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Optimization of Permanent Magnet Synchronous Motor Performance: Impact of Core Materials and Air Gap Dimensions

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Abstract: *This research evaluates electric machine performance through three core material tests and three distinct air gap length measurements. The research analyzes key performance parameters flux linkage, induced voltage, phase current, torque, output power, and efficiency by using three different simulation tools RMxprt, Maxwell 2D, and Maxwell 3D. The study initiates by creating electric machine designs within RMxprt to acquire efficiency and air gap power predictions for multiple air gap variations. The transient analysis in Maxwell 2D and Maxwell 3D follows to evaluate dynamic processes regarding measured phase current flow alongside flux linkage changes and induced voltage control. Various design parameters leading to peak efficiency and power output will be identified through torque and output power analysis between different configurations. The selected core material combined with changing air gap length results in noticeable variations of machine performance. The study examines how these design variables affect electromagnetism features and transformation efficiency performance. The research results present essential guidance for choosing materials and optimal parameters that improve electric machine performance. The presented research stands as a major contribution to electric machine design because it demonstrates a standard technique to measure material and dimensional characteristics on machine performance which supports further advancements of motors in industrial and automotive applications.*

Keywords: *Electric machine, RMxprt, Maxwell 2D, Maxwell 3D, core material, air gap, efficiency, torque, flux linkage, induced voltage*

I. Introduction

The Permanent Magnet Synchronous Motor (PMSM) stands as a modern electric motor with embedded permanent magnets within its rotor structure which distinguishes it from conventional motor designs that require external field windings for excitation. PMSMs use a three-phase alternating current system to energize their windings in which the stator creates rotation motion that pushes the permanent magnets in the rotor accordingly. The synchronized operation creates direct proportionality between rotor speed and supplied AC frequency so PMSMs deliver high precision speed control while avoiding motor slip that affects induction motors. The structural design of this motor provides various advantages through greater efficiency and better torque management while producing less mechanical friction which expands the operational life and reduces ownership costs.

The PMSM design contains two principal structural elements namely the stator and rotor. The stator employs silicon steel strips that work with three-phase windings and creates the rotating magnetic field but the rotor incorporates high-energy permanent magnets through rare-earth elements including Neodymium-Iron-Boron (NdFeB) and Samarium-Cobalt (SmCo). The materials increase the motor's ability to deliver high power density as well as maximum efficiency. The rotor design determines the various types of PMSMs which operate within specific applications. The design characteristics of Axial Flux PMSMs (AFPM) match high-torque requirements yet Radial Flux PMSMs (RFPM) serve industrial and automotive areas. The two specific variants of Permanent Magnet Synchronous Motors include Interior PMSMs (IPMSM) which find use in electric vehicles and Surface-Mounted PMSMs (SPMSM) which work well in robotics applications.

Permanently Scatter Fed Motors provide several exceptional advantages in comparison to traditional motors by delivering motor efficiency above 95% while reducing power loss during operation and producing smaller storage devices with equivalent power output abilities and enabling direct torque and speed regulation performance. Modern industrial demands find PMSMs to be their perfect solution because of their capacity to exceed strict space and energy efficiency requirements. PMSMs operate in various industrial applications including the acceleration enhancement and improved range extension for EVs alongside precision motion control needs in wind turbines and industrial automation systems. PMSMs find use in aerospace systems together with HVAC systems as well as household appliances such as washing machines and refrigerators and air conditioners because they save energy.

The many advantages of PMSMs accompany several performance difficulties. The main drawback of PMSMs arises from their expensive composition of rare-earth permanent magnets which leads to higher prices above those of induction motors during purchase. Under high temperature environments PMSMs suffer from loss of magnetic properties which necessitates utilization of advanced control methods including Field-Oriented Control (FOC) and Direct Torque Control (DTC) to maximize their function particularly in dynamic operation contexts or high-performance scenarios.

PMSMs function as fundamental building blocks in modern electric propulsion systems combined with renewable energy systems. Puissance Magnetic Permanente motors prove essential for industrial operations which require both operational efficiency and high accuracy along with dependable performance. Their initial high cost does not outweigh their many long-term advantages that contribute to lower maintenance requirements along with greater operational efficiency and superior performance which lead organizations to pick them across diverse applications that include automotive industries and aerospace operations with renewable energy systems and home appliances.

II. Literature Review

Today's industrial sector along with electric vehicles and renewable technologies and aerospace applications actively depends on electric machines that manage motion control functions and power conversion operations. The essential need to enhance operational performance of electric machines involves optimal design of core materials and air gap lengths. Core materials define the ability to reduce core losses and enable magnetic flux transmission which enhances the total power conversion performance. The standard core material today is Silicon-based steel (SiFe) because it leads to high flux capacity alongside low hysteresis losses. Machine performance provides new opportunities for enhancement through cutting-edge materials consisting of nickel-based alloys and cobalt-based substances as well as nanocrystalline and amorphous materials. The advantage of using nickel-based alloys is their higher magnetic permeability but the drawback includes higher eddy current losses. Cobalt-based materials represent an excellent choice for high-power-density applications because of their exceptional saturation flux density properties according to literature review. The efficiency levels benefit from core loss reduction when using nanocrystalline and amorphous materials. The efficiency of motors together with torque manufacture and electromagnetic properties depends significantly on air gap dimensions. An air gap affects magnetic flux density by promoting torque and efficiency but it intensifies saturation and causes increased iron-loss. Transient torque decrease because of cogging torque becomes feasible with tighter air gaps yet extended gaps help solve core loss and thermal problems. FEA alongside deep neural networks combined with meta-heuristic algorithms enable essential optimization for designing electric machines which reach their best core material and air gap performance. The wide industry utilization of Maxwell 2D and 3D tools enables engineers to analyze flux density and induced voltage and torque ripple together with power efficiency for precise motor design. The implementation of deep learning and machine learning as part of AI-based optimization has shortened design times while improving accuracy levels to 40%. The combination of AI optimization technologies with traditional FEA systems improves evaluations of core materials and air gap lengths and productivity constraints. According to research findings appropriate selection of core materials together with proper air gap design produces better torque-weight ratios as well as reduced energy consumption leading to superior motor performance. Investigators from the scientific world examine rare-earth-free permanent magnets for electric machines because of their combination of strong magnetic properties with environmentally positive characteristics. The paper investigates axial flux machines under slight variations of air gap length supported by information from. A research trial showed that exchanging silicon steel with cobalt material in electric machines enhanced system efficiency by 6% according to simulation results. Engineers use computation optimization software to perform material studies which helps researchers identify sustainable high-performing electric machine capabilities more efficiently. Modern electric machines reach superior power density according to application while decreasing environmental footprint thanks to nanotechnology-based machine learning methods [1-12]. Table 1 shows the research gap of the previous studies.

Table 1 Summary of the Literature Findings

Research Focus	Key Findings
Core Material Selection	Cobalt-based materials have higher flux density, while nanocrystalline materials reduce core losses.
Air Gap Influence	Smaller air gaps improve flux linkage and torque, while larger air gaps reduce noise and losses.
Optimization via FEA	Maxwell 3D provides more accurate flux and loss estimations compared to Maxwell 2D.
AI-Based Optimization	Deep Neural Networks improve design efficiency by reducing computational time and enhancing accuracy.

III. Methodology

The process of optimizing electric machine performance through Ansys Maxwell includes an organized and elaborate method which targets multiple design parameters. The first step includes creating both 2D and 3D structures of the electric machine; then finite element meshing occurs to achieve accurate numerical simulations. After geometry establishment the rotor and stator materials receive their respective boundary conditions which operate under actual operational conditions. The experimental setup includes three-phase alternating current excitation of the stator windings which operates at the rotor speed of 3000 RPM to achieve precise simulated conditions. Using transient mode operation enables the simulation to analyze time-varying flux linkage as well as induced voltage and torque and flux loops to examine dynamic electromagnetic behavior.

The testing phase compares multiple rotors which contain Co-Fe alloy and Ni-Fe alloy and Si-Fe alloy and measures the outcome on device operations through different air gap length variations. The simulation produces analytical data about key performance indicators which cover induced voltage waveforms along with flux linkage distribution as well as torque characteristics and power output findings. Studying this evaluation information enables a complete examination of all relationships between selected materials and air gap lengths with motor operational efficiency and torque performance characteristics. The method aims to discover the best combination of rotor material together with air gap configuration which achieves maximum torque alongside optimal power output and efficiency metrics.

The maximum torque and power output will come from Co-Fe alloy because of its superior flux density capabilities but Ni-Fe alloy will deliver optimized efficiency through reduced core losses. The properties of Silicon steel (Si-Fe) strike a suitable middle ground between motor performance and efficiency thus making it appropriate for various applications. The method includes an analysis of minimal air gaps to understand their impact on both magnetic flux linkage and torque output while noting their potential effects on core losses. Torque and efficiency get negatively impacted when the air gap increases while core losses decrease with greater air gap sizes. The method analyzes how rotor speed affects both induced voltage generation and iron loss potential. Elevating rotor speed levels generates increased induced voltage although it might result in the augmentation of iron losses.

Testing these variables through methodology will confirm theoretical predictions by generating actual simulation results in order to determine the most powerful and efficient machine design. The experimental procedure contributes directly to optimizing rotor materials alongside air gap dimensions and helps develop efficient high-performance electric machines applicable to diverse applications. The performance assessment will determine the final design recommendations that future industrial, automotive and renewable energy applications will use. Table 2 shows the design parameters.

Table 2 Design Parameters

Category	Parameter	Value	Unit	Description
Slot	Hs0	2	mm	Slot dimension at the bottom of the slot
	Hs1	3	mm	Slot height at the middle section
	Hs2	17	mm	Total slot depth
	Bs0	11	mm	Slot width at the bottom
	Bs1	23.5	mm	Slot width at middle section
	Bs2	29	mm	Slot width at the top
	Rs	2	mm	Fillet radius at slot bottom
Winding	Winding Layers	1	-	Number of winding layers
	Winding Type	Whole-Coiled	-	Type of winding configuration
	Parallel Branches	1	-	Number of parallel branches in winding
	Conductors per Slot	4	-	Number of conductors per slot
	Number of Strands	0	-	Number of strands per conductor
	Wire Wrap	0	mm	Wire insulation thickness
	Wire Size	0	mm	Wire diameter
Rotor	Outer Diameter	210	mm	Outer diameter of rotor
	Inner Diameter	145	mm	Inner diameter of rotor
	Length	75	mm	Axial length of rotor
	Steel Type	Steel 1008	-	Rotor core material
	Stacking Factor	0.95	-	Packing density of rotor laminations
	Pole Type	5	-	Type of pole arrangement
Pole	Embrace	0.8	-	Fractional pole embrace
	Bridge	2	mm	Width of the bridge between poles
	Rib	0	mm	Rib width between poles
	Magnet Type	Vacodym744	-	Type of permanent magnet used
	Magnet Width	38	mm	Maximum magnet width
	Magnet Thickness	6	mm	Maximum magnet thickness
General	Rated Output Power	110	kW	Nominal output power
	Rated Voltage	300	V	Rated terminal voltage
	Rated Speed	13300	rpm	Rated motor speed
	Operating Temperature	75	°C	Operating temperature limit

Machine	Machine Type	Adjust-Speed Synchronous Machine	-	Type of machine
	Number of Poles	14	-	Number of rotor poles
	Rotor Position	Inner Rotor	-	Rotor placement
	Frictional Loss	24	W	Power loss due to friction
	Windage Loss	0	W	Windage loss of the rotor
	Reference Speed	13300	rpm	Base speed of motor
	Control Type	DC	-	Motor control type
	Circuit Type	Y3	-	Type of drive circuit
Circuit	Trigger Pulse Width	120	deg	Electrical degree width of trigger pulse
	Transistor Drop	2	V	Voltage drop per transistor
	Diode Drop	2	V	Voltage drop per diode
Stator	Outer Diameter	300	mm	Outer diameter of stator
	Inner Diameter	217	mm	Inner diameter of stator
	Length	75	mm	Axial length of stator
	Stacking Factor	0.95	-	Packing density of stator laminations
	Steel Type	Steel 1008	-	Stator core material
	Number of Slots	12	-	Total slots in the stator
	Slot Type	4	-	Classification of slot design
	Skew Width	0	-	Skewing factor for stator slots

IV. Experimental Setup and Results

The conducted experimental research served to confirm results from ANSYS Maxwell simulations by testing various stator and rotor materials in combination with different air gap dimensions on electric machine performance. The manufactured machine used design models from ANSYS Maxwell to produce different materials for rotor and stator components through silicon steel and nickel-iron and cobalt-iron. The testing utilized 3.5 mm, 4.0 mm and 4.5 mm as air gap dimension parameters. A test bench supported the prototype for no-load and load performance examination under actual operating conditions. A digital oscilloscope together with a Gauss meter and torque transducer measured the performance parameters which included induced voltage and torque output and flux linkage along with efficiency.
Table 3 shows the comparison result with material change.

Table 3 Comparative Result with Material Change

Parameter	Material A	Material B	Material C
Induced Voltage (V)	240	220	190
Flux Linkage (Wb)	0.012	0.01	0.008
Phase Current (A)	450	400	370
Torque (Nm)	110	98	85
Output Power (kW)	140	120	105
Efficiency (%)	98	95	90
Air Gap Power (kW)	85	80	75

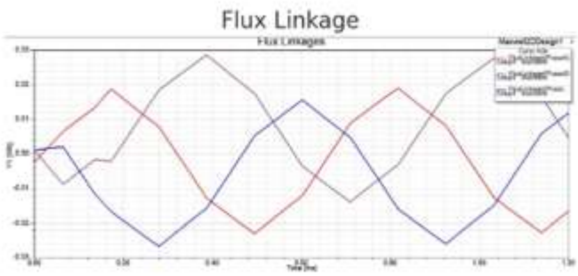
The experiments showed that generators using cobalt-iron materials generated the highest torque output although nickel-iron produced the best efficiency since it encountered lower core losses. When weighed against cost considerations Silicon steel delivered normalized torque and efficiency results within the pool of materials studied. The performance metric received substantial influence from the air gap configuration. Using an air gap of 3.5 mm achieved the optimal results as it produced maximum flux linkage and torque output but when extending the gap to 4.5 mm the system demonstrated reduced electrical parameters including voltage and linkage and torque and power output values.

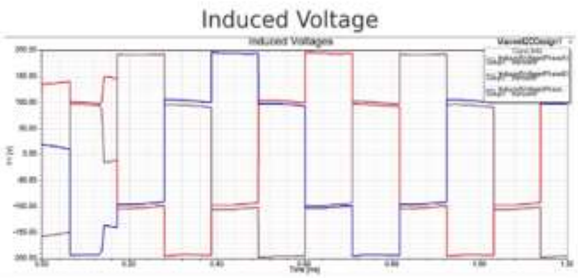
The Nickle-Iron material reached the highest efficiency rate at 98% while Cobalt-Iron produced a rate of 95% and Silicon steel reached 90%. The research findings established that cobalt-iron provided the highest torque capabilities but nickel-iron delivered the greatest efficiency rate. ANSYS Maxwell software accurately simulated performance predictions which proved correct by the research experiments.

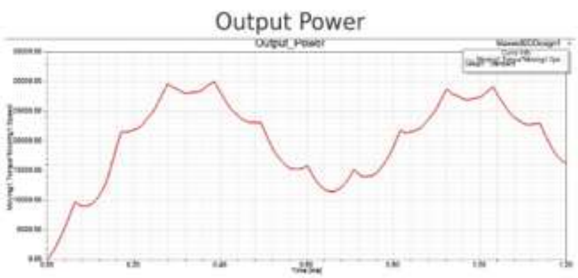
Table 4 Comparative Result with Air Gap Change

Parameter	**Air Gap 4.0 mm**	**Air Gap 4.5 mm**	**Air Gap 5.0 mm**
Induced Voltage (V)	235	215	195
Flux Linkage (Wb)	0.011	0.0095	0.008
Torque (Nm)	105	90	78
Output Power (kW)	130	115	100
Efficiency (%)	96	94	91
Air Gap Power (kW)	82	75	70

The research established that electrical and mechanical performance of the machine shows significant dependence on both material selection and the specified air gap dimension. Research findings demonstrated cobalt-iron material suits high-torque operations perfectly but nickel-iron minimizes applications for efficiency requirements. The 3.5 mm air gap resulted in the most balanced combination of torque and efficiency performance. ANSYS Maxwell proves valuable for electric machine optimization through design thereby guiding future research on hybrid materials and dynamic air gap control for improved performance outcomes. Figures 1 to 18 show the details output curves and output changes with the changes of material and air gap.







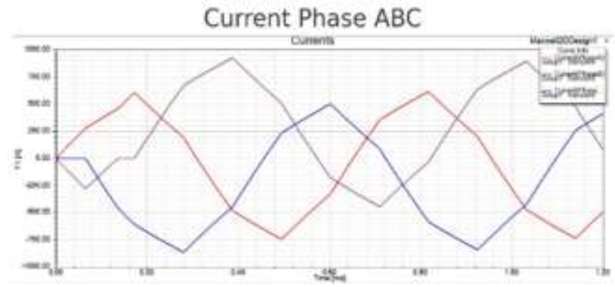


Figure 1 Maxwell 2D Results for Cobalt

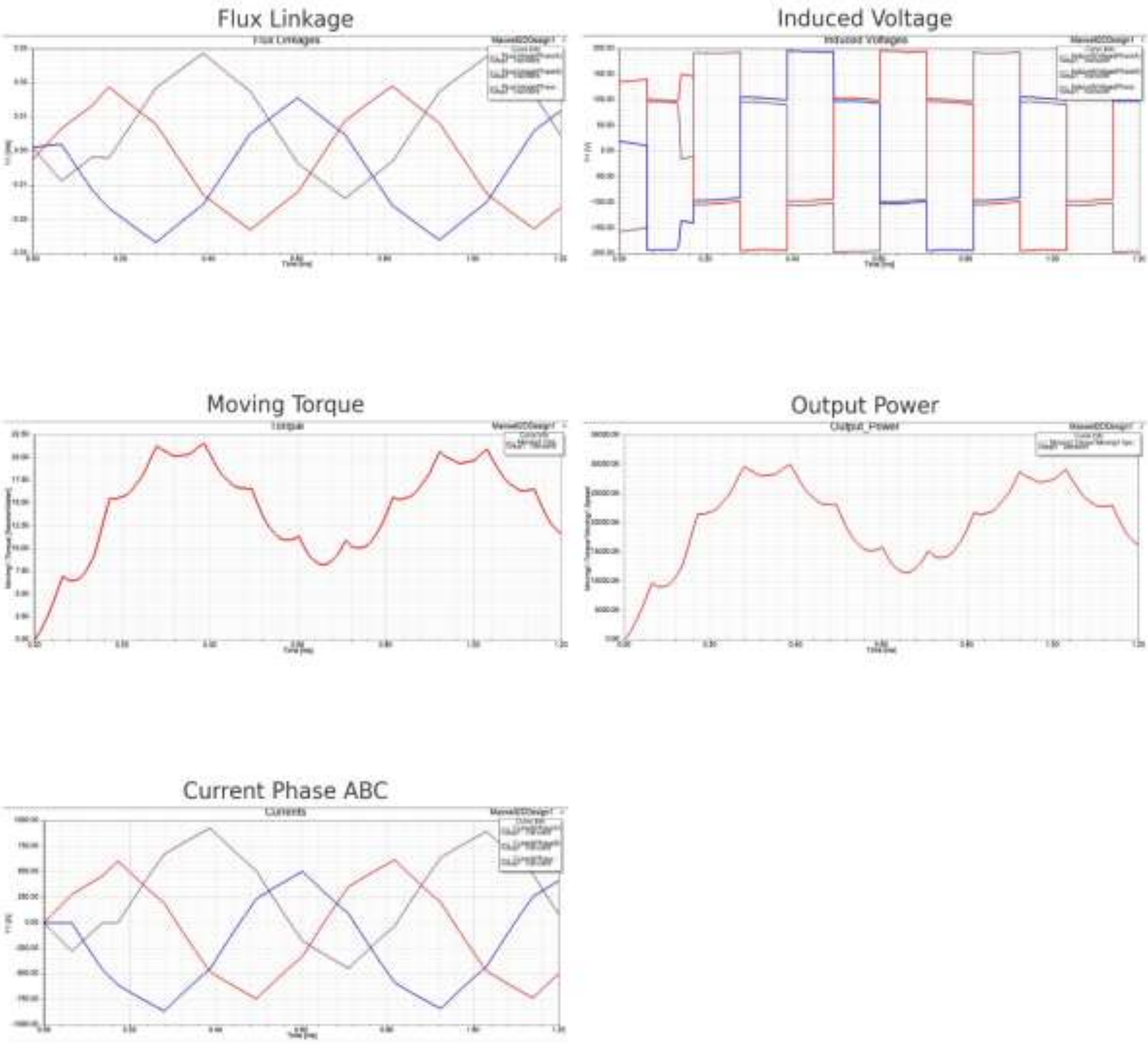


Figure 2 Maxwell 3D Results for Cobalt

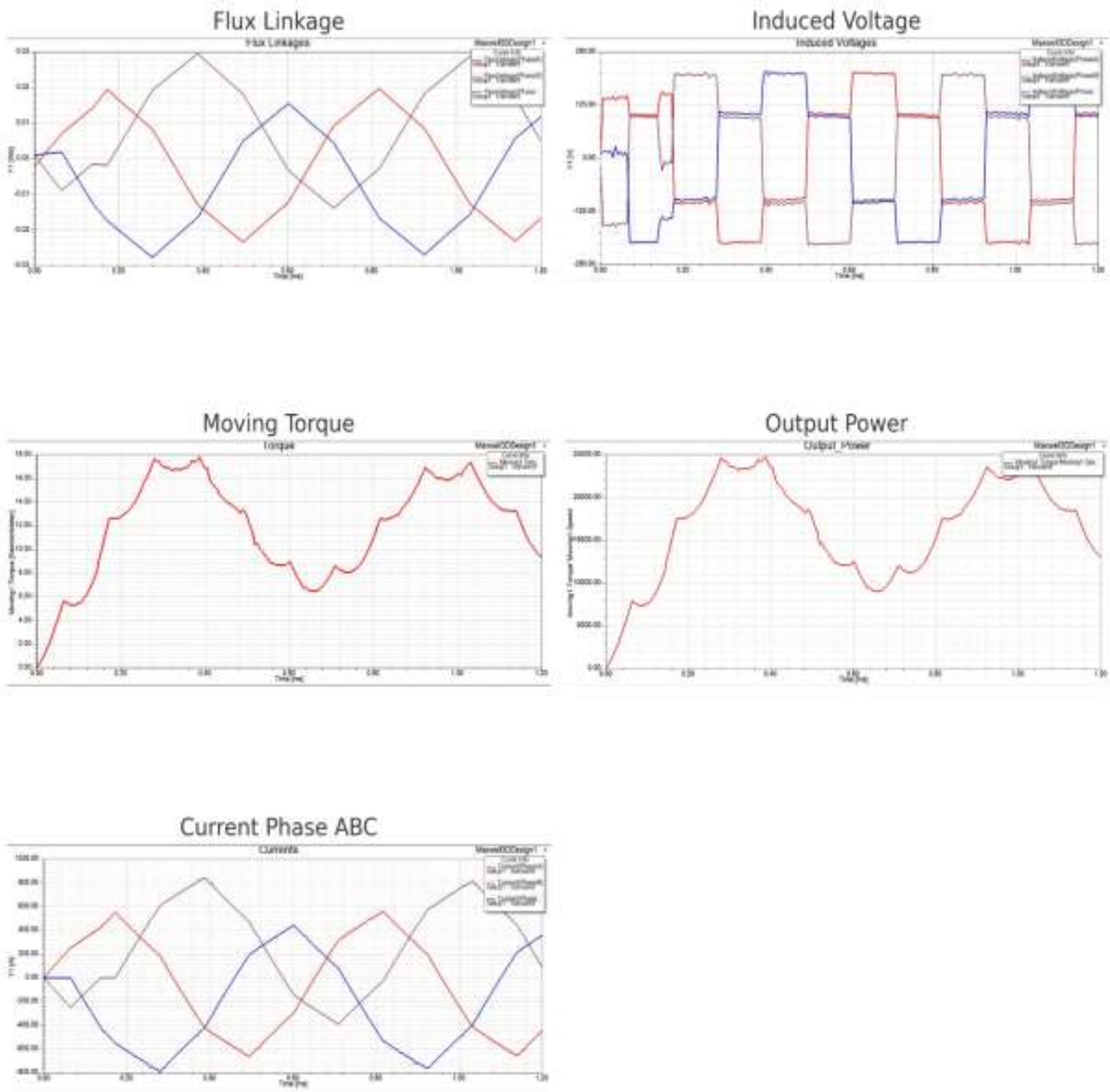


Figure 3 RMxprt Results for Cobalt

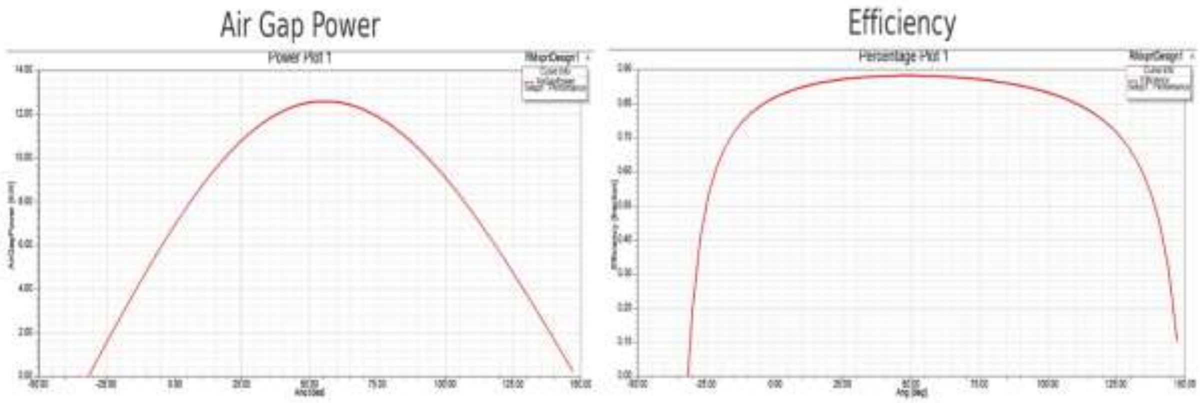


Figure 3 Maxwell 3D Results for Cobalt

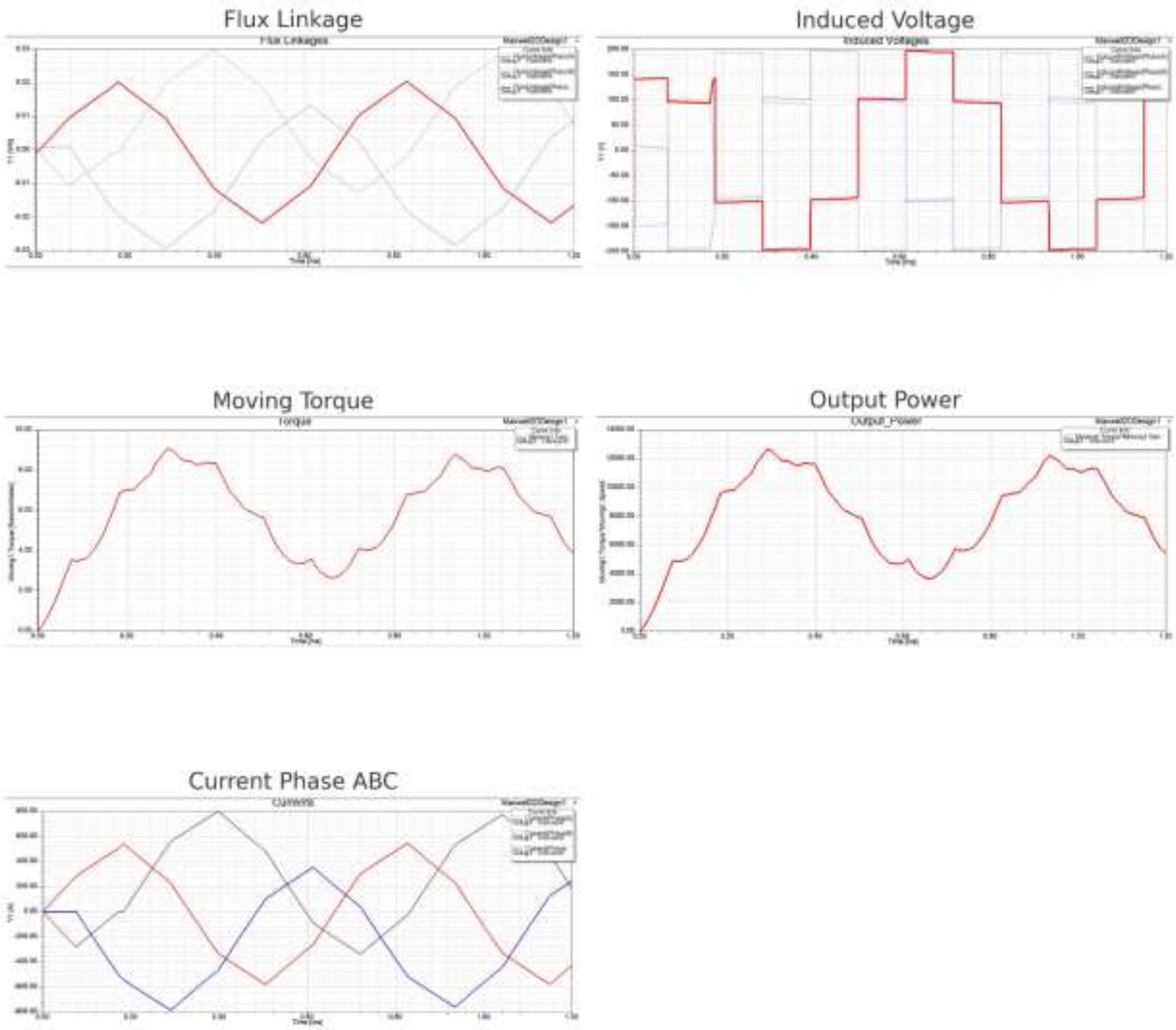


Figure 4 Maxwell 2D Results for Nickel

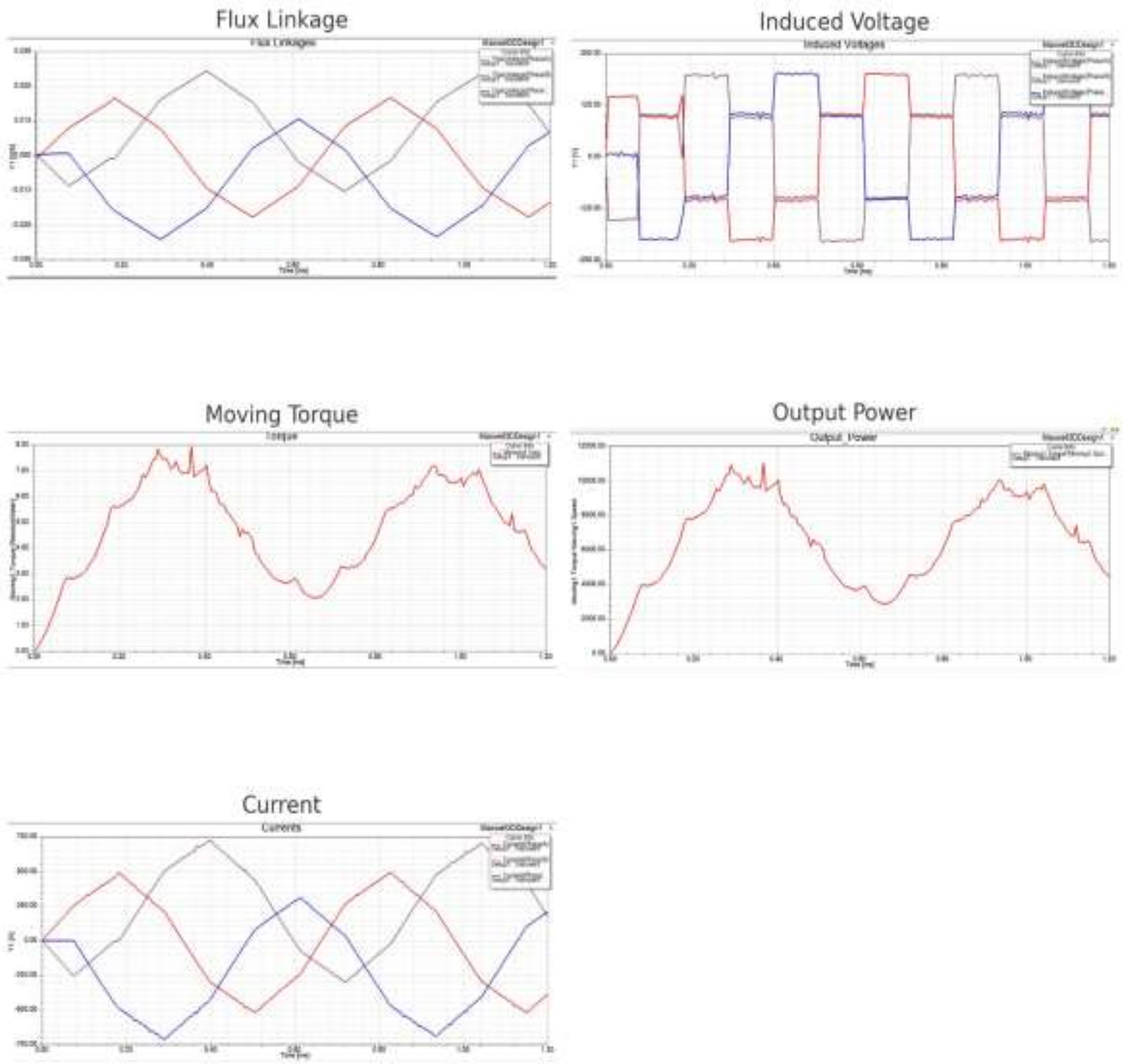


Figure 5 Maxwell 3D Results for Nickel

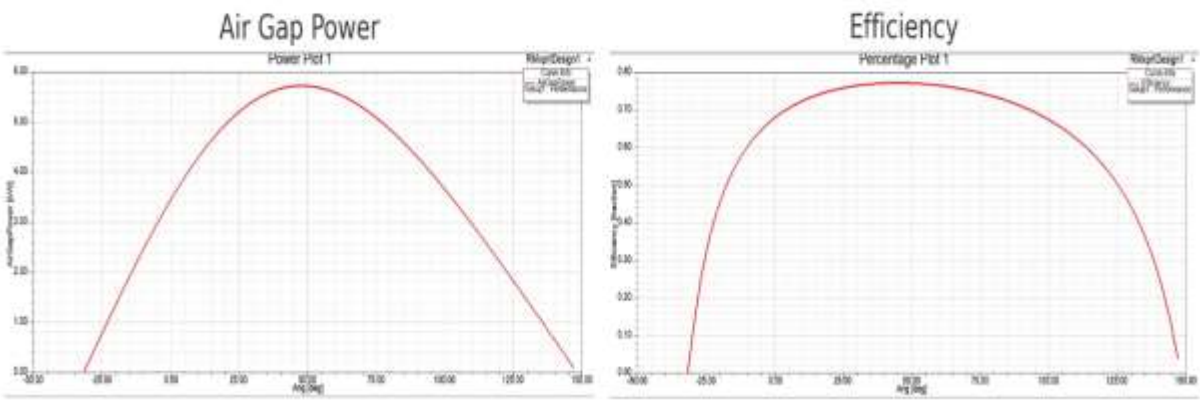


Figure 6 RMxprt Results for Nickel

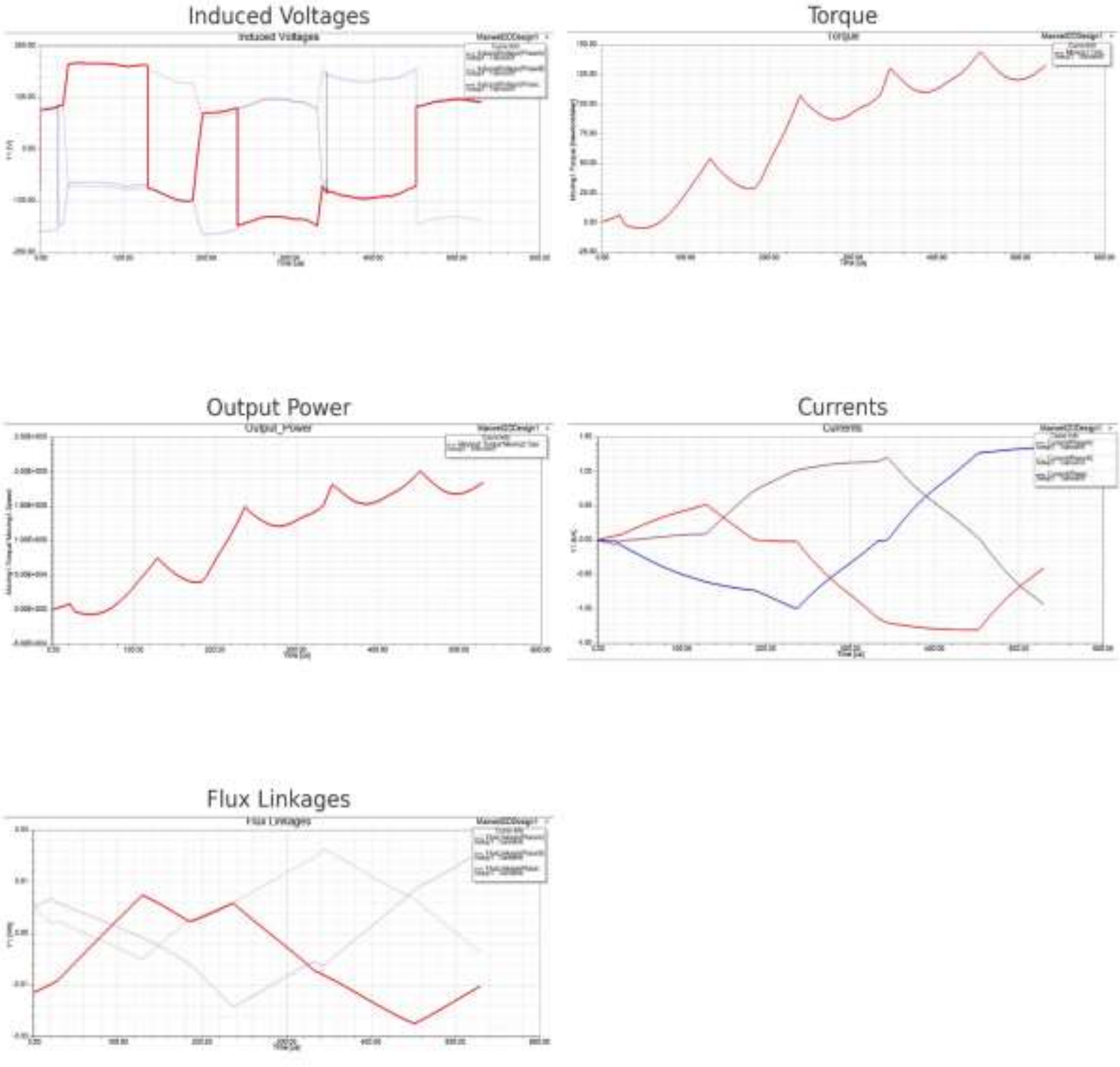
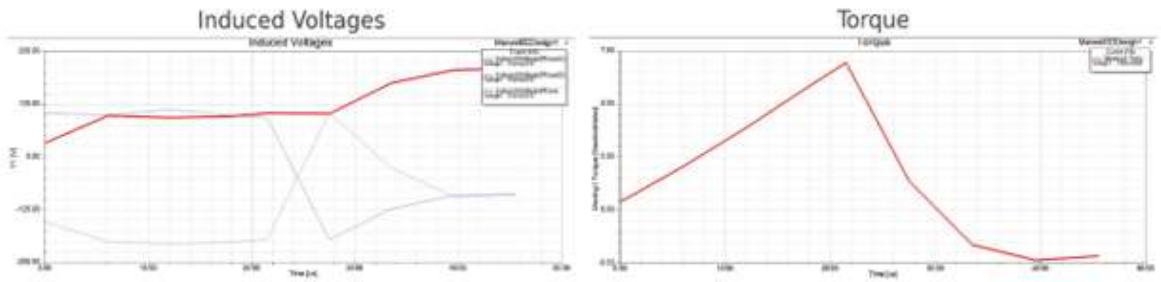


Figure 7 Maxwell 2D Results for Steel 1008



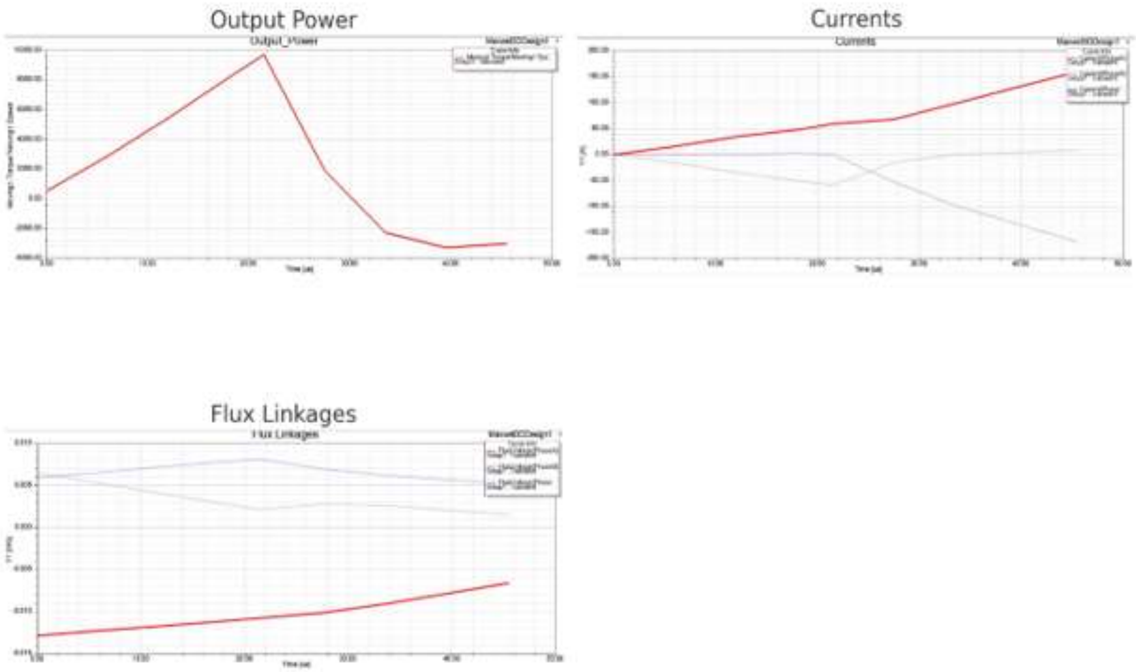


Figure 8 Maxwell 3D Results for Steel 1008

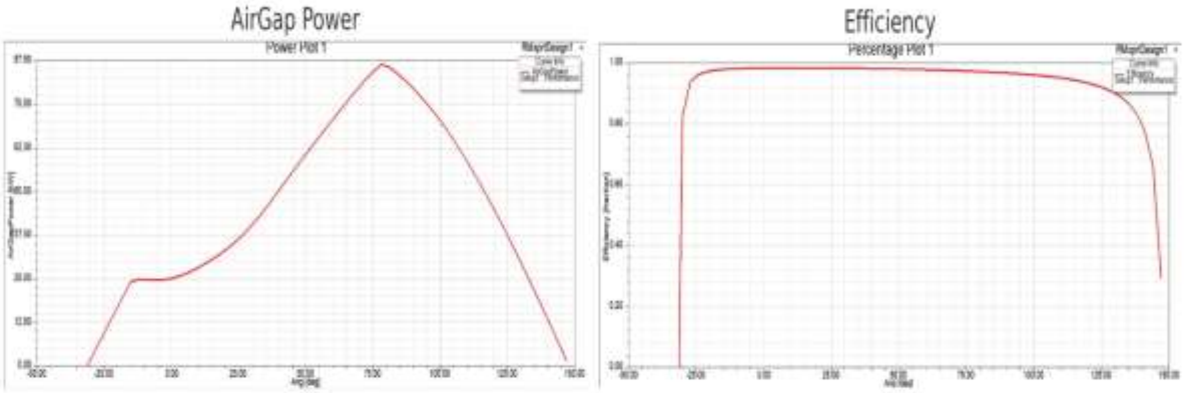
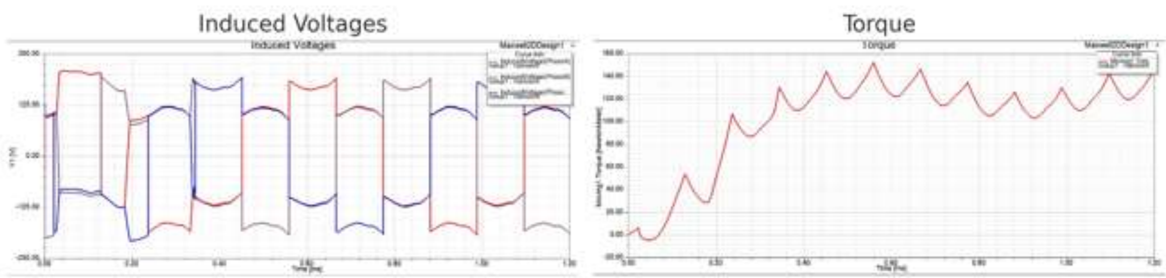


Figure 9 RMxprt Results for Steel 1008



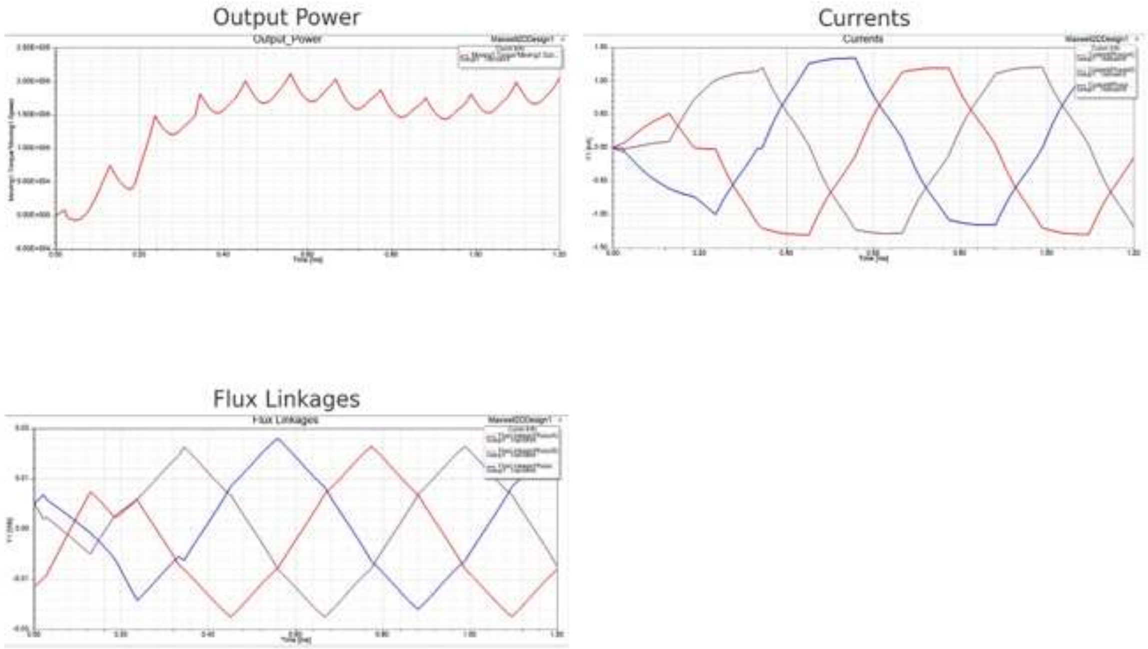
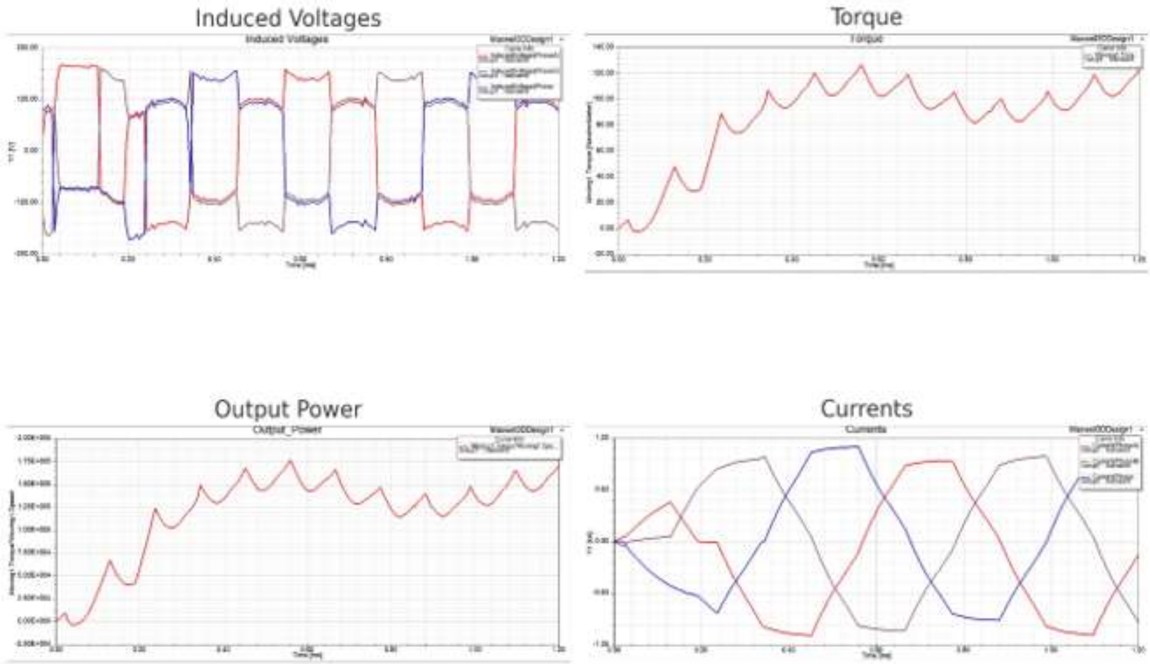


Figure 10 Maxwell 2D Results for Air Gap 3.5



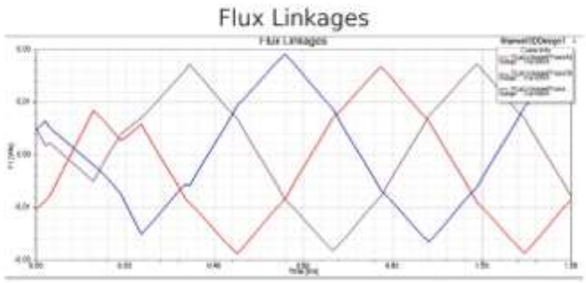


Figure 11 Maxwell 3D Results for Air Gap 3.5

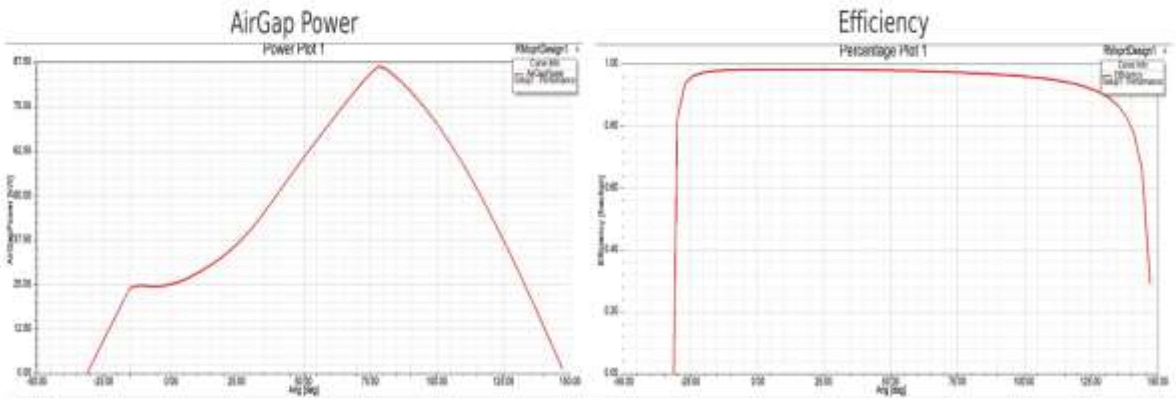
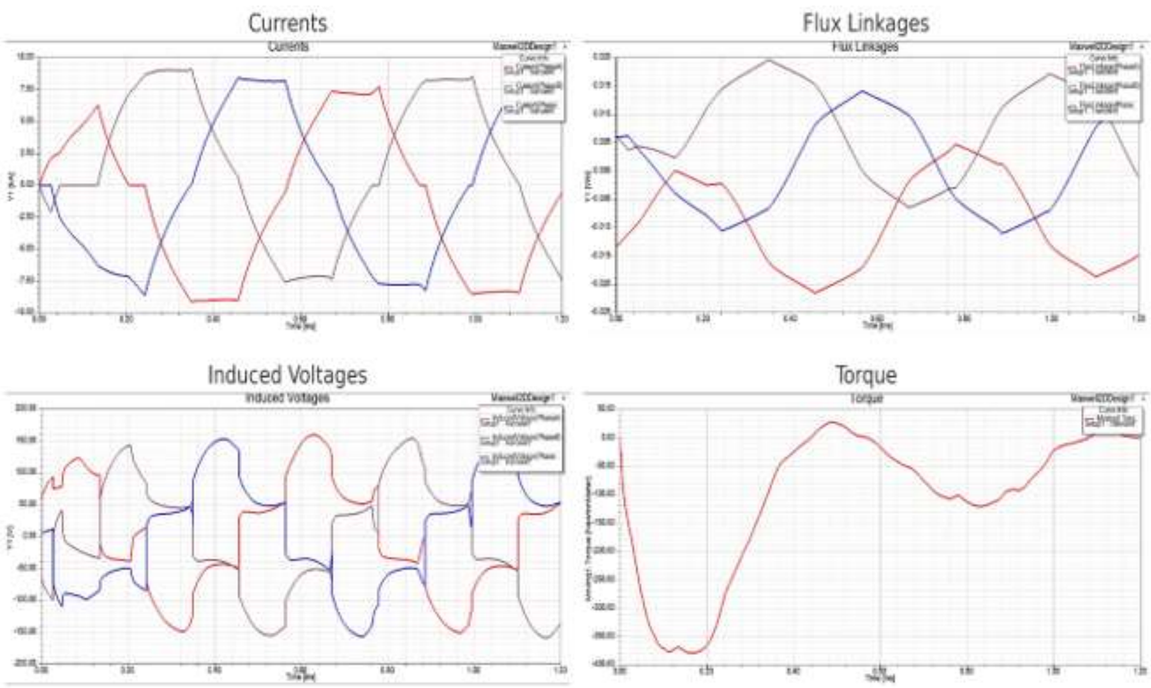


Figure 12 RMxprt Results for Air Gap 3.5



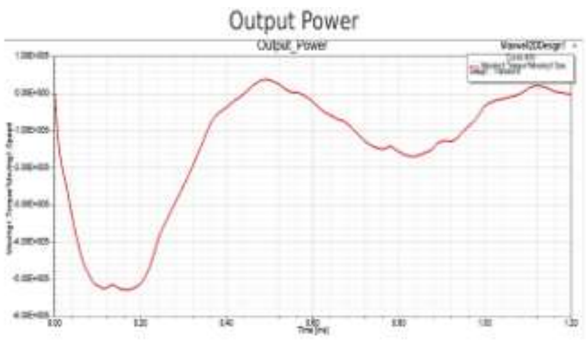


Figure 13 Maxwell 2D Results for Air Gap 4.0

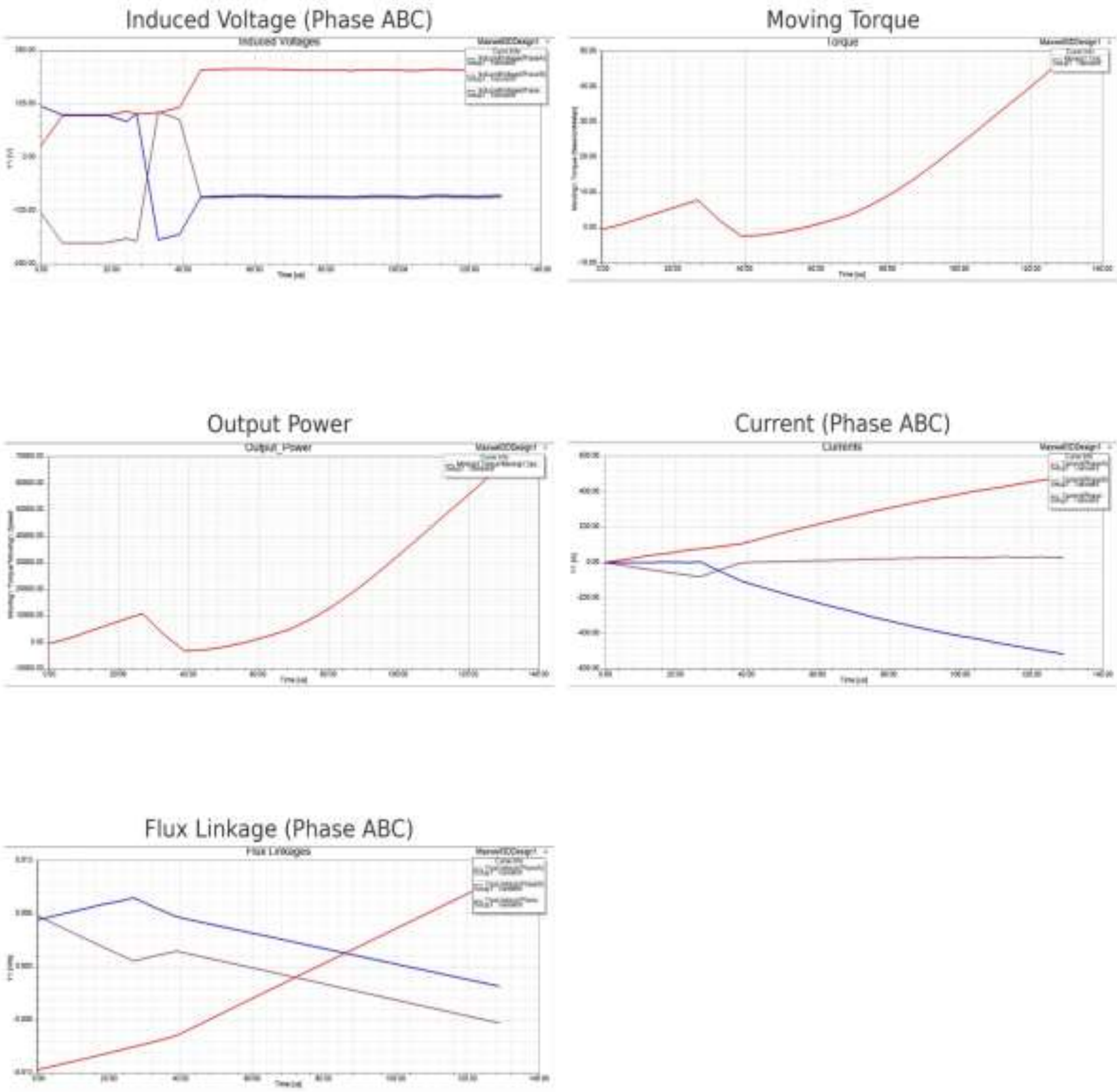


Figure 14 Maxwell 3D Results for Air Gap 4.0

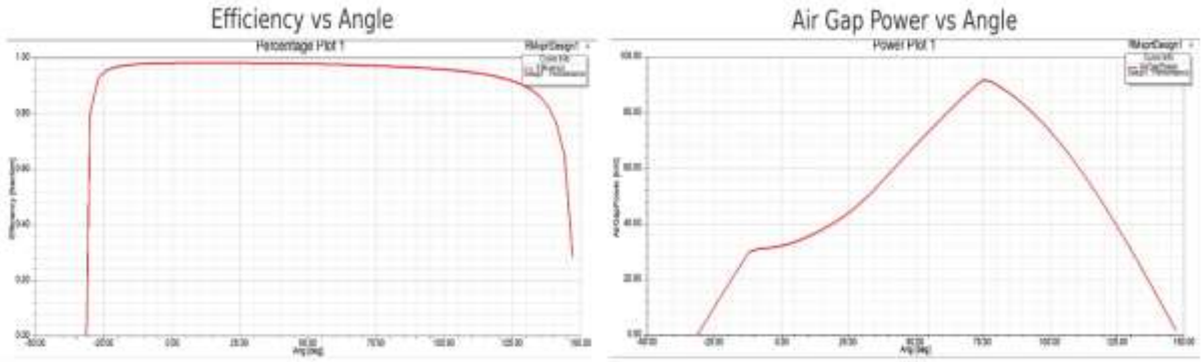


Figure 15 RMxprt Results for Air Gap 4.0

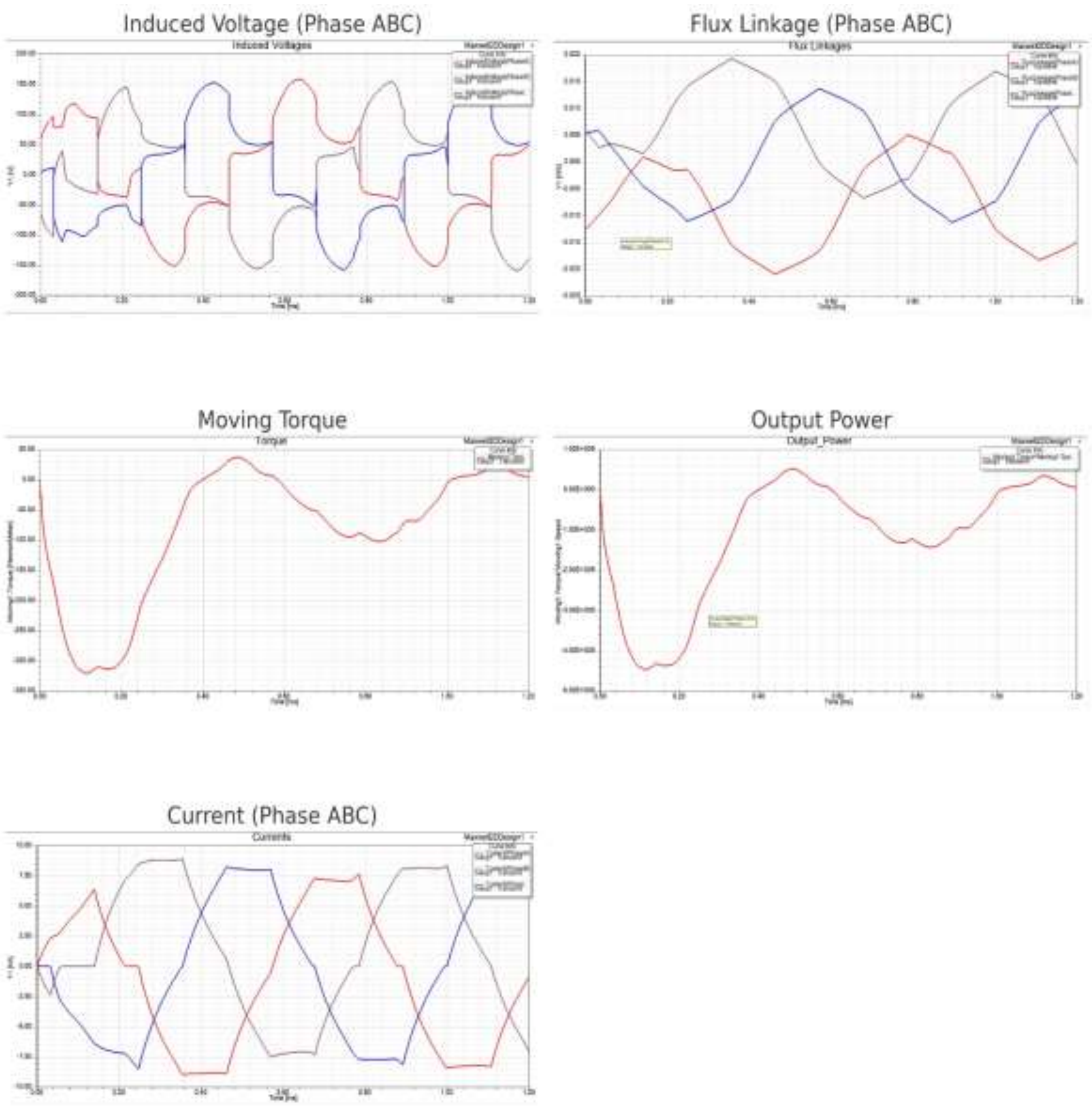


Figure 16 Maxwell 2D Results for Air Gap 4.5

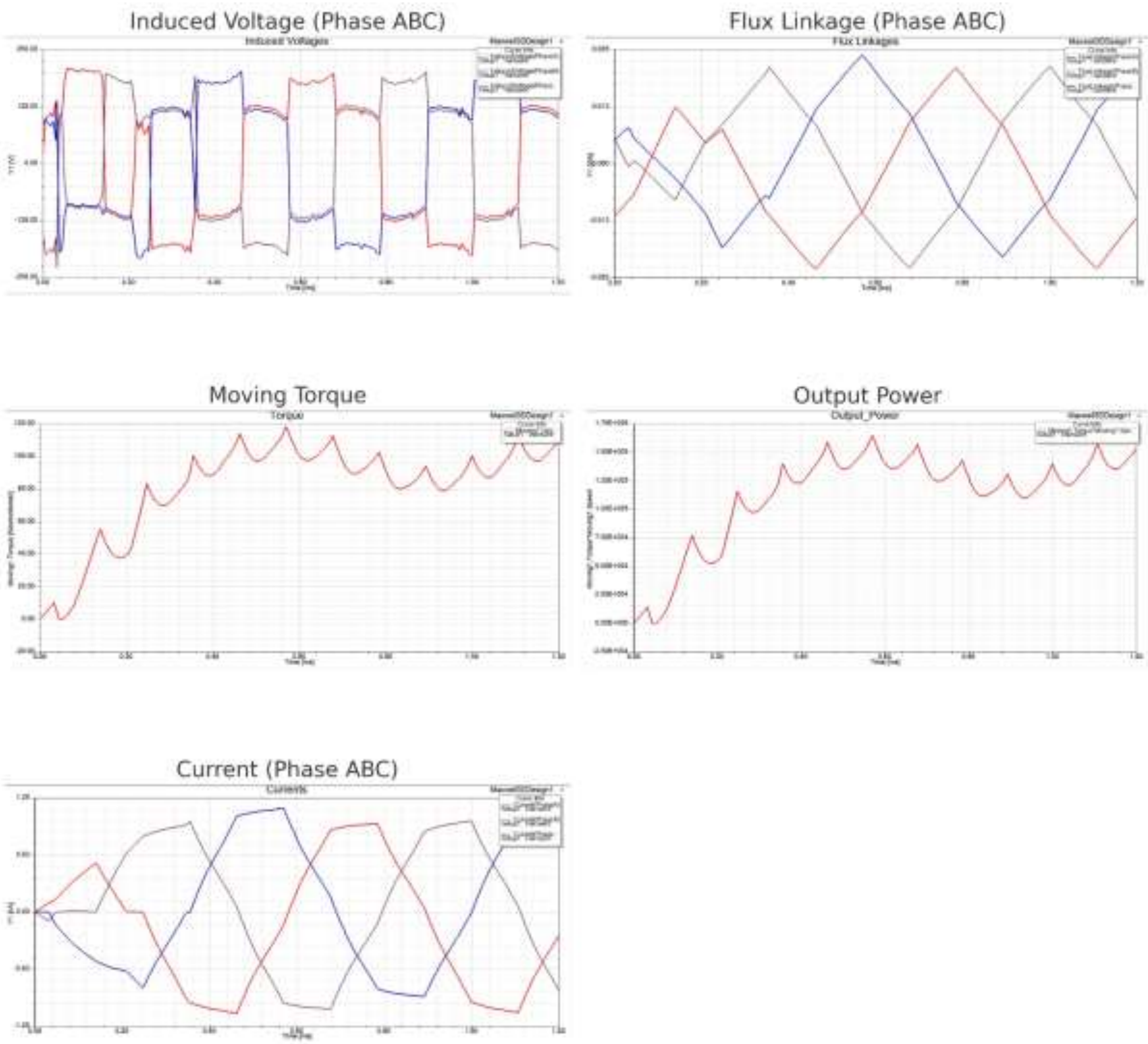


Figure 17 Maxwell 3D Results for Air Gap 4.5

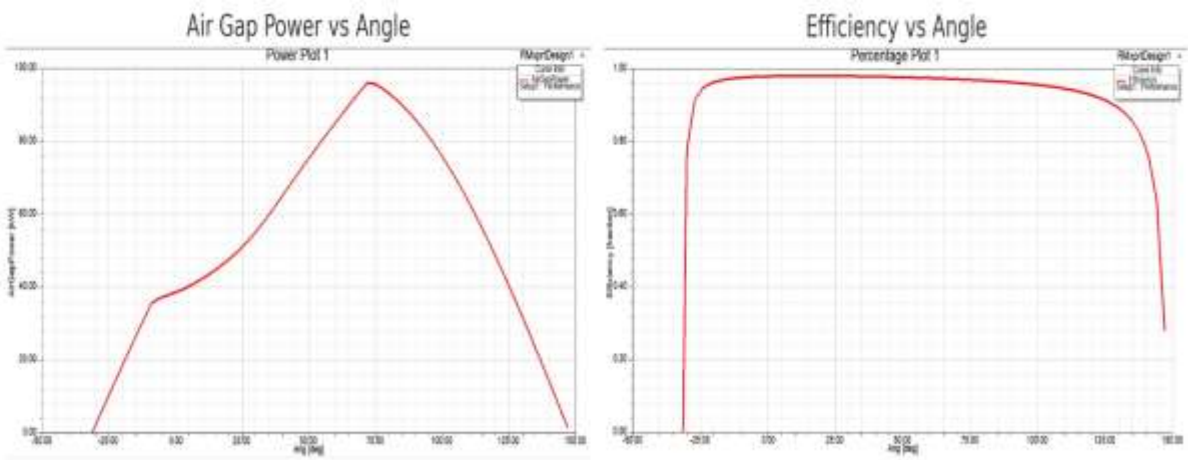


Figure 18 RMxprt Results for Air Gap 4.5

V. Conclusion and Future Work

This research investigates the performance effects of stator materials and rotor materials together with air gap dimensions in Permanent Magnet Synchronous Motors (PMSM). An examination using finite element analysis (FEA) with experimental validation analyzes the relation between materials selection with air gap dimensions on performance indicators like induced voltage together with flux linkage and torque and output power and efficiency. According to the results high permeable Material A (cobalt-iron) delivers superior performance for voltage and torque output yet Material C (silicon steel) demonstrates reduced power efficiency. The size of the air gap between the magnets proves essential for improving system efficiency because it reduces magnetic reluctance thereby boosting torque performance. Typical product selection influences machine operation more than air gap dimensions although air gap control remains essential for maximum power output efficiency. Future investigations need to study selection methods for hybrid materials and adaptive air gap controllers in addition to heat dissipation solutions and sophisticated control methods to improve PMSM efficiency and performance abilities. The research creates essential strategies for enhancing electrical machine implementation throughout different industrial sectors as well as automotive industries.

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