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2019

Permanent Magnet Motors for ESP Applications – Updating the Track Record of Performance

Lorne Simmons – VP Sales & Marketing

Technology Development – Milestones and Achievements

- Late 1990s – Permanent Magnet Motor (PMM) technology development (for ESP application) initiated by Borets.
- 2005 – First PMM field installation.
- 2006 – First PMM (462 Series) commercialized.
- 2009 – 406 Series PMM commercialized.
- Since 2010
  - Higher horsepower PMMs through enhanced rotor bearing technology
  - Expanded PMM series released
  - High and low-speed PMMs released.
- 2011 – Extensive development and release of first proprietary PMM control algorithm in dual compatible (IM & PMM) surface variable frequency drive.
- 2015 – Release of second generation (dual compatible) PMM surface drive.
- 2015 – State-of-art PMM testing facility opened in Tulsa, Oklahoma.
- 2018 – Borets installs it **250th PMM** in the **Permian Basin.**

Induction Motor vs Permanent Magnet Motor

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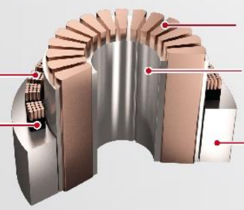
Traditional downhole ESP motors used are three-phase, two-pole, squirrel-cage AC induction motors.

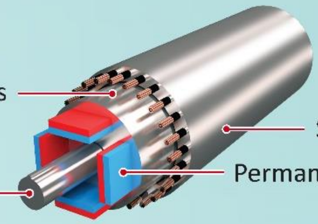
The downhole PMM for ESP application introduced to the industry in 2006.

Induction Motor



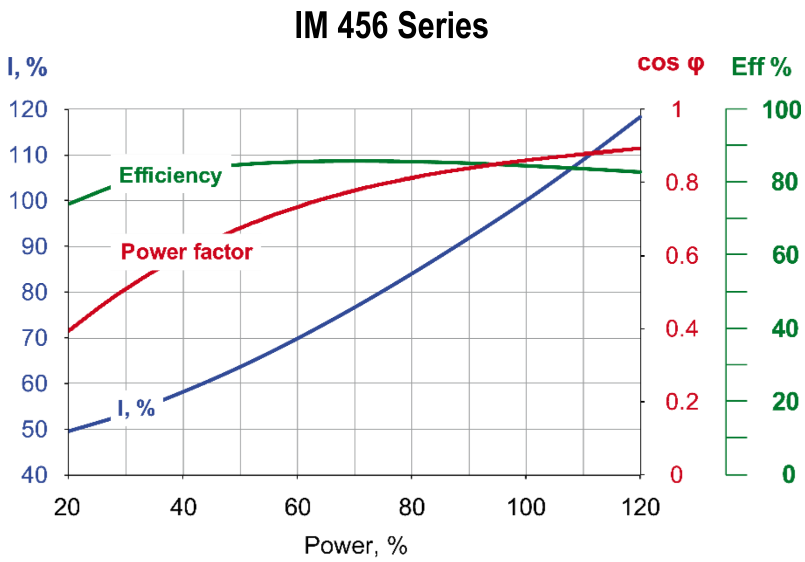
- Rotor constructed using copper bars short-circuited by two copper end rings
- Rotor magnetic field is generated by current induced in the (rotor) copper bars
- Rotating magnetic field created in the stator when alternating current is applied to non-rotating stator windings
- Interaction of the rotor magnetic field and (rotating) stator magnetic field results in:
  - rotor torque
  - slip
- No special VSD control algorithm required

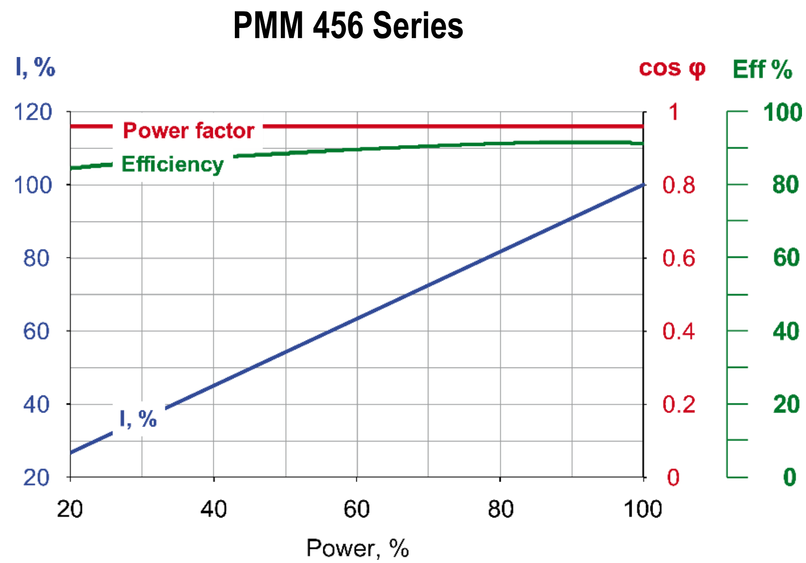
Permanent Magnet Motor



- Rotor constructed to include permanent magnets made from hard-sintered rare-earth metals
- (Constant) Rotor magnetic flux created by presence of permanent magnets
- Rotating magnetic field created in the stator when alternating current is applied to non-rotating stator windings
- Interaction of the rotor magnetic field and (rotor) stator magnetic field results in:
  - rotor torque
- Special control algorithm required

Standard Performance Curves – 456 Series IM vs 456 Series PMM





At BEP, PM motors are 7 – 10% more efficient than the equivalent IM.

Induction Motor		Permanent Magnet Motor
180	Motor power (hp)	180
18	Number of Rotors	9
24.5	Length (ft)	14
88	Max. Efficiency (%) @ 60 Hz	93

456 Series IM vs Equivalent 406 Series PMM Comparison

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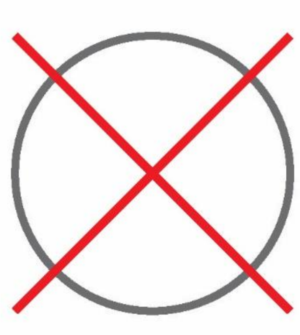
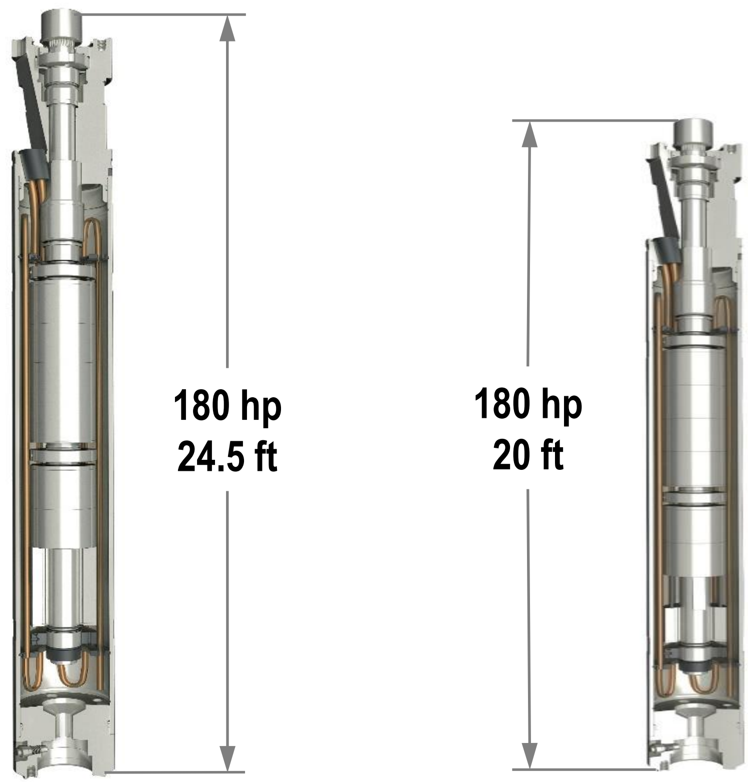
456 Series IM

Casing OD: **5.5 in.**
Weight: **20#**
Drift ID: 4.653 in.



Casing OD: **5.5 in.**
Weight: **17#**
Drift ID: 4.767 in.



406 Series PMM

Casing OD: **5.5 in.**
Weight: **20#**
Drift ID: 4.653 in.

Casing OD: **5.5 in.**
Weight: **17#**
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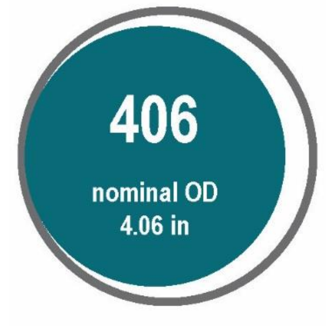

Current PMM Portfolio

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PMM Motor Series

● *Commercial products*
◍ *Under development*

	319	375	406	456	512	562	728
Standard Speed (3,600 rpm – 4 pole)	–	✓	✓	✓	✓	✓	✓
High Speed (6,000 rpm – 4 pole)	✓	TBD	✓	✓	✓	✓	TBD
Low Speed (500 rpm – 10 pole)	–	-	–	✓	–	✓	–
Power Factor	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Max. Efficiency, %	up to 93	up to 93	up to 93	up to 93	up to 93	up to 93	up to 93
Rated Winding Temp, °C	200	200	200	200	200	200	200
# Motor Sizes Available	17	TBD	18*	16*	18*	18*	TBD
Min. Power (hp)	24	TBD	24*	40*	80*	100*	TBD
Max. Power (hp)	150	150*	228* (264)*	400*	760*	980*	1500*
HP / Rotor	8	TBD	12*	20*	40*	50*	TBD

* For Standard Speed Motors

Realizing the Advantages of PMMs – Drives Matter

- 7 – 10% increase in motor efficiency at rated power

  Reduced power consumption (up to 20%)

- 10 – 15% lower operating current

  Reduced motor heat rise improves equipment and system reliability

- Higher rotor HP density

  Up to 40% reduction in motor length

- Wider operating range

- Improved adaptive control

- Soft start capability

Advantages of PMMs are realized when operated as part of a “tuned” drive-downhole motor system.

Comparison of Different PMM Control Methods

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Back-EMF control ✓

- Only two of three phases conduct current at any one time
- Rotor position detected by back-EMF induced in (idle) third phase as motor rotates at any time.

Advantages:

- Independence from motor parameters
- Simplicity - requires only step-up transformer and long power cable.

Limitations:

- Cable length, motor inductance and speed yield fluctuations in zero current phase resulting in failure to locate rotor position.
  - reduced efficiency

Scalar control ✓✓

- Inverter circuit ensures sinusoidal phase voltages and currents
- Voltage across the motor is a function of pre-set speed (U/F control)

Advantages:

- Overcomes limitations associated with back-EMF method
- Optimized performance for static motor loads

Limitations:

- Drive performance NOT optimized across entire (or variable) range of motor speeds and loads.
  - sub-optimal efficiency across variable motor loads

Vector control ✓✓✓

- Advanced process running complex algorithm
- Resolves rotating phase vectors
- Results in precision control of flux (magnetizing) and torque producing currents. Voltage to the motor is applied based on:
  - Motor inductance vector values
  - Permanent magnet flux linkage
  - Active resistance of the phase windings
  - Amperage
  - Motor design characteristics

Advantage:

- Performance and energy efficiency of the VSD/motor system is continually optimized across all speeds and loads.

The vector control method consistently delivers exceptional efficiency and lower heat rise as compared to the other methods of PMM control.

Case Example #1: Induction vs Permanent Magnet Motor Comparison Test – Howard County, Texas

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Test Objective:
Prove / disprove energy savings using PMM technology

Well

- TD: 7,725 ft
- TVD: 7,599 ft
- Completed: April 2010
- Casing OD: 5.5 in.
- Casing weight: 17# / ft
- Pump setting depth: 6,000 ft

Equipment Used in Test

- **Induction Motor (IM):** 456 Series, 240 hp, 2x1,295 V, 59 A tandem motor
- **Permanent Magnet Motor (PMM):** 117 mm, 266 hp, 2466 V, 62 A motor
- **Variable Frequency Drive (VFD):** Borets-VD250-300 Current Source Drive
- **ESP Cable:** 6,000' #4 AWG SL-450 Lead Flat
- **Motor Seals:** 400 Series Tandem
- **Pumps:** 400 Series, 3,000 bpd (285 stages, 3 sections)
- **Intake pressure measurement:** Borets Viewpoint ESP downhole sensor

Test 1: measure power consumption maintaining constant (surface) flow rate

Flow Rate (BPD)	IM (kW)	PMM (kW)	Delta	Delta (%)
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**

Test 2: measure power consumption maintaining constant intake pressure

	Frequency (Hz)	Pump Intake (psi)	Motor Load (%)	Motor Winding Temp (°F)	Motor Efficiency (%)	Power Consumed – Meter (kW-Hr)	% Savings (kW-Hr)
IM	55.8	601	67	182	80.4	161.8	-
	61.6	545	83	187	82.9	211.3	-
	65.9	505	97	192	84	245	-
PMM	52.7	603	63	186	90.8	133.3	↓ **17.6**
	57.5	545	78	199	91.1	177	↓ **16.2**
	60.5	505	89	210	90.7	210.9	↓ **13.9**

Case Example #2: Induction vs Permanent Magnet Motor Comparison Test – Ector County, Texas

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Test Objective:
Compare IM vs PMM technology to evaluate power consumption results against manufacturer claims and lab test results

Well

- TD: 4,690 ft; TVD: 4,690 ft
- Completed: 1975
- Casing OD: 5.5 in.
- Casing weight: 14# / ft
- Pump setting depth: 4,305 ft

Equipment Used in Test

- **Permanent Magnet Motor (PMM):** Borets 456 Series, 60 hp, 1,022 V, 35 A motor
- **Variable Frequency Drive (VFD):** Borets Axiom II, 125 kVA, 150 A
- **Motor Seals:** Borets 400 Series Tandem
- **Intake pressure measurement:** Borets Viewpoint ESP downhole sensor
- **Induction Motor (IM):** 456 Series, 60 hp
- **Pumps and ESP Cable**: 3rd party provided

Test conducted in three stages:

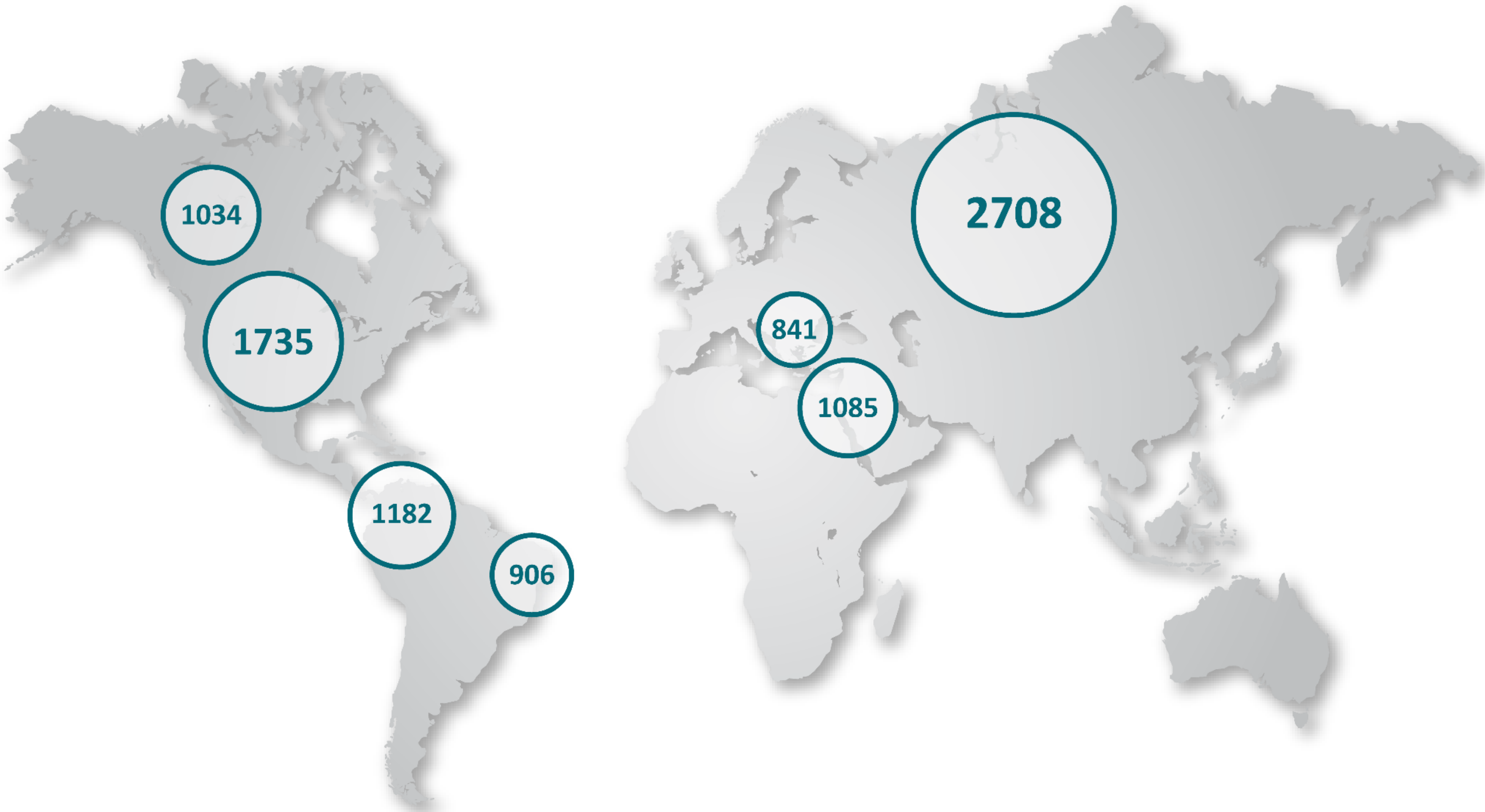
1. ESP system (IMs) operated on switchboard at 60 Hz
2. ESP system (IMs) operated on VFD
3. ESP system (PMM) operated on VFD

The same surface drive, cable used in stages 2 and 3.
New downhole motor and seals installed.

	Frequency (rpm)	Pump Intake (psi)	Motor Load (%)	Motor Winding Temp (°F)	Flow Rate (BFPD)	Power Consumption (kW)	Change in Power Consumption (%)
IM	2900	610	72	U/A	520	31.0	
	3200	275	77		557	37.4	
	3450	80	79		737	44.1	
PMM	2900	620	51	127	650	25.0	↓ **19**
	3200	355	61	135	770	32.7	↓ **13**
	3450	125	63	135	830	38.5	↓ **13**

Global PMM Experience – PMMs Currently Operating

Global PMM Experience – Maximum Run Days Achieved



Summary and Conclusions

Physical design characteristics of PMMs contribute to:

- **Reduced energy consumption**, even under variable / reduced load conditions
- **Improved reliability** – reduced electrical losses – **lower heat rise** during operation contributes to longer equipment run life
- Increased power density – more HP per rotor – **shorter overall equipment length**.

The type of motor control method used by the surface VSD is critical to realizing maximum benefit of PMMs

- Not all PMM surface drive control algorithms are equal
- **Vector control optimizes PMM control** taking into account the design characteristics of the downhole motor.

The **benefits of reduced energy consumption and lower heat rise** during operation are **being realized by operators in the Permian Basin**.

Questions?

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