Induction Versus Permanent-Magnet Motors for Electric Submersible Pump Field and Laboratory Comparisons

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***Abstract*—Most hydrocarbon production using submersible pumps requires pumping of fluid that is 95% water or higher. Energy used to produce salt water is wasted, and disposal is expensive. Electricity costs are significant, and system efficiency is a major concern. In this application, induction motors (IMs) are less efficient than permanent-magnet motors (PMMs). Laboratory tests measured efficiency, power factor, kilowatts, current, and speed at various loads and frequencies. Field tests measured input power and flow using the same pump for both systems with negligible well drawdown. On average, the PMM used 20% less power than the IM.**

***Index Terms*—Electric submersible pumps (ESPs), gas production, gas-well dewatering, oil-well ESPs, permanent-magnet motors (PMMs), water flood.**

I. Introduction

THE electric submersible pump (ESP) used for oil- or gas-well production is a very unique product. Head and flow requirements dictate a horsepower rating commonly between 50 and 500. To obtain this kind of power near the bottom of a well, medium voltages, typically 1000–3000 V, are used to permit power cables of a reasonable gauge. Obviously, the motor and pump must have small diameters to fit inside an oil well. The motor is normally oil filled to prevent well fluid intrusion by equalizing inside pressure with that of the surrounding wellbore. This oil is also electrically insulating [1].

Multistage centrifugal pumps are required to move the amount of fluid essential for production. For fluid-specific gravity = 1, hydraulic horsepower (HHP)

$$\mathrm{HHP} = (H \times Q)/3960 \tag{1}$$

where H is the head in feet, and Q is the flow in gallons per minute (gal/min). However, oil-field operations measure flow in barrels per day (B/D), and an oil barrel is 42 gal. Thus,

$$\mathrm{B/D} = 34.3 \times \text{gal/min}. \tag{2}$$

A typical example might be pumping of water from 5000 ft at 3000 B/D. The required HHP would be approximately 110, but with a 63% efficient pump, the motor would have to be 175 hp. These numbers are for 3500-r/min operation.

Centrifugal pumps running on two-pole 60-Hz motors have been the standard. At lower speeds, pump head is greatly reduced. To compensate, many more pump stages would be required, making the pump excessively long. Furthermore, at four- or six-pole speed, the torque required would be much higher. Designing and building higher pole-number induction motors (IM) in a small diameter are extremely challenging. Except for possible stalling, the centrifugal pump only requires maximum torque at maximum speed.

Historically, the two-pole three-phase IM has been the machine of choice for these applications. Ambient well temperatures can often reach 250 °F. The IM usually only has two failure modes, bearings or stator windings. Consequently, it is a very rugged machine.

However, designing and building a small-diameter IM to meet the horsepower requirements in an ESP application required major deviations from normal NEMA motor designs. To comfortably fit inside common oil-well casings, the industry has mostly settled on outside diameters of 3.75, 4.56 or 5.62 inches for the motors. Laminations for such motors are more typical of NEMA fractional-horsepower motors. Achieving the necessary horsepower means designing a very long motor [2].

Rotor length was a major consideration. Achieving an optimum length, given common manufacturing tolerances, imposed a limit due to magnetic side-pull that caused rotor–stator interference. The result was a concatenated multirotor design with bearings between adjacent rotors.

Stator design had to choose between open and closed slots. Generally, the closed slot proved easier to manufacture and more reliable. The stator lamination stack had to be equal in length to the multirotor assembly. Sometimes, nonsteel laminations were inserted opposite rotor bearings. Because the slots were closed, manual needle winding was the only possible alternative. To accommodate additional motor sections or tandems, windings start at the motor top and end at the bottom. Thus, each phase has one half-turn extra.

Because each rotor added an equal incremental amount of horsepower to the motor, it was possible to use a per-unit

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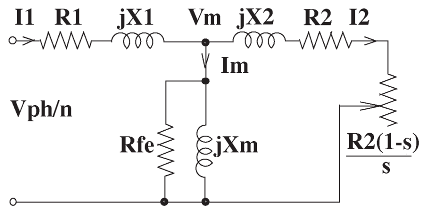

Fig. 1. Per-phase IM equivalent circuit.

equivalent circuit to represent all horsepower ratings in a given frame size [3]. For any given horsepower, multiple voltage ratings are possible depending on the turns per phase. This can be accounted for by multiplying base impedance, calculated from the voltage and current ratings of the motor, by the per-unit values to obtain the parameters in Fig. 1.

Today the ESP industry has no specified temperature-rise (TR) rating standard for motors. The temperature of produced fluids varies widely from field to field and well to well. Higher horsepower and current ratings are possible in cold wells, and this has led the industry to adopt temperature-dependent ratings. This complicates calculation of base impedance.

A shaft capable of supplying the needed pump torque had to be small enough to fit inside the rotor laminations. Obviously, this shaft had to be long enough to extend through all the motor rotors. Practical shaft design pushed the torque rating limits and incurred significant flexibility and windup. Coupling this with the rotary inertia values of the rotors and pump stages, torsional vibrations could be produced under certain circumstances.

Initially, all ESP operation was direct on line (DOL), i.e., a suitably rated three-phase contactor started and stopped the ESP. Because of the small rotor diameter and resulting low inertia, typical ESP starting times were less than half a second. However, for high-horsepower ESPs, DOL starting produced significant inrush current and voltage sag on the power system. Frequently, the power utility would impose inrush current restrictions, and solid-state soft starters (variable voltage and constant frequency) were often installed to meet those restrictions. Overzealous operators, thinking longer starts were better, caused the breakage of motor shafts between tandem motor sections, not at the maximum torque location between the motor and pump. Speed hunting and torsional vibrations were attributed to the negative damping characteristic of an IM at slips greater than breakdown-torque slip [4], [5].

The major problems with DOL starting were changing well productivity and operation of the pump outside its best efficiency range. With fixed frequency operation, the pump was incapable of compensating for this change.

Adjustable-speed drive (ASD) operation of ESPs was introduced in the late 1970s, and this allowed pumping at speeds that better produced the well and kept the pump within its best efficiency range. Outside that range, electric costs changed little, but the reduction in fluid produced was unacceptable. Furthermore, the ASD solved the problem of reducing inrush current during starting while still maintaining the IM in the low-slip positive-damping speed range. Today, ASD operation is commonplace.

With the advent of permanent magnets capable of withstanding the temperatures inside an oil well, the synchronous permanent-magnet motor (PMM) has become a viable power source for ESPs. Four magnets are embedded and constrained inside each rotor. An IM rotor has copper bars and end rings. Except for this and the PMM being four-pole, there is no physical difference between the motors.

Equipment operating in oil-well environments must be able to handle temperature, pressure, and corrosives. Because of these constraints, it has not been feasible to design control and power electronics inside an ESP motor. With all electronics on the surface, the only alternative for powering the PMM has been a sensorless drive control. Additionally, a current source drive is preferred to protect against demagnetization. Combining such a drive with a PMM, the torque produced by the motor is nearly proportional to the current. For production of wells with appreciable gas, a torque control automatically speeds up the pump to compress the gas and avoid a gas-lock condition.

The central issue in this paper is the comparison of the efficiency values and operating costs of small-diameter ESP induction and PMMs. Motor equivalent circuits are used to explain various loss factors in the motors. Laboratory tests were run to confirm performance curves with 60- or 120-Hz power provided by ASDs and step-up transformers, cf., Figs. 4, 10, and 11. These data were used to explain variations in efficiency, power factor, and current for the three ESP motors and a common NEMA design motor. Additional tests were run at various speeds with 5000 ft of cable and a dynamometer load on the motors. The dynamometer was adjusted to simulate centrifugal pump performance in a low-drawdown well. Finally, field-testing procedures and measurements are presented, and field data are used to compare ESP IM and ESP PMM system performance in an actual low-drawdown well.

II. Equivalent Circuits

Although an ESP motor has multiple rotors and stator windings that extend the length of the motor, the impedance of winding segments opposite rotor bearings can be included in the stator resistance and leakage reactance [2]. Thus, the familiar IM equivalent circuit (see Fig. 1) is still applicable.

For most of the past century, one motor design (IM5, 5-hp/rotor) has dominated the industry, and components for it have now been manufactured overseas for 25 years. Since components are readily available, barriers to entry into this industry are very low.

Before the advent of temperature-dependent motor ratings, winding TR ratings were firmly established and per-unit equivalent circuits had been determined. Each motor had specified ratings for horsepower, voltage, and current, and base impedance could be easily calculated. Values for all parameters are presented in Table I.

A 456 series 240-hp motor of this design rated 5 hp per rotor was used for the field tests. In the 60-Hz performance curves that follow, values were calculated using this equivalent circuit and labeled as ESP IM5.

By present motor design standards, this design had several deficiencies. Stator lamination teeth did not have parallel sides, probably to make needle winding easier. The rotor had 16 round bars. For an 18-slot stator, 16 is a poor choice for the rotor.

TABLE I
PER-UNIT EQUIVALENTS FOR FOUR MOTOR SERIES

Series	TR °F	R_1	X_1	R_2	X_2	R_{fe}	X_m	FW/hp_r
375	40	0.046	0.080	0.053	0.095	84.71	1.414	88.7
456	50	0.036	0.069	0.049	0.104	122.82	1.842	69.6
540	60	0.029	0.067	0.047	0.113	154.15	1.980	46.1
738	70	0.022	0.073	0.042	0.094	174.23	2.064	122.1

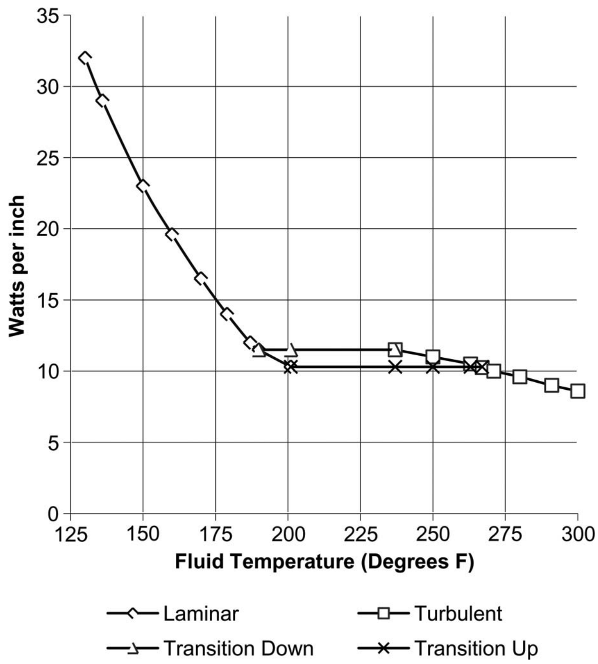

Fig. 2. FW loss at 3000-r/min 456 Series Motor.

Modern design would use an 18–23 or similar odd stator slot to rotor bar combination. Although round bar stock is readily available, contemporary design would use either coffin or teardrop-shaped bars. Such a new design rated at 10 hp per rotor and labeled ESP IM10 is presented in the following performance curves.

Losses are commonly catalogued as follows:

copper loss $= 3(I_1^2 R_1 + I_2^2 R_2)$;
iron loss $= 3\ \mathrm{V}_m^2/R_{\mathrm{fe}}$;
friction and windage (FW);
stray load.

By definition, stray load is the difference between total loss and the sum of copper, iron, and FW losses. FW losses are unique to ESP motors because the motor is oil filled. It has an "oil gap" instead of an air gap, and FW losses are a significant consideration.

The nature of oil flow in the gap has an effect on FW losses (see Fig. 2). At low temperature, that flow is laminar and the losses are quite high. At high temperatures, the flow is turbulent and the losses are considerably less. The IEEE recommended practice for IMs having liquid in the magnetic gap [6] does not adequately address this issue.

This phenomenon has led to "temperature-dependent motor ratings." If the well fluid surrounding the motor is reasonably cool, higher torque, current, and TR ratings are acceptable. The motor actually runs more efficiently at the higher temperatures because FW losses are less. Obviously, winding temperature should stay below the rating of the insulation, normally class H, 180 °C.

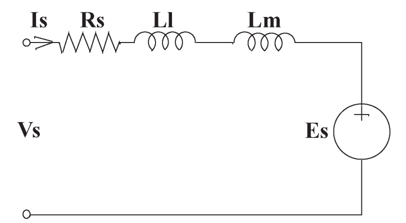

Fig. 3. Equivalent circuit for rectangular-fed PMM.

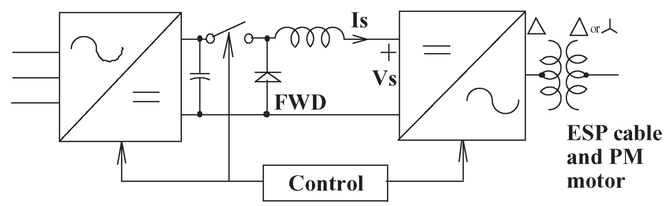

Fig. 4. Current source rectangular feed drive six-step output.

NEMA motors typically have an 80 °C winding TR. As aforementioned, there is no standard TR for ESP motors. Possibly, a standard is not feasible because different types of oil are used; however, because no standard exists, customers are unable to compare products. Nonetheless, FW losses for either an ESP IM or ESP PMM should be the same for equal pressures, temperatures, rotor diameters, gaps and speeds.

A brushless PM motor can be operated on three-phase sine wave power like a synchronous ac motor or be fed rectangular voltages where two phases are conducting, and the third is open during sequential 60 electrical degree intervals, one-sixth of a cycle. An IEEE-IAS design procedure stated that "It is convenient to use the rated controller link current I_s as the base current. The current I_s is switched sequentially to two phases in series. During the time two phases are conducting, the voltage induced in them is essentially constant. E_s is the induced voltage in the two phases in series, I_s is the approximately constant current, and V_s is the average voltage applied to the terminals [7]." R_s, L_l, and L_m are the winding resistance, leakage inductance, and magnetizing inductance of two phases in series. The equivalent circuit for such a rectangular-fed PM motor is illustrated in Fig. 3.

One possible drive source for this motor is shown in Fig. 4. The input converter and chopper regulate the bus current I_s. A bus inductor and a freewheeling diode (FWD) insure current continuity. Current control is advisable to insure that faults in the system do not produce large currents resulting in demagnetization.

The inverter section must provide brushless sensorless power to the remotely operated PMM. As aforementioned, incorporating rotor position sensing or electronics inside the motor is quite infeasible.

III. Laboratory Tests: 60 and 120 Hz

Parameters in the Fig. 1 equivalent circuit are normally determined by locked-rotor and no-load tests. The locked rotor test requires a variable voltage source to raise the current up to rated value. For most NEMA motors, the voltage-to-current ratio is nearly constant, i.e., the impedance is linear. However, ESP IMs have closed stator slots, and at low voltage, the impedance is very high. The impedance does not become linear until the bridges between stator lamination teeth saturate. The ESP PMM also had closed, stator-lamination slots, but in operation flux provided by the magnets saturates the bridges.

No-load tests measure magnetizing inductance and core-loss resistance. To minimize the influence of FW, the rated voltage test can be performed with no oil in the motor and ball bearings.

With regular bearings and oil filled, FW becomes a major loss factor in the motor. Power measurements are taken as the applied voltage is reduced from rated down to motor stalling. Power in the stator windings is subtracted from these measurements, and the result is extrapolated to zero voltage for the determination of FW [8]. Unfortunately, attempts to simulate actual oil-well temperatures and pressures and measure FW are problematic and extremely dangerous.

Additional tests required the use of a dynamometer to apply various loads to the motor. A saturation test measures input current at rated load and frequency as voltage is varied about the rated value. At fixed frequency and constant voltage, performance tests measure efficiency, kilowatt value, current, power factor, and speed as the load is varied. Motor output power is measured with the dynamometer. An average motor temperature is determined from the measurement of the stator winding resistance at short intervals immediately after the motor is stopped. These data are extrapolated back to the stopping instant. Because copper wire changes resistance in proportion to temperature and knowing the initial ambient temperature and resistance, an average value of running temperature can be calculated.

A comparison of various performance parameters for the IM10, PMM, IM5, and a common 200-hp class-B 460-V 444TS frame IM (NEMA) is presented below. Of vital importance is motor efficiency, i.e., mechanical output shaft power divided by input electrical power. Higher efficiency values mean that the same work is being done with less electrical energy. Efficiency values are compared in Fig. 5.

The NEMA motor compared had a much larger rotor diameter and was running in air. The latter makes FW losses substantially less. Of the three oil-filled ESP motors the two IMs had lower efficiency because of copper and iron losses in the rotor. Since a PMM has no rotor copper, those losses are zero. Turning at precisely synchronous speed, only minor fluctuations in flux occur, and these produce minimal rotor iron loss.

At light loads, efficiency drops off for both the IMs and the PMM. This is attributed to the oil-filled factor. Shaft output power of an ESP motor must divide between FW and the

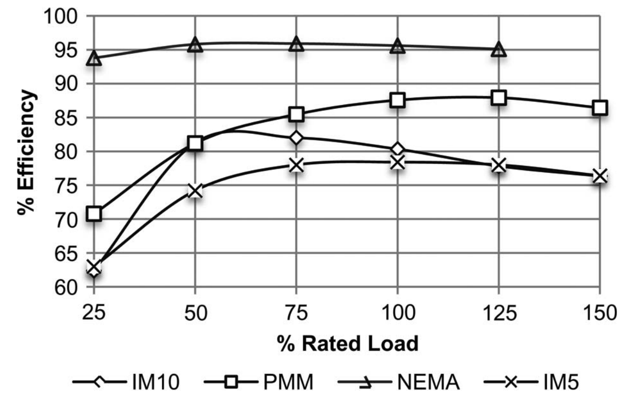

Fig. 5. Efficiency comparison.

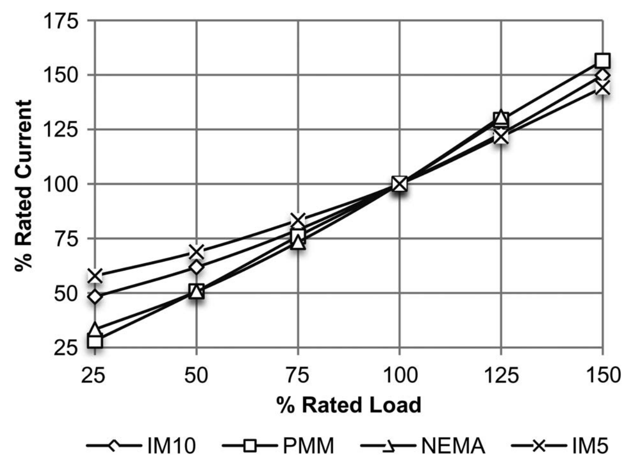

Fig. 6. Input current versus load.

mechanical load. Thus, as the mechanical load is decreased, FW becomes a larger percentage of the mechanical power output.

The IM10 compared had improved lamination designs. Obviously, its peak efficiency is at approximately 65% of rated load. This motor was rerated to 10 hp/rotor for competitive reasons and because at 100% load its efficiency was still greater than the IM5.

Variations of input currents versus load are displayed in Fig. 6. As a percentage of full-load current, the NEMA and ESP PMM motors behave almost identically. At 150% of rated load, the ESP PMM draws more current than the ESP IM. This is attributed to FW because the PMM is running at synchronous speed, i.e., 3600 r/min, but the IM is running at only 3350 r/min.

On the other end of the curve, the ESP IM has much higher current due to relatively smaller magnetizing reactance. This is not a problem with the ESP PMM because the magnets provide the flux. In the much larger diameter, NEMA motor magnetizing reactance is much greater relative to the winding resistance and leakage reactance than it is in the ESP IM.

At no-load input, current relative to rated current is 24.8% for the NEMA motor and 43% for the IM10. For the PMM, it is only 16.9%. However, for the IM5, it was 52%. It was aforementioned that the IM5 was a very old design. This high no-load current was attributed to magnetic saturation in both stator and rotor teeth and in the rotor yoke. Rotor flux must also pass through the shaft. Consequently, the magnetizing

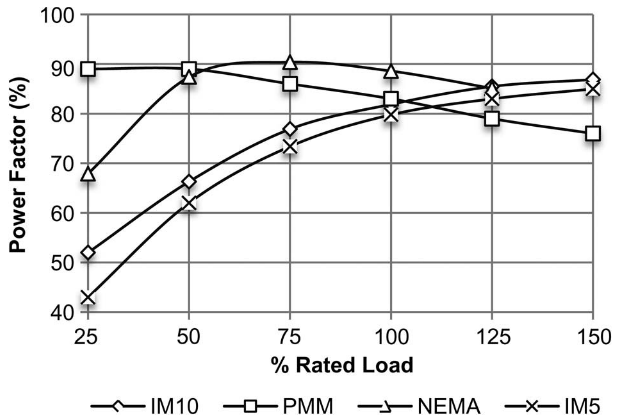

Fig. 7. Power factor versus load.

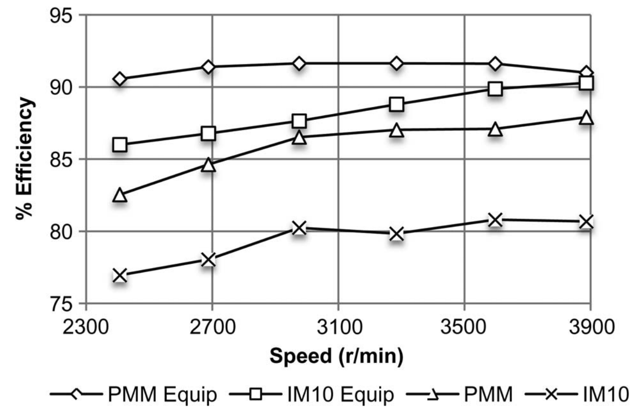

Fig. 8. Equipment and motor efficiencies at various speeds.

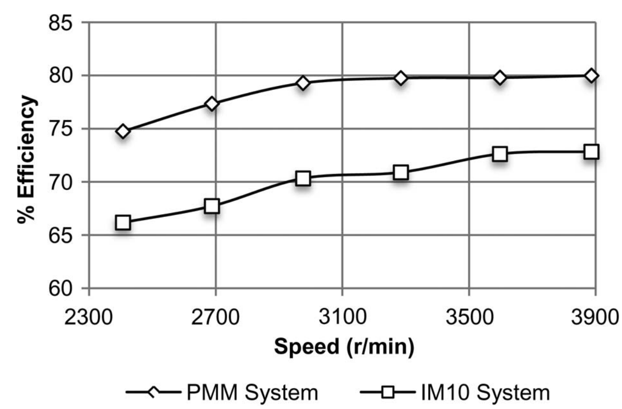

Fig. 9. Total system efficiency.

inductance is relatively lower. Because current is often used for detection of gas-lock and pump-off conditions, the greater range of input currents with an ESP PMM makes accurate detection easier for these two underload conditions.

At 150% rating, it was noted that current into the PMM was higher than currents into IM10 and IM5. This was attributed to speed cubed change in FW. The PMM was running at 3600 r/min, whereas the IM10 and IM5 were running near 3300.

The major effect of low magnetizing inductance for the ESP IM is a dramatic decrease in power factor at reduced loads (see Fig. 7). This decrease in power factor indicates that, by definition, motor current has become much more reactive. As a result for the same light loads, the current into the two IMs is much greater than for the PMM, i.e., a much higher kilovar value is required. This is a problem if the electric utility charges a penalty for low power factor.

Reduced power factor at higher loads for the PMM is surmised to result from the increased voltage drop across the leakage and magnetizing inductances.

IV. Laboratory Tests: Variable Speed

Data presented to this point have been only for the motors themselves running on 60-Hz power (120 Hz for four-pole PMM) with variable load. An IM5 was not available for these tests, preventing a direct comparison with equipment in the field test. However, a more efficient IM10 was substituted in an effort to identify system losses.

For centrifugal pumps, head varies as speed squared and flows directly with speed; thus, the motor load varies as speed cubed, cf., (1). A pump running at half rated speed would only require one-eighth rated power and one-quarter rated torque. Given these pump affinity laws and having an ASD to set the speed, dynamometer torque was adjusted to change with speed squared. The reference point was rated torque at 3600 r/min.

Drives for ESP IM applications are nearly always in the constant torque (constant V/f) mode that keeps breakdown torque nearly constant over the frequency range. For the two-pole ESP IM, frequency for a given speed N is

$$f = N/\left[60(1-s)\right] \tag{3}$$

where $N =$ speed in revolutions per minute, and $s =$ slip. This is important for comparison with the field tests because pump speeds must be identical.

In the laboratory, it was possible to measure input 460-V power to the ASD, input power to the motor, and motor shaft power. Equipment efficiency, labeled Equip in Fig. 8, was determined from the first two power measurements and included the combined efficiency of the drive, filter, step-up transformer, and cable. This equipment is illustrated in Figs. 10 and 11. Motor efficiency was calculated from the last two measurements.

Total efficiency is the product of equipment and motor efficiency values (see Fig. 9).

Finally, it is noted in passing that required pump torque increases as the square of the speed and a motor sized for rated output around 3600 r/min will be overloaded at higher speeds. To avoid severe overloading, the common ESP industry practice is to restrict the speed to $+10\%$ and -20% about 3600. This provides more than adequate flow range to produce nearly any well due to the variable-speed characteristics of centrifugal pumps.

V. Field Tests

Table II lists the identical equipment that was used for both IM5 and PMM field testing. It was felt necessary to have as much common equipment as possible to conduct an unbiased field test.

TABLE II
COMMON EQUIPMENT USED FOR ESP IM5 AND ESP PMM FIELD TEST COMPARISON

ESP cable	6000' #4 AWG Lead Flat
Lower Motor Seal	400 Series
Upper Motor Seal	400 Series
Intake section	400 Series Bolt-on intake
Pump	285 stage 400-3000
Flow measurement	Liquid turbine flow meter
Pressure measurement	Wellhead pressure gauge
Input power measurement	Industrial grade power analyzer
Output power measurement	Industrial grade power analyzer
Output (step-up) transformer	520 kVA, VFD, connected delta-wye
Input (step-down) transformers	3-100kVA,12470/480, connected wye-delta
Input disconnect	400 A, 600 V
Output junction box	Medium-voltage rated
Test well	High productivity minimal draw-down
Pump intake pressure measurement	

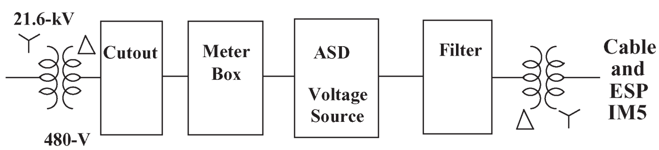

Fig. 10. ESP IM equipment configuration and instrumentation.

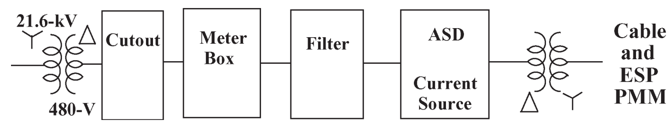

Fig. 11. ESP PMM equipment configuration and instrumentation.

If the same pump was used for both tests, it should be run at the same speed for both tests. Because IM speed is slightly less than synchronous speed due to the slip factor, i.e., (3), the ESP IM5 system should be run at a slightly higher frequency to compensate.

The most reasonable approach appeared to be adjusting the frequency to have identical flow rates at the wellhead with constant wellhead pressure. However, from experience, turbine flowmeters can be erratic due to entrained gas in the produced fluid. Pump intake pressure was more easily regulated because the fluid at the intake is under considerable pressure eliminating any gas breakout. Maintaining constant pressure across the pump ensures constant flow. Still, flowmeters are needed to measure the cumulative quantity of fluid produced, and this averages out between the two systems.

When pulsewidth-modulated (PWM) drives were first used with ESP systems, serious current oscillations were encountered that quickly destroyed the drives. This was particularly true for systems with cable longer than 5000 ft [9], [10]. Analysis indicated that step-up transformer leakage inductance resonated with cable input capacitance, and this series resonant circuit was easily excited by the harmonic-rich output of a PWM drive. Since then, low-pass filters have been designed and installed between the drive output and the transformer to convert voltage source PWM waveforms into sine waves before being stepped up. This is one feature the ESP IM5 system had that was different. The ESP IM5 system electrical configuration and instrumentation are shown in the Fig. 10 diagram.

Input power harmonics were felt to be a problem with the operation of the ESP PMM system in current mode. An input filter was installed between the input 460-V, three-phase power, and the drive input. This is a feature that the ESP PMM system has that is different. A slightly different equipment configuration was required (see Fig. 11). This placed the filter ahead of the ASD. Otherwise, instrumentation was identical to that used in Fig. 10.

Fig. 12. ESP PMM drive, filter, transformer, and instruments.

The actual surface equipment used for the ESP PMM test is shown in Fig. 12.

Test system differences were as follows:

1) IM5 - 456 series, 240-hp, 2 × 1295-V, and 59-A motor;
2) filter between drive and step-up transformer;
3) PMM - 117-mm, 266-hp, 2466-V, and 62-A motor (this rating is for 3600-r/min operation);
4) 250-kVA input harmonic filter;
5) current source drive.

Data collection involved the use of telemetry to continuously monitor parameters and display them via a website. Data included flow, intake pressure, power quality, kilowatt values, voltage values, and ampere values. The well was produced at similar stabilized production rates to ensure test accuracy. With each system, tests were run at various identical speeds for several days. From the instantaneous data collected, average and cumulative data were calculated. Between system change-outs, the pump was laboratory tested per American Petroleum

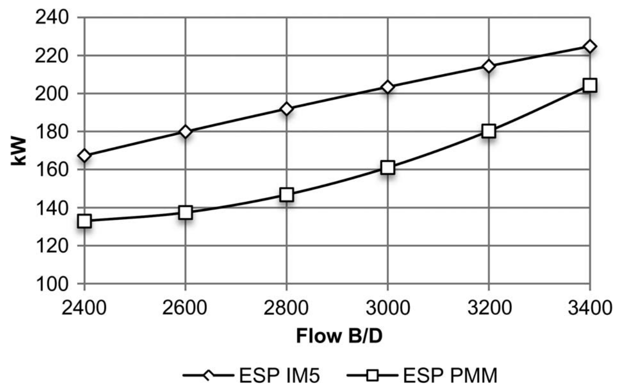

Fig. 13. Cost of production comparison.

TABLE III
KILOWATT COMPARISON AT THREE FLOW RATES

	kW			%
B/D	IM5	PMM	Difference	Change
2400	167.3	132.9	34.4	20.6
3000	203.4	161.0	42.4	20.8
3400	224.8	204.3	20.5	9.1

TABLE IV
ROTOR DIMENSIONAL COMPARISON

Type	hp	hp per rotor	#	diameter (inches)	length (feet)	Total (feet)
NEMA	200	200	1	10.67	0.89	0.89
IM5	240	5	48	2.27	1.08	51.8
IM10	240	10	24	2.21	1.16	27.8
PMM	266	22	12	2.64	1.13	13.6

Institute standard [11] to check for any performance deterioration. The net result is shown in Fig. 13.

Table III and Fig. 13 represent a significant decrease in power usage with ESP PMM production. At 3000 B/D, the difference in power was 42.4 kW. Assuming that energy costs are $0.1/kWh, a 24-hour day, and a 30-day month, this results in savings of 30540 kWh per month. The monthly dollar saving would be $3053. Furthermore, these savings continue month after month.

Last, Table IV depicts a comparison of the physical size of all the motors used. Motor diameters are 4.56 in for the IMs and 177 mm or 4.61 in for the PMM. Concentrating on just the active part of the motors, i.e., the rotors, the differences in length are striking. For the IMs, the old design rated for 5 hp/rotor (IM5) is essentially twice as long as the rerated new design at 10 hp/rotor (IM10). IM5 has two tandem sections each rated for 1295 V for a total voltage rating of 2590. The rating for the PMM is possible because there is virtually no heat generated in the rotors. Furthermore, being a four-pole design, the stator windings can be closer to the housing making heat transfer easier. Overall, the PMM runs much cooler.

A short motor has two additional advantages. Since samarium–cobalt (SmCo) magnets are probably the most expensive component in the motor, that cost can be offset against the increased amount of copper and iron in IMs of equal power. Second, shorter motors have lower FW losses and are more easily installed in deviated wells.

VI. CONCLUSION

Laboratory tests have been run to verify and emphasize the improvement in ESP PMM efficiency over ESP IM for same-size small-diameter motors. The current source ASD was also more efficient than the PWM ASD with a filter. Field tests were run to relate these efficiency improvements to production operating costs. The ESP PMM was shown to use 20% less power for the same production.

APPENDIX
SAFETY

Introducing a new technology into a mature industry can be very dangerous, particularly when most of those involved with servicing the product have a mindset as to how things should be done. In the past, a check valve was included in the tubing string a few feet above the pump discharge. This kept the tubing string filled when the ESP was shut off, which avoided the need to refill the tubing before production could begin again after restart.

In recent years, the check valve has been almost completely eliminated so that well acidizing can be done down through the tubing string. Now, the column of oil in the tubing flows back down through the pump until the static level in the well is reached. In the process, the pump spins backward, often at speeds exceeding synchronous. This is referred to as backspin.

Typically, the electric cable is continuous from the motor pothead through the wellhead into a junction box. The cable is opened up inside this box to prevent conducted explosive gases from reaching an ignition source, such as a switchboard or drive. Voltage measurements are commonly made inside the junction box.

In backspin, an ESP IM will generate from 8 to 12 V phase to phase due to residual magnetic flux in the motor. Attempting a start during backspin frequently causes shaft breakage due to plugging and hunting. Therefore, service personnel monitor this voltage until it drops to zero. At that point, the motor has stopped turning, and it can be safely started. Controls are programmed to lock out a restart during backspin. This is a common operating practice.

Following this practice with an ESP PMM is extremely dangerous. Magnetic flux in the motor is provided by SmCo permanent magnets. From zero to almost any speed, the flux level is unchanged. However, voltage changes directly with speed. At a backspin speed equivalent to operating speed, the PMM will generate operating voltages, and these are lethal.

Obviously, appropriate warning labels must be placed on the junction box. An additional insulating, possibly transparent shield plate, might be provided between the door and the cable connection terminals. Certainly, personnel training must emphasize this hazard.

Pulling an ESP PMM out of a well or running one back into a well will cause motor rotation. Under such circumstances, voltages will be also produced at the open end of the cable at the bottom of the spool. Frequently, the ESP is pulled because an electrical short occurred in the cable or motor. Thus, it is possible that spooling equipment and possibly the rig itself could see hazardous voltages. During work-over operations, all equipment must be grounded to the wellhead. Furthermore, the phase wires at the bottom of the spool should be shorted together and grounded.

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