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Design Challenge of High-Speed High-Power Density Motor For Advanced Electrical Submersible Pump

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***Abstract*— Electrical Submersible Pumps (ESP) have been widely used in oil and gas extraction as a reliable and efficient method of artificial lift to enhance flow rate of oil and gas from a well. However, as the world shifts towards a less fossil-fuel based future, the role of ESP will need to evolve in order to continue to play an important role in the transitional period. One key challenge facing ESP technology is the increasing depth of exploitable oil reserves, with many new ones located at depths of 3km-4km. This implies the need for more advanced ESP technology that operates at high-speed and high-power density to generate additional artificial lift while keeping a compact and robust structure. These competing features demand a disciplined design methodology. This paper presents the electromagnetic design considerations of a 150kW permanent magnet (PM) motor driving an advanced centrifugal pump at 10,000rpm through a 90mm tubing. Three motor designs are undertaken, and their performances are compared. The results show all three designs meet the target specifications. However, the most optimal option will be dependent on its adaptability in integrating thermal management on the cable length and the operating voltage.**

Keywords—*Electrical Submersible Pumps, Permanent Magnet Motors, High Speed Machines, Rig-less*

I. INTRODUCTION

In recent years, Electrical Submersible Pumps (ESP) have been widely used in oil and gas extraction as a reliable and efficient method of artificial lift to support and enhance the flow of oil and gas from a well [1-3]. According to an industry intelligence report, as of 2019, it has estimated that 94% of the existing one million wells require artificial lift, and 15-20% of wells currently use ESP whilst others use mechanical and hydraulic systems. The average run life of an oil production is 3 years, with a typical 10-month waiting for the rig to do 'work over' or maintenance [4]. To maximize production, the leading innovative players in the oil and gas market have started to explore high performance, reliability and safe rig-less deployment that can reduce the 'work-over' to just one day. On the other hand, as the world begins to shift away from a fossil-fuel based economy into a decarbonized future, it is envisaged that advanced ESP technology can play an important role in the transitional period [5]. Induction motors are commonly used in most EPS due to its low cost and robustness [7]. However, they suffer a relatively low power-factor operation due to the intrinsic high stator and rotor impedances, resulting in larger connecting cable, higher losses, and reduced oil production [8]. A key challenge facing the ESP technology is the increasing depth of exploitable oil reserves, with many new ones likely to be located at depths of 3km-4km under the earth surface [9]. This implies the need for more advanced ESP technology that can operate at these depths efficiently and reliably, and with a cost-effective maintenance regime [10-11]. Since deep well operations involve long electric cables to reach the EPS, this will lead to high capacitive impedance and increased cable size to deliver power to the motor. A body of research work has been dedicated to compensation methods to mitigate the effects of high capacitive impedance [12-16]. The compensator is generally embodied close to the motor within the EPS, and has resulted in a more compact system with reduced electrical losses [17]. Another body of study is dedicated to the effects of long cables on EPS. A detailed analysis of the losses of long cables to the EPS motor has been undertaken with a view to finding improved solutions to reduce the losses [18], whilst the estimation of the total power losses including the control station is reported in [19]. In another study, the impact of the starting up of the EPS motor due to long cables on oil extraction operations is studied in [20].

Besides, new applications for advanced ESPs are emerging, such as the extraction of freshwater, which is usually found above and/or below oil reserves in great depths. With freshwater becoming an increasingly scarce resource, it is strongly felt that ESP technology would become a potentially viable solution to extract freshwater from oil production wells in water-scarce regions [21]. Providing a secure source of water supply virtually anywhere with underwater reserves (including deserts), ESP can transform the oil and gas infrastructures into a green hydrogen production based on electrolysis by solar energy. Advanced ESPs can also be deplored for geothermal wells to extract high quality heat sources that lie in great depths [22]. Moreover, it is believed heat pumps will also benefit from advanced EPS. Here, we present the comprehensive finite element analysis (FEM) design of a high-speed, high-power density permanent magnet (PM) motor that drives a 10,000 rpm multi-stage centrifugal pump at an output power of 150kW within a constrained space envelope to meet the requirement of a multi-stage drill. Permanent magnet machines are likely to set the future trend in ESPs, and research into the optimal control of these machines is evident in the literature [23]. Recent research of PM motors has focused only on the rotor optimisation [24], we extend our scope on optimising the rotor, stator and slot options, and three selected designs are then compared for their viability to meet the target specifications.

II. ELECTRICAL SUBMERSIBLE PUMP

Electrical submersible pumps (ESPs) are an important tool for the oil extraction industry to lift fluid from the bottom of a well to the surface. ESPs are typically used in oil wells that have reached a point where natural pressure is no longer sufficient to bring the oil to the surface. They are commonly used in mature oil fields or in wells that have low productivity. ESPs can also be used in combination with other artificial lift methods such as gas lift, plunger lift, or progressive cavity pumps to optimize production.

A. *Convenational ESP*

An ESP typically includes the following key components, as shown in Fig.1:

- Motor: This is the prime mover that drives the pump. The motor is typically an induction motor, but can also be a gas turbine or a hydraulic motor. In a 'bottom-drive' configuration, the motor is located below the pump in a condition of less thermal stress.
- Centrifugal pump: The pump consists of the impeller and the diffuser that move the fluid upward by centrifugal force and pressure difference.
- Compensator: This component buffers the motor from the pump during thermal expansion and contraction.

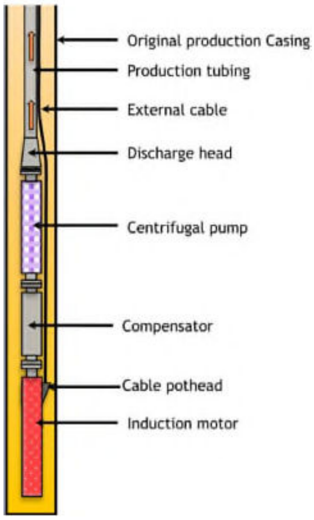


Fig. 1. Structure of a traditional ESP

B. *Proposed High Speed High Power Density ESP*

The proposed high-speed high-power density ESP, shown in Fig.2, offers some important features that is aimed to disrupt the oil industry during the decarbonization transition period, as well as other emerging markets. The key enabling technologies are the high-speed high-power density PM motors and high-speed multi-stage centrifugal pumps. The latter is outside the scope of this paper. The high-speed operation not only leads to high power density, but also ultra-slim profile for greater flexibility in pump placement and retrofit-ability. The compactness also leads to superior protection for electrical connections and integrated monitoring with no separate communication wires. It is envisaged that the following target specifications of the proposed PM motor will deliver a disruptive ESP technology:

- Power outputs: 150kW (200kW advanced option)
- Nominal speed: 10,000 rpm
- Voltage: 3-4kV
- Motor length: 2.5m
- Efficiency: >90%
- Duty cycle: Continuous

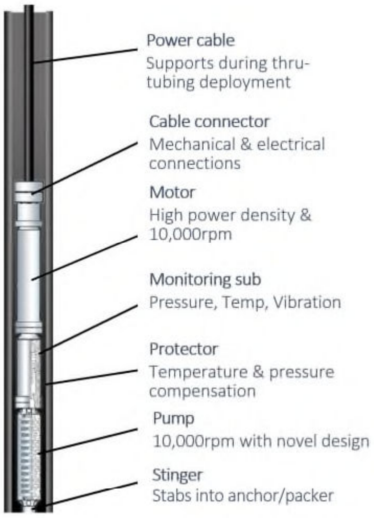


Fig.2. Proposed high-speed high-density ESP

III. MOTOR DESIGN AND MODELLING

The required motor specifications present many design challenges due to the competing requirements for high performance, high efficiency, and high reliability under hazardous working conditions, with operational temperature of at least 120°C in confined space.

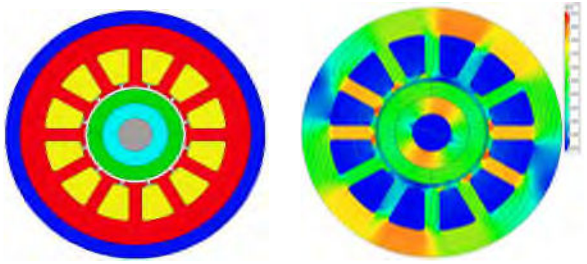
A. *Magnet Choice*

Working temperature is a major consideration for PM machines. The maximum temperature recommended for high-energy NdFeB magnets is generally 120°C, except for the highest SH grades. From Table 1 below, SH grades could work at 150°C maximum, with both Br (remanence) and Hc (coercivity) significantly reduced according to the respective temperature coefficients (-0.105 and -0.55) at elevated temperatures. Not only the remanence or flux will be reduced, there is a high risk of demagnetization (high coercivity coefficient) during the working conditions, especially for long term non-stop working cycles. The industry has limited experience of using magnets in high operating temperatures. On the other hand, SmCo magnet is a well-established technology and is routinely chosen for very high temperature operations, up to working temperatures at 250-350 °C. In Fig.3(a), it shows the difference in the remanence (flux level) between NdFeB and SmCo at the elevated temperatures will be diminishing, and there is a much less risk of demagnetisation in SmCo. From the data sheet in Fig.3(b), all high temperature grade SmCo has higher remanent flux density when operation temperature is higher than 250°C. Clearly, SmCo is the choice of permanent magnet materials in this application.

B. *Motor Topology Designs*

The motor high-speed and high-power requirements have largely pre-determined the options of stator-rotor configuration. The potentially high temperature operation means SmCo33E, being the most stable at the highest temperature, is the most favourable choice for the permanent magnet materials. Three motor designs are proposed, and their performance studied, all based on SmCo33E.

Design 1 - Surface-mounted PM (SPM) configuration with a 2-pole and a 12-slot structure

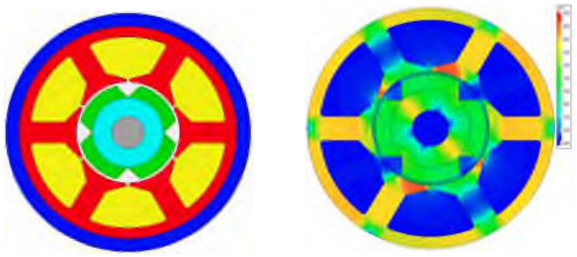


(a) CAD model (b) Flux distribution

Design 1 – SPM 2-pole 12-slot

The model and its flux distribution of SPM (Design 1) is depicted in Fig.4. The design has two rotor poles and 12 stator slots. It is a typical integral slot/pole combination with 2 slots per pole per phase. The advantages of the structure include high winding factor, more sinusoidal flux distributions and low harmonic contents. Non-magnetic shaft is considered in this design to eliminate the eddy current loss in the solid shaft. A key design consideration for surface mount PMs at high speed is the necessity of sleeve for PM retainment. Additional airgap must be allowed for. As shown in Fig. 4(b), the maximum flux density under open-circuit conditions is about 1.7 T, which lies on the knee point of the BH curve of the lamination. With loading, the working flux density is around the knee point, making sure the full utilization of the core material.

Design 2 - SPM configuration with 4-pole and a 6-slot structure

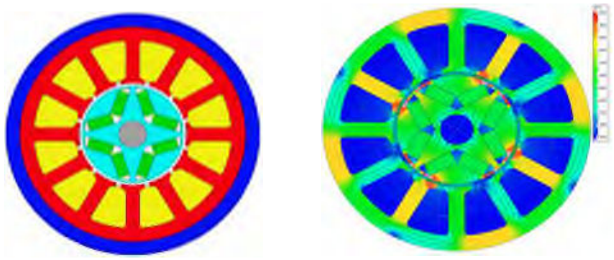


(a) CAD model (b) Flux distribution

Design 2 – SPM 4-pole 6-slot

It is depicted in Fig.5(a), the model of SPM motor (Design 2) adopts a 4/6 rotor pole and stator slot combination. Since there are 2 flux loops in the motor with 4 poles, the thickness of the stator yoke can be reduced by half. Accordingly, more space is available for windings. What is more, the fractional slot configuration is applied with the number of slots per pole per phase of 0.5. The advantage of this structure is the use of concentrated windings, which can reduce the ending-winding length and increase the slot filling factor. With over-lapping windings, the slot filling factor is usually 0.4-0.5, and that can be increased to 0.5-0.6 with better utilization of the space inside the slots. However, the fractional slot concentrated structure is usually combined with higher winding inductance and thus stronger armature reaction, which is a disadvantage in this case. High armature reaction field can potentially cause higher core loss and eddy current loss. Compensation circuitry may be necessary.

Design 3 – Interior PM (IPM) configuration with a 4-pole and a 12-slot structure



(a) CAD model (b) Flux distribution

Design 3 – IPM 4-pole 12-slot

Design 3 is based on an interior PM configuration that is particularly suitable for high-speed operation without the need of retention sleeve of the PMs. From the aspects of utilization of materials and space, it is apparent that a 2-pole structure in an IPM structure will be cumbersome and highly impractical. Thus, the 4-pole 12-slot combination is adopted for the IPM design. The cross-section model and the open circuit flux distribution are illustrated in Fig.6. The stator teeth number is the same with SPM1, but the stator yoke is much thinner.

IV. Results And Disscussions

The three designs are comprehensively studied and their predicted performances are compared and discussed. It is important to noted that the designs are primarily based on the electromagnetic models, which are crucial in meeting the fundamental requirements for the targeted specifications in the proposed ESP, in particular the operational speed, electrical power output/torque, and operational temperatures. Mechanical and structural performances are outside the scope of the current study. Cooling is based on natural conduction and convection of the operational environment. While some advanced cooling methods could improve the motor performance, it will be very challenging due to the limited space and challenging operating conditions.

A. *Overall performance*

Based on the simulation results from the FEA electromagnetic models of three design options, insightful ‘first-order’ performance predictions can be made and are summarised in Fig.7.. Overall the IPM design (Design 3) appears to show some key advantages over the SPM ones (Design 2 and 3). It has the lowest overall weight for active materials at 72kg, and highest efficiency at 97.09%. It also has the shortest stack length at 2.4m, compared with 2.65m for the SPM designs, which is another distinctive advantage for high speed rotor dynamic stability. Since the area of stator slots of SPM1 (design 1) is the lowest because of thicker stator yoke, the amount of copper used is small with much higher armature resistance. Thus, the copper loss is high. However, due to the lower frequency, more sinusoidal PM flux field and armature MMF, the core loss and eddy current loss is extremely low. From the cooling perspective, the heat generated in the stator is always easier to be dissipated compared with the rotating rotor. The 4-pole SPM2 (design 2) has very high eddy current loss in the PMs, which would increase the temperature in PMs and degrade the motor performance. One method to effectively reduce PM eddy current loss is magnet segmentation. Assembly issue may need to be addressed.

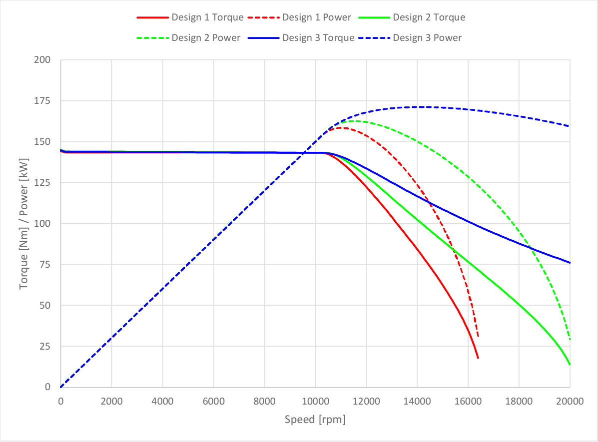
		Design 1	Design 2	Design 3
Geometry	Housing OD [mm]	90	90	90
	Stator OD [mm]	80	80	80
	Stator ID [mm]	35	38	38
	Air Gap [mm]	1	1	1
	Rotor OD [mm]	33	36	36
	Stack Length [m]	2.65	2.65	2.4
Winding	Parallel Paths	1	1	1
	Winding Layers	1	2	2
	No. Turns	2	2	1
	Fill Factor	0.45	0.45	0.45
Material	Winding	Copper	Copper	Copper
	--- weight [kg]	14.6	20.7	16.4
	Lamination	M235-35A	M235-35A	M235-35A
	--- weight [kg]	59.8	47.0	49.9
	Magnet	Recoma 33E	Recoma 33E	Recoma 33E
	--- weight [kg]	9.7	8.8	5.7
	Total Act. Weight [kg]	84.1	76.4	72.0
EMAG Performance	DC Voltage [Vdc]	566	566	566
	L-L Voltage [Vrms]	400	400	400
	Ph. Voltage [Vrms]	231	231	231
	Ph. Current [Arms]	234.6	240.4	253
	Phase Angle [deg]	7.846	10.72	27.61
	Rated Torque [Nm]	143.2	143.2	143.2
	Rated Speed [rpm]	10000	10000	10000
	Rated Power [kW]	150	150	150
Losses	Copper Loss [W]	3543	2484	2937
	Core Loss [W]	936.7	1878	1532
	Magnet Loss [W]	120	900	30
	Total Loss [W]	4600	5262	4499
	Efficiency	97.02%	96.61%	97.09%
Thermal Test	Ambient Temp. [C]	120	120	120
	Starting Temp. [C]	120	120	120
	Duration [min]	60	60	60
	Magnet End Temp [C]	329	313	339
	Winding End Temp [C]	353	334	356
	Max. Wnd Temp [C]	461	357	407

Fig.7 Summary of the three proposed designs

Otherwise sufficient cooling is necessary to ensure the PM is within the working temperature. Special cooling methods must be devised as it is generally difficult to cool a rotor spinning at high speed. Although the IPM design is able to achieve higher torque density and hence shorter stack length, its low power factor is a distinct disadvantage and this would imply an increase in the size of the cable in order to carry the same active electric power. As a long cable is always required to reach deep wells, some reactive compensation circuit must be deployed close to the motor. Both SPM designs will need to factor into magnet retention due to the high-speed operations. There are however established methods, such as using carbon fibre sleeve, that can be employed.

B. *Torque speed characteristics*

The three proposed motors all present a typical torque-speed curve for a PM machine as shown in Fig.8, which has a constant torque region up to the rated speed, followed by a field weakening route. The SM designs (Design 1 and 2) tend to have a much more rapid field weakening effect than the IPM (Design 3). If the speed often operates over the rated speed, then Design 3 will have a distinct advantage.



Torque speed characteristics

C. *Thermal performance*

Thermal management of the machine is always critical for high performance applications. For ESPs operating within confined space in great depth underground, temperature can get very high during operation. From Fig.7, the electromagnetic losses alone are about 5kW, excluding other mechanical losses. These can cause significant temperature rise due to the trapped space. The transient temperature curves of the three designs is shown in Fig.9. It is noted that the temperatures of the three designs are rising steadily from an initial ambinet temperature of 120 ^{0}C. After one hour of continuous operation with natural cooling, the temperatures of the permanent magnets are at 328 ^{0}C, 310 ^{0}C and 335 ^{0}C for Design 1, 2 and 3 respectively. Importantly, these are all well below the 350 ^{0}C temperature limit of SmCo33E. However, it is evident that continuous operation beyond the

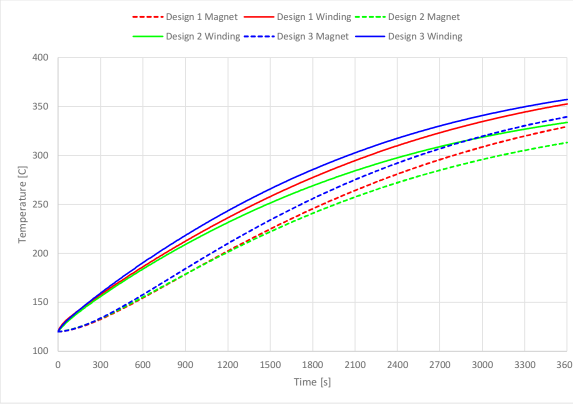


Fig.9 Transient temperature curves

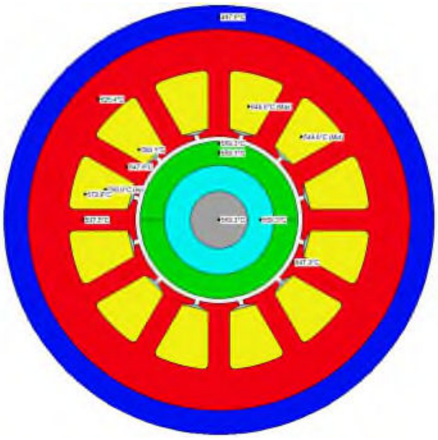


Fig.10 Transient temperature curves

one hour limit will result in temperature higher than 350^0C. It is therefore important that an intermittent mode, rather than a continous mode of operation may be necessary if there is no other cooling method. For example, a continuous operation of 1 hour may be followed by a cool down period of 1 hour, so that maximum temperature may be kept below 350^0C. Otherwise there is a real risk of demagnetisation of the permanent magnets.

By way of example, the temperatures at various parts of the motor at the rated load will reach a very high temperature of over 500^0C at the steady state. This is illustruted in Fig. 10 for the the surface mount (Design 1) motor, where no special cooling method is assumed. The high temperatures displaced at various parts of the motor are not acceptable for the insulation materials and the magnet will be demagnitised. This shows thermal management remains an extremely challenging aspect of this ESP application, and warrants further investigation.

D. *Torque performance*

Torque ripples and cogging torque can lead to vibration and noise, and mechanical wear and tear. It is therefore important to minimize these undesirable features at the design stage where possible. In general, cogging torque can be minimised with careful electromagnetic design, whereas torque ripples may be mitigated with optimal operation. The torque ripples for each of the designs are shown in Fig.11 under rated conditions. The surface mount designs have a relatively low ripples, at 5Nm pk-pk (Design 1) and 8Nm pk-pk respectively (Design 2). These compare favourably with the IPM design, which has a significant ripple of 40Nm pk-pk.

The cogging torques for each of the designs are shown in Fig. 12. It seems surprising that the cogging torques for the surface mount designs are very different, at 0.6Nm pk-pk (Design 1) and 30Nm pk-pk (Design 2) respectively, whereas the interior PM (Design 3) has a peakier waveform at 8Nm pk-pk. Both torque ripple and cogging torque effects tend to be diminished at high speed due to rotor inertia. However, their long-term impacts on the structural integrity and on the bearing systems at lower speed operations and during start-ups cannot ignored.

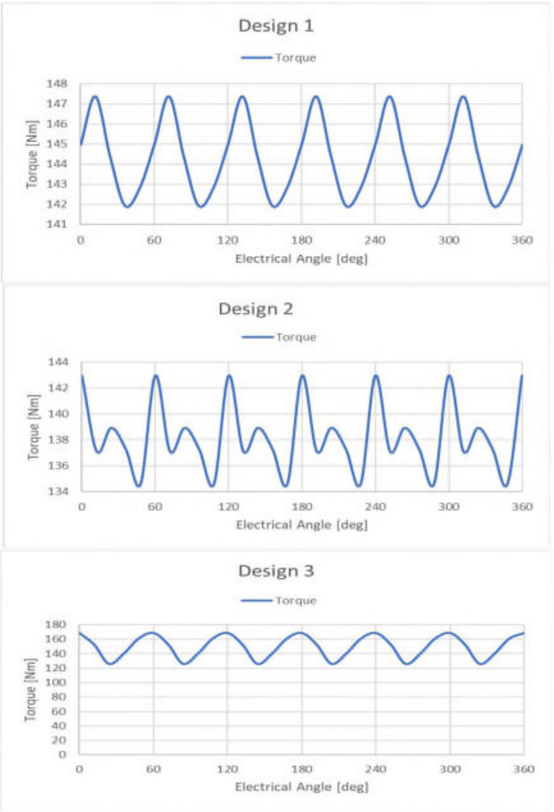


Fig.11 Rated torque and torque ripples

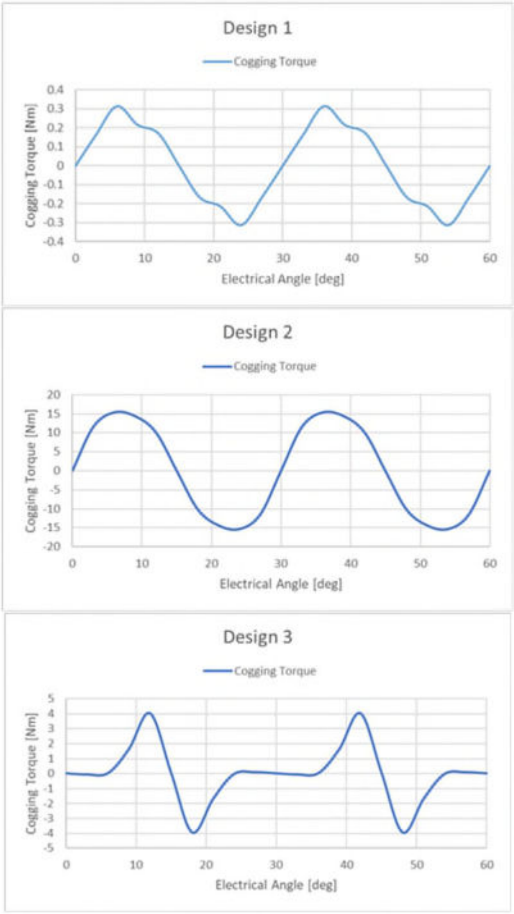


Fig.12 Cogging torque

V. CONCLUSION

High-speed high-power density PM motors is a key enabling technology for advanced ESPs, which will find their utility in many promising future applications beyond the current investigation focussing on an oil extraction pumping system. In this study, a comprehensive study of all the key electromagnetic performances of the three most promising electromagnetic design candidates for a high-speed high-power ESP application is presented. This study provides an initial examination for the key design challenges of the motor, and provides an informed and clear path to proceed to the next stage, where detailed information about the operating conditions can be specified. From the study, there is clear that whilst all designs pass the key specified targets, each has its own strengths and weaknesses, and the best candidate depends on its adaptability to the integration of the overall pump system, including the cabling, power electronics and other infrastructure. Further study should be dedicated to some key design aspects including cooling and thermal management, rotor dynamics, and reactance compensation.

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