range (AC)	Typical Examples	Common in ESP / Oilfield Applications?
Low Voltage (LV)	0–600V (or up to 1000 V)	120V / 208V / 240V / 480V	Standard for smaller motors and surface equipment
Medium Voltage (MV)	601 V – 69000V(69 kV)	2300V / 4160V / 6600V / 13.8kV	Direct line start Induction Motors
High Voltage (HV)	Above 69 kV	115kV / 138kV / 230kV+	Rare in downhole ESPs (mostly transmission)

The proposed ESP system includes both surface electrical equipment and downhole pumping components.

Power flow through the system for a standard ESP, low voltage application. These systems typically max out at a 5000V rating for the step-up transformer and cabling which necessitates upgrades to operate a medium voltage rated motor.

480-V Field Power > Variable Frequency Drive > **Step-Up Transformer > ESP Cable > ESP Motor** > ESP Pump

Table 7 - ESP Electrical System Architecture

Component	Function	Voltage
Field Power	Surface electrical supply	480 V
VFD	Speed control	480 V
Transformer	*Voltage step-up*	*<4000V*
ESP Cable	*Power transmission*	*<4000V*
PMM Motor	*Mechanical power*	*<4000V*

Medium-Voltage Pad-Mounted Transformer

A pad-mounted transformer increases voltage from 480V to approximately 7200V. Pad-mounted transformers rated 480 input and can step up to 7200V are widely available and commonly used in oilfield power systems.

Table 8 - SUT Parameters for Medium Voltage

Parameter	Value
Primary voltage	480 V
Secondary voltage	7200 V
Power rating	2–3 MVA
Cooling	Oil-filled
Configuration	Three-phase

ESP Power Cable System

ESP power cables are subjected to harsh wellbore conditions and are already a large portion of failures seen in applications. Common failure modes include overheating due to pump gas locking, mechanical damage during installation, gas migration through insulating materials, poorly constructed mechanical cable splices, and more.

Increasing the rating of the power cable requires a thorough review of insulating materials and overall materials for cable construction to ensure fault free operation.

Electrical power transmitted through the cable is defined below.

$$P = \sqrt{3}VIPF$$

The cable losses through the system is further defined below. The squared current term is the dominating characteristic of the cable which is the main driver behind increasing voltage to lower the motor operating current.

$$P_{loss} = 3I^2R$$

High-voltage ESP systems require cables capable of operating under severe downhole conditions. The table below shows some existing classes of voltage ratings for downhole power cables. The 8.6-kV cable rating provides adequate insulation margin for PMM motors operating between 7–9 kV.

Table 9 - Cable Classes

Voltage Class	Application
5 kV	Conventional ESP
8.6 kV	High-voltage ESP
10 kV+	Ultra-deep wells

Construction methods and materials vary widely in the industry, and the typical ESP cable components include the following.

Table 10 - Power Cable Materials

Layer	Function
Copper conductor	Power transmission
Polyimide Tape	Electrical insulation
EPDM insulation	Sealing and Electrical insulation
Metal shield	Electric field control and gas isolation
Outer jacket	Mechanical protection
Flat cable geometry	Tubing installation

PMM ESP System Design and Performance Comparison

The exercise below demonstrates how increasing the motor terminal voltage can increase the performance characteristics of the ESP system. This produces a reduction of 34% in operating current with an increase of 60% in operating voltage. Through the current reduction, the cable size can be significantly reduced which will lower capital costs for the well.

Table 11 - 1600-HP System Comparison

Parameter	**PMM MV**	**IM**
Voltage	7200 V	4500 V
Current	120 A	183 A
Efficiency	0.95	0.89
Motor length	18 ft	69 ft
Motor weight	1100 lbs.	6000 lb.

For the 2800HP example below a 31% drop in operating current with a 33% increase in operating voltage will also provide a capital cost reduction through smaller copper core power cable.

Table 12 - 2800-HP System Comparison

Parameter	**PMM MV**	**IM MV**
Voltage	9200 V	6900 V
Current	145 A	209 A
Efficiency	0.95	0.89
Motor length	19 ft	72 ft
Motor weight	1600 lbs.	9000 lbs.

Operational advantages include simplified installation, transportation, and reduced rig handling complexity.

Electrical Performance and Economic Analysis

The voltage loss across the power cable is generated heat and can add up to a significant amount of electricity consumption. Below is the analysis based on the two motor HP sizes detailed – 1600 and 2800 HP.

$$V_{drop} = IR$$

Table 13 - Voltage Drop Comparison

Motor	**Voltage Drop**
PMM (1600 HP)	184 V
Conventional	357–367 V
PMM (2800 HP)	252 V
Conventional	409 V

Table 14 - Total Electrical Loss Comparison

System	Motor Loss, kW	Cable Loss, kW	Total Loss, kW
PMM	110	80	189
Conventional	258	130	388

Table 15 - Annual Energy Consumption

System	Energy, kWh	Annual Cost
PMM	19,260,612	$1,926,061
Conventional	20,559,720	$2,055,972

Table 16 - Cable Capital Cost

Cable	Cost per ft	Cable Cost 10kft Well
AWG 1	$20	$200,000
AWG 2/0	$30	$300,000

Table 17 - Economic Benefit Summary

Category	Savings
Cable purchase	$100,000
Energy savings	$129,911
Cable loss reduction	$44,238

Total first-year estimated benefit $274,149 per well.

Conclusions

Permanent Magnet Motors offer significant performance benefits due to their increased air gap flux density.

- Front end electromagnetics design can unleash significant performance benefits for demanding high horsepower applications
- Increased efficiencies for 500 and 700 series motors
- Increase in power densities >3X
- Shorter overall lengths enabling more deployment freedom
- 2000HP PMMs could save up to $9MM per year with 25 well install base

High-voltage permanent magnet motor ESP systems significantly improve electrical efficiency and reduce operating cost.

- Motor current reduction >30%
- Cable voltage drop reduction ~50%
- Electrical loss reduction ~50%
- Potential savings ~$274k per well

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