PERMANENT-MAGNET MOTORS FOR SUB-SEA APPLICATIONS

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Abstract

This paper is a technology overview of permanent-magnet (PM) motors for sub-sea applications, which offer a significant benefit over induction motors. With exploration and production moving to deeper waters, higher differential-pressure pumps are being required. In order for conventional centrifugal and helico-axial sub-sea pumps to deliver higher pressures either more stages have to be added to the pumps (rotor-dynamic limitations) or existing pumps need to operate at higher speeds above 4kRPM, up to 6kRPM and beyond, where they are normally operated for topside applications. Because of the fluid filled gap, existing induction motors suffer a significant decrease in efficiency beyond 4kRPM due to the sensitivity to mechanical gap length for power conversion. The larger-gap PM machine is able to deliver efficiency between 85% and 90% (including drag and cooling pumping losses) up to and beyond 6kRPM. In particular, at 2.5MW and 4kRPM an efficiency of over 91% is expected – this is compared to published data for a similarly rated induction machine which achieves an efficiency of less than 75%. System-level trade-offs are explored and a few case studies will be presented covering pumps up to 6MW and compressors up to 9MW.

I. INTRODUCTION

Permanent-magnet (PM) motors for sub-sea applications offer a significant benefit over induction motors. The performance of the PM machine is less sensitive to larger mechanical gaps than the induction machine (IM), since the magnetic gap of a PM machine is typically many times larger than the mechanical gap. The additional space available in the gap can be used to reduce the rotor diameter and/or provide a sleeve between the fluid-filled gap and the stator. High-energy-product magnets provide the rotor flux in a modern PM machine (rather than currents induced from the stator flux as in the case of an IM) – this allows a simpler rotor construction than a squirrel-cage induction-machine rotor; the elimination of rotor-conductor losses; and load-independent speed-control. The potential of a smaller rotor diameter, larger mechanical gap, and simpler rotor construction allow higher speeds (and higher power density) to be achieved in a PM machine than similarly sized induction machines – ultimately, more power can be delivered to the load in a smaller package.

The stator construction for a PM machine is typical of most machines. A well designed stator core for an IM would serve well as the stator core for a PM machine (assuming the same rated voltage, current and frequency). However, the ability of the rotor to produce flux independent of the stator excitation, and the likely different optimal solutions for a PM machine and an IM (iron area vs. copper area, length, inner and outer diameters, etc.) means that a PM rotor should not be considered a direct replacement for an induction machine rotor. Many of the factors discussed below impact the design choices for PM and induction machine alike, although the best motor (or stator) design for the system could be significantly different between the two topologies.

There are a few distinct advantages that PM machines have by virtue of the differences in their equivalent circuits or topology. A PM machine will be able to develop full torque at start-up with only rated current, while an IM can require up to 400% rated current during starting. The magnetic gap of the PM machine is larger than the mechanical gap by the magnet thickness and since the magnetic gap is a key parameter in determining unbalanced magnetic pull (UMP) due to an offset rotor the PM machine has an advantage here as well.

A few of the key considerations in designing the drive system (power electronic (PE) converter, cables, and motor) are the available and cost effective drive input and output ratings (voltage, current, and frequency); the available and cost effective terminators, penetrators, and connectors; the necessary cable length; and machine performance trade-offs (vs. cost and system level impact): size, power output, power factor, and efficiency among others. Terminal voltage, current, and rotor speed are the principal factors determining the power output for a motor. The motor current can be limited by any of the following: terminators, connectors, penetrators, and PE converter rating. The PM motor speed is determined by the frequency and pole count of the machine since the rotor spins “synchronously” with the magnetic field, as opposed to the induction machine which has a rotor that “slips” past the magnetic field and is therefore load-dependant. The terminal voltage at the machine will be limited by the PE converter output voltage and voltage drop in the cables (which increases linearly with frequency). Terminal voltage and phase current can be easily traded against each other in the machine design, but there are some limits due to the integral nature of the number of slots and poles.

In a conventional multi-megawatt machine the windage or drag losses are a small fraction of the power output of the machine, however in the case of fluid-filled-gap machines running at high speed, the drag losses become a significant factor in sizing the machine. Whereas in a conventional land-based application, a higher efficiency machine can be obtained by increasing size, the opposite is true for the fluid-filled-gap machines typical in sub-sea pumping applications. The current density of the stator is a key limiting design factor in conventional air-cooled machines, but the highly effective cooling available in sub-sea fluid-filled applications and the high drag losses relative to the iron and copper losses make this factor less significant, but still limiting when sizing the stator. Electric machines are fundamentally sized by torque, not power, so higher power densities (and smaller machines) are available with increasing frequency (and speed). The limiting constraint (other than mechanical construction) of the frequency at which a motor is designed to operate is the ability to remove heat – not only are the losses (especially electrical) higher, but the size is decreased which exacerbates the temperature rise. The sub-sea applications being considered here will have frequency limits which are imposed by the voltage available at the machine terminals and not necessarily the electrical losses, since discrete voltages are readily available from the PE converter and cable voltage-drop increases with cable length and frequency.

II. CASE STUDIES

A. Permanent-magnet rotor replacing a squirrel-cage rotor in the same stator

The oil-filled pump motor considered here was a high-speed, multi-megawatt induction machine. A PM rotor was designed to fit in the same form-wound stator and to operate at a speed 16% higher and deliver 16% more power to the load. More performance gains were possible with a purpose-designed PM rotor and stator, but this simple case shows clear advantages while holding the stator size constant. The phase current at rated operation for both machines was fixed. The IM had a gap typical for machines of this type while the PM machine allowed for a mechanical gap almost four times the size. The final PM rotor design resulted in roughly a 3:1 reduction in unbalanced magnetic pull for the same bearing offset, which should extend bearing life significantly. Figure 1 compares the efficiency of the motor with a PM rotor operating at full power to the IM operating 86% of that output.

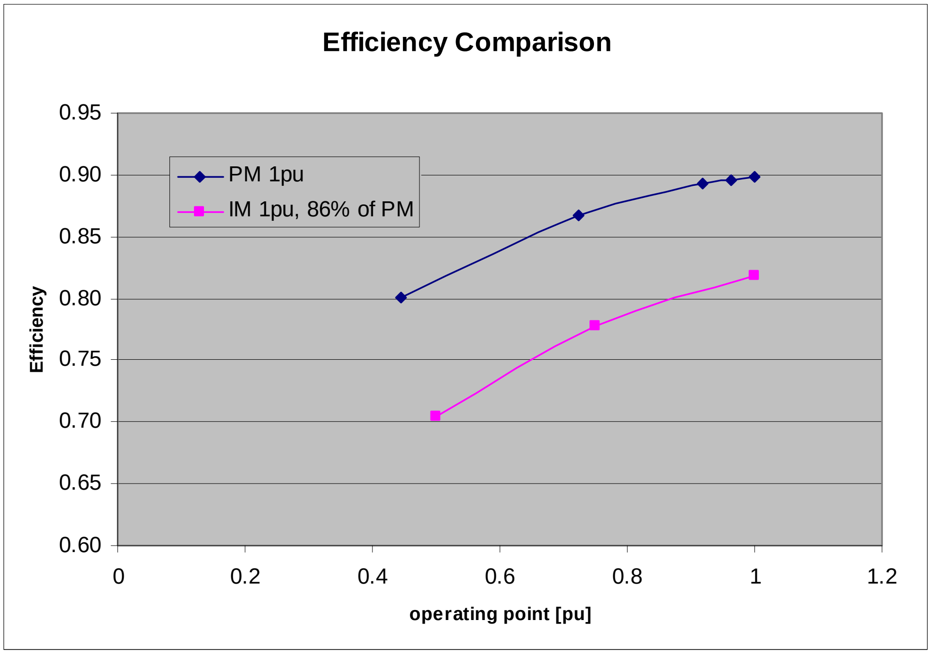

Figure 1: Efficiency comparison between PM machine (predicted) and IM (measured)

The efficiency of the PM machine over the IM is achieved primarily because of a reduction in the absence of rotor losses. The rotor conductor losses are absent in the PM machine, but this contribution to the total loss is a minor effect. The dominant advantage is that although the PM machine operates at a higher speed, the drag losses are 60% lower than those of the IM because of the significantly larger mechanical gap in the PM machine. Figure 2 shows that the power factor of the PM machine is higher than that of the IM at rated conditions and continues to rise as the power rating drops. In contrast, the power factor of the IM drops as the current is lowered. The frequency is held constant for each machine, but the IM speed changes as the slip changes. The power factor and efficiency curves combine in Figure 3 to show the total advantage in power conversion that the PM machine has over the IM, even when restricted to use the same stator.

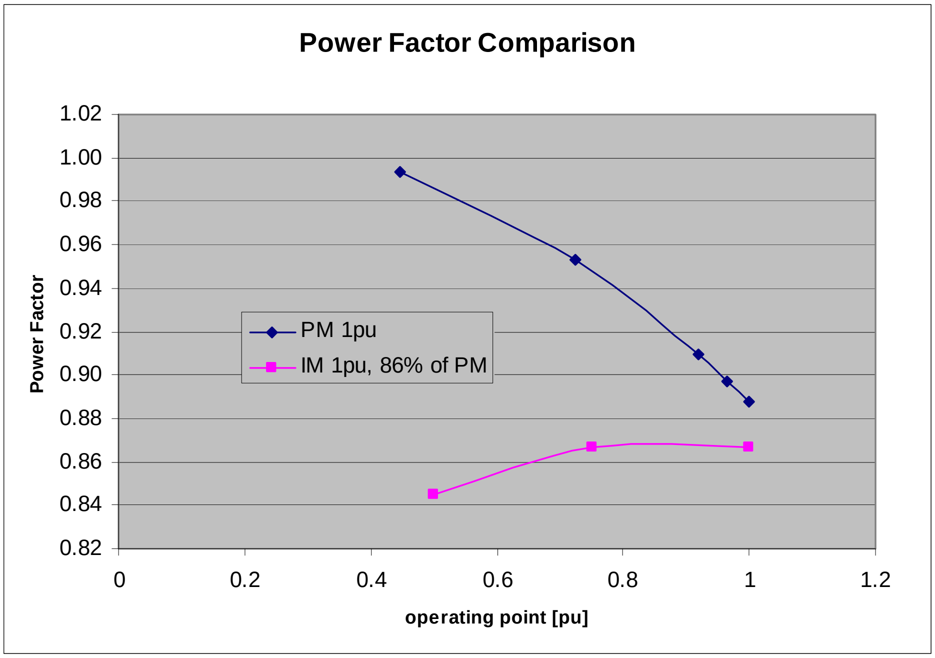

Figure 2: Power factor comparison between PM machine (predicted) and IM (measured)

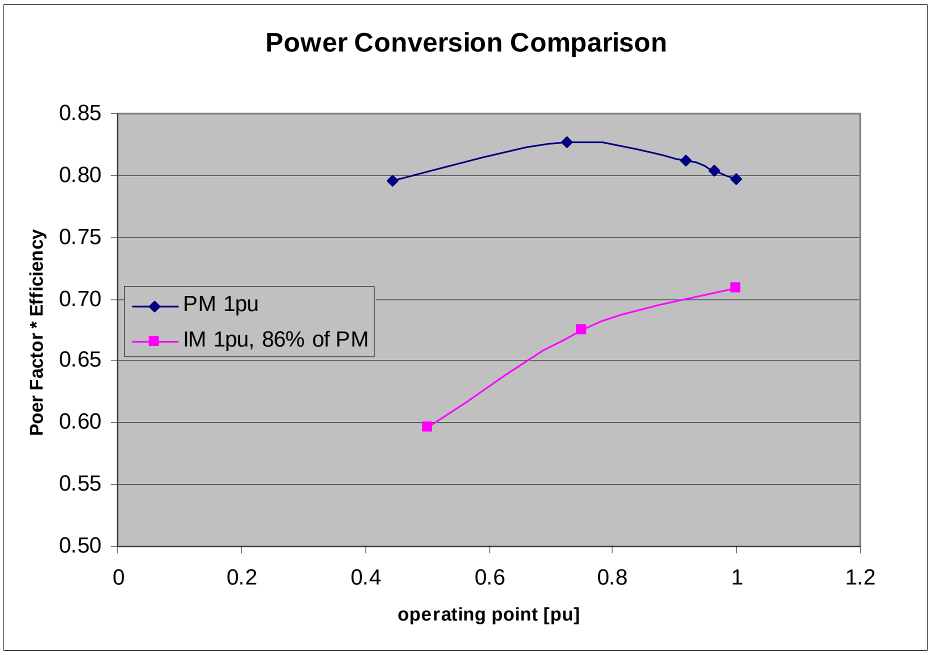

Figure 3: Power conversion comparison between PM machine (predicted) and IM (measured)

B. Product family of permanent-magnet machines compared to an induction machine

The state-of-the-art for an IM was taken from [1] and provided enough technical data to predict competitive performance into the operating region of interest. Several designs of DDS PM machines were analyzed for performance at a number of operating points and those designs are compared directly to the IM. The IM design is shown to be inadequate at higher speeds, while the DDS PM machine can operate at the desired, elevated speeds and has a significant advantage in efficiency in general. The IM is rated at 2500kW, 6.6kV and 60Hz. As a two-pole induction machine, 60Hz excitation will provide operation just under 3600rpm.

An included torque-speed curve gives an approximate operating point for this machine at 60Hz of 3575rpm, 5000Nm and 275A at 6.6kV (output power of 1864kW and input power of 2500kW). The technical data provided includes total output power (2059kW), total losses (530kW), and electromagnetic (EM) losses (74kW) at 3300rpm. Also provided was the bearing and pumping losses (205kW) at 4000rpm and a future power output goal of 2343kW. While there is no explicit statement that this output power is at 4000rpm, a constant torque assumption in the operating region of interest indicates that this is a good assumption. This data set allows an estimation of the IM performance over an extended speed range.

The rotor-stator-gap was given as 4mm for this machine. A stack length of 1m and a rotor outer diameter (OD) of 433mm was assumed for the prediction of drag loss in the extended speed range. A physics-based model for drag loss, including axial flow of fluid in the gap was used for the drag loss predictions. Predicted drag loss for the higher speeds did not vary significantly as different stack length and rotor OD assumptions were used, provided the drag loss at 3300rpm was maintained. As, the speed increases, so does the drag loss, until a point where the electric machine (torque limited) reaches a maximum output power. Speeds above 6000rpm will penalize the machine by providing decreasing output power as the speed increases. This machine would appear to be impractical to operate at speeds around 5000rpm. Attempts to over-power the drag loss at 6000rpm by increasing the machine stack length may allow an output power of 5.5MW to be reached, if the machine size is doubled.

Figures 4 and 5 show the advantages of using a PM machine over a conventional IM solution for the desired operating points in both efficiency and power conversion respectively. The results of the IM with projected performance presented is plotted with blue diamonds ("SOA IM") – this is a single machine operated at the four given operating points. The magenta squares indicate a family of DDS PM machine designs. The performance calculations for the PM machines utilized a commercial analysis tool that relies on a lumped-parameter model. However, the model parameters were corrected with the use of an electro-magnetic finite-element model. These results are not intended to be used as a baseline for design or quotation, merely comparison.

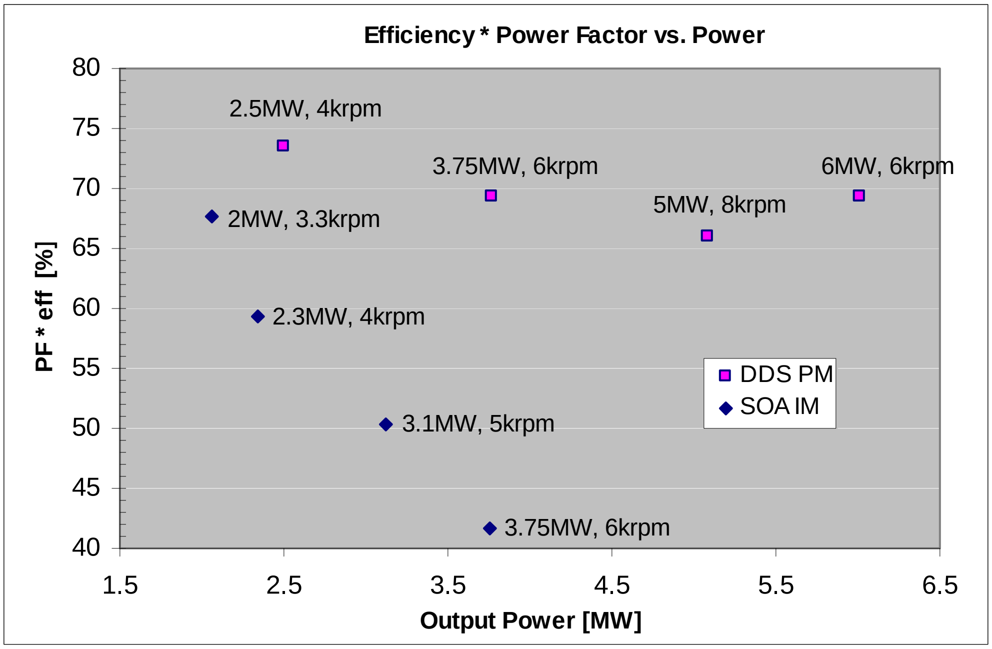

Figure 4: Power conversion comparison between family of PM machines and "state-of-the-art" IM

The DDS PM machines were designed as a product family, using the same stack length and stator laminations. While this restriction has the result of arriving at electromagnetic designs that are not entirely optimized for the desired operating points, this is practical limit that facilitates ease-of-manufacture and late-point-identification in the part stream. The goal of this case study was not to exhaustively explore the design space for the optimal solution, but to confirm the feasibility of PM machines for these applications and the advantages over other solutions.

It is clear from Figure 4 that the higher drag losses (due to smaller gap and presumably larger rotor diameter) of the IM severely penalize this machine when compared to a high aspect ratio PM machine with a relatively large mechanical gap. The lower predicted loss DDS PM machines show a marked improvement in both efficiency and power conversion over the higher loss PM machines. Not only do they benefit from the drop in losses directly, but since those losses are a significant portion of the total loss, less current needs to be fed to the machine to offset those losses thereby further improving the power factor.

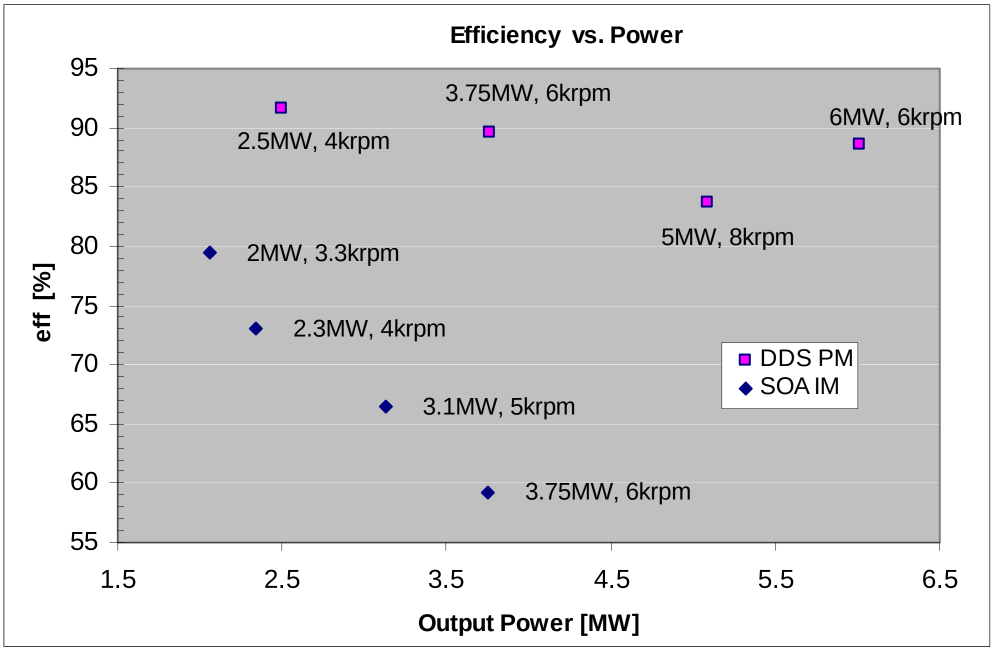

Figure 5: Efficiency comparison between family of PM machines and "state-of-the-art" IM

A general trend for these filled-gap machines is that a larger rotor penalizes the machine with higher drag loss, but a machine that is operated below the rated power will have an improved power factor. So, a design must be carefully selected to maximize total power throughput. The highest power factor machine may ultimately require a more complex power (MVA) to deliver a particular real power (MW) to the load than a lower power factor machine, if that lower power factor machine is more efficient. For this reason, the total power conversion ratio (efficiency * power factor) must be considered. The efficiency of the machine alone directly correlates with operating cost, but the power conversion ratio is a stronger indicator of installation cost. Figure 5 plots this ratio for the designs indicated versus output power. The higher assumed power factor of the IM does not offset the higher efficiency of the PM machines – which were sized for a relatively lower power factor and lower losses. This effect is apparent even within the PM machine designs: the trends of power factor, efficiency, and power conversion ratio versus machine rating can be seen more clearly when looking at a particular machine at a constant speed and varying current. Figures 6, 7, and 8 present the PM designs for this comparison.

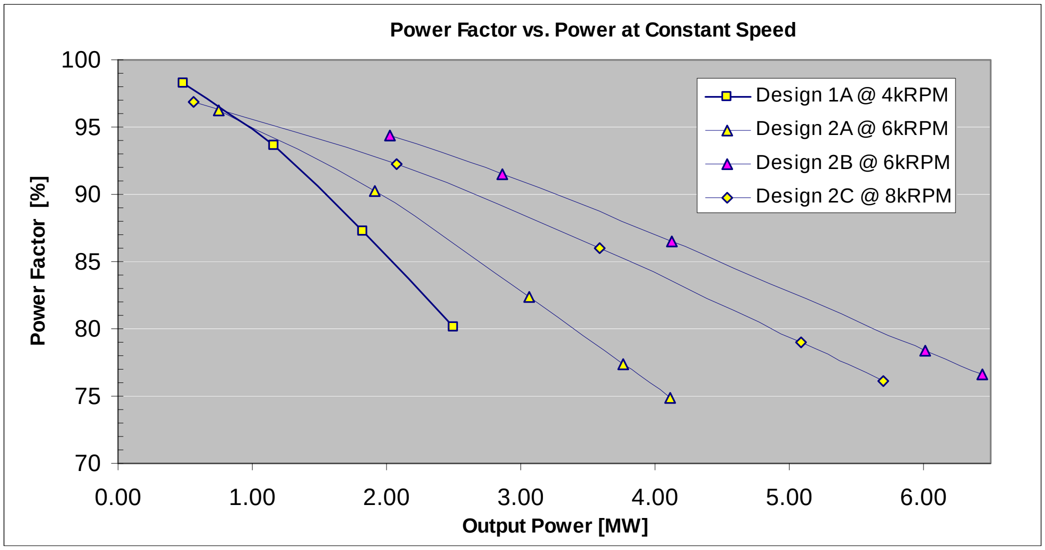

Figure 6: Power factor comparison for a family of PM machines

Design 1A, Design 2B, and Design 2C are the same size machines, but operated at different speeds (series turns are adjusted to trade voltage and current ratings at the different speeds). Design 2A is a larger diameter and longer machine than the other three designs. It is clear from Figure 7 that machine size is a dominant parameter in determining power factor. Figure 8 shows the penalties paid in efficiency for increased machine size (Design A2) and the benefits of operating at a lower speed (Design 1A). Design 2C shows the penalty that higher speeds exact – the PM machine of a given diameter is not exempt from a practical speed limit that the IM is subject to, the speed limit is merely higher, in this case about 100% higher.

Figure 8 is the resultant product of Figures 6 & 7. The opposite trends of power factor and efficiency with varying load create an optimal operating point at roughly half the rated power of the machines.

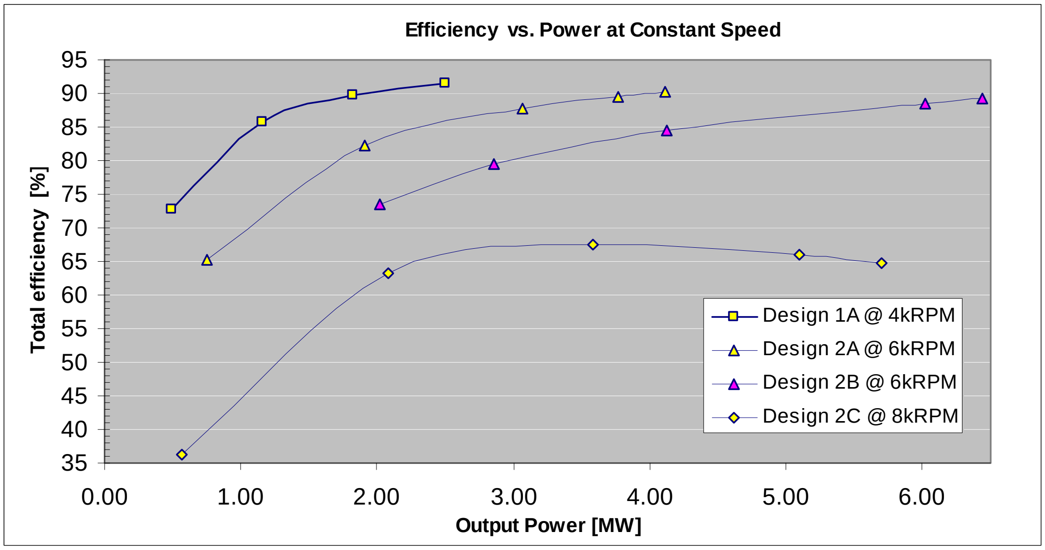

Figure 7: Efficiency comparison for a family of PM machines

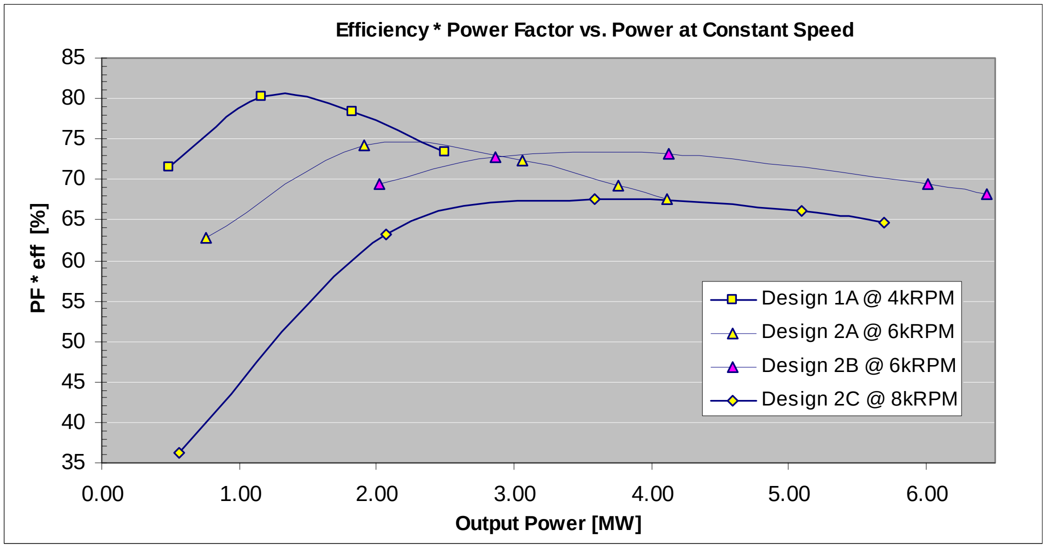

Figure 8: Power conversion comparison for a family of PM machines

This analysis shows that obtaining 6MW at 6kRPM with a fluid-filled-gap PM machine is feasible and practical. Furthermore, an entire product family (along a constant torque line) can be realized with the same stator core without undue penalty to performance. It is likely that the PM machine designs can be further optimized for the operating points, and the design calculations revised pending prototype testing. However, even with the assumptions made herein and the known uncertainties of the design calculations these results clearly show the DDS PM machines to have an advantage over an IM.

C. Permanent-magnet machine design studies for a compressor drive

The design studies for a 9MW compressor drive are tabulated in Table 1. The designs with an operating frequency of 200Hz are 2-pole designs and the 400Hz designs are 4-pole machines. Only one mechanical gap is presented here, 6.9mm - larger gaps tended to inordinately penalize the performance. The row heading of “Efficiency” includes the drag loss associated with the fluid in the gap. An indicator of motor size is tabulated in the row labeled “Motor Envelope”, which includes an estimate of the end-turn bundles in addition to the active stator-stack-length, multiplied by the area of the circle inscribed by the stator-lamination outer-diameter (OD). The stator ID was chosen to be fixed for all designs. However, further optimization can be made between gap, stack length and stator ID. A 50-50 mix of methane and ethane (by volume at 40C) was assumed to be in the gap. The current limit selected here was chosen as a commercially available rating at the necessary voltage and frequency. The mechanical gap used to calculate the windage in Table 1 is between the rotor OD and stator ID – the undetermined stator sleeve thickness was neglected, but would slightly increase the windage.

Design	3A	3B	3C	3D	3E	3F	3G
Speed [rpm]	12000	12000	12000	12000	12000	12000	12000
Frequency [Hz]	200	200	200	200	400	400	400
Power In [kW]	9172	9240	9102	9127	9172	9137	9104
Power Out [Hp]	12125	12150	12083	12100	12189	12138	12109
Terminal Voltage [Vll]	5745	5680	5241	5253	6018	5521	6571
Phase Current [Arms]	1103	1103	1104	1095	1096	1096	866
Mechanical Gap [mm]	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Power Factor	0.836	0.852	0.909	0.916	0.803	0.872	0.924
Electrical Loss [kW]	130	180	92	104	82	85	75
Gap Windage [kW]	40	40	37	37	24	23	27
Efficiency [%]	98.1	97.6	98.6	98.4	98.8	98.8	98.9
Shaft Power Avail [Hp]	12071	12096	12033	12050	12157	12107	12073
Motor Envelope [m^3]	1.049	0.905	0.844	0.844	0.441	0.415	0.489

Table 1: Rough-size design studies for 9MWe compressor drive – this is raw data and should only be used for comparison in this table

The best 2-pole candidate design from Table 1 is design 3C when considering gap (ultimate) efficiency and motor size. The 2-pole, design 3D has a higher power factor than design 2C and marginally lower ultimate efficiency. As opposed to the pump-drive cases, the compressor designs' output drops slightly or not at all with increasing power factor. The compressor drive application is not penalized with drag losses as dramatically as the pump-drive applications, however it can be seen that it takes a significant increase in machine size to deliver only a marginal increase in output (for the best designs). The best 4-pole candidate design from Table 1 is design 3F, which has less than half the volume of the best 2-pole design. In general, higher power factors and smaller size can be achieved for this application with a 4-pole design as opposed to a 2-pole design.

III. CONCLUSION

This short trade-study demonstrates that the DDS PM motors can be designed to a variety of system-level optimization goals while offering higher performance than induction machines. DDS's experience with designing and manufacturing high-speed integrated-motors/generators for compressors and turbines has proven that it is critical to have a system-level understanding and to not lose site of the top-level requirements – the most efficient components individually will not create an optimal integrated-compressor/pump system. Having thermal, stress and electromagnetic analysis and manufacturing capabilities as well as the expertise and experience of integrating electrical and mechanical systems, places DDS in an advantageous position to serve hermetically-sealed integrated-compressors or pumps for sub-sea or top-side applications. The case studies in this report showed some possibilities with the DDS PM machines, and highlighted the value of demonstrating the simplicity and robustness of a DDS PM motor as part of a new product test and qualification plan for these applications.

IV. REFERENCES

[1] DOT'07 paper "Practical Challenges of Manufacturing a 2500kW Subsea Motor" by Brian Millward

V. VITA

Dan Saban earned a BSEE degree from the University of Illinois - Urbana in 1992, a MSEE degree from Purdue University - West Lafayette in 1993 and a PhD degree in Electrical Engineering with a minor in Mechanical Engineering from the University of Wisconsin - Madison in 2006 where he specialized in electric motor analysis. Additionally, he holds an MSEE (2002) and a MSME (2003) from University of Wisconsin - Madison with focuses on power electronics and controls, respectively. He is currently the Director of Technology for Direct Drive Systems. Throughout his 17 year career (including time spent with General Electric and Hamilton Sundstrand) he has been involved in advanced electromagnetic design of electric machinery including new lamination and winding designs, design tools, and both prototype and product family development for commercial, industrial and aerospace applications. Dr. Saban is a senior member of IEEE and a registered professional engineer in Indiana and Illinois.

Herman Artinian holds a Bachelor's of Science degree in Engineering from the University of California, Los Angeles. Currently, he is the Vice President of Corporate Development for Direct Drive Systems. He has held various roles including senior-level sales with a worldwide distributor of turbo-machinery equipment and posts at Calnetix. At Calnetix he was the Director of Business Development where he was responsible for the implementation and supervision of all sales and marketing activities. Additionally, he led Calnetix's efforts in identifying opportunities in various industries to create product-focused and market-focused subsidiaries. During that period, he was responsible for driving the market studies and business cases leading to the formation of Direct Drive Systems and Vycon.