

Comparative Study of Generator Voltage Performance by Varying Generator Materials using COMSOL Multiphysics.

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ABSTRACT

This paper studies the comparative performance of generated voltage and magnetic flux distribution of an electrical machine due to the variation of stator and rotor materials using COMSOL Multiphysics. This simulation is done in 2D that shows how the circular motion of a rotor with the variation of magnetic and non magnetic materials generates an induced EMF in a stator winding. The modeling deals with both the material magnetic properties and the circuit equations related to different parts of the machine. The generated voltage is calculated as a function of time during the rotation with a single number of turn.

Keywords : Generator, Magnetic material, Non magnetic material, Electromagnetic Field, Permeability

1 INTRODUCTION

Permanent, soft and electro-magnets are a crucial part of our everyday life whose uses are surprisingly numerous and often go unnoticed. It finds ever-increasing uses in both the home and in industry. It is found in or used to produce almost every modern convenience today. Low voltage dc motors utilizing permanent magnets are becoming increasingly important for portable appliances such as the toothbrush and electric knife and to operate automobile accessories. There are a number of major families of permanent magnets available for designers, ranging from ferrite, known for its low cost and low energy, to rare earth materials, which are more expensive and offer higher performance [1],[5]. Designers need to analyze magnetizing field strength and magnetic output of magnetic materials prior to deciding on the appropriate magnet [2],[6]. The magnetic performance of a material is characterized by the parameters remanence, the coercivity, all of their respective temperature coefficients and the energy product $(BH)_{max}$ [1]. The values of these parameters are obtained from the magnetization loop, or rather the demagnetization loop as the second quadrant of the full loop \mathbf{B} , \mathbf{J} vs. \mathbf{H} with $\mathbf{B}=\mu_0\mathbf{H}+\mathbf{J}$ (induction \mathbf{B} , magnetic field \mathbf{H} , polarization \mathbf{J}) [1]. Permanent magnet electrical machines are probably the most investigated electrical machines now a days. The popularity of these machines is due to the fact that they present many advantages over the other types of electrical machines [4].

The purpose of this paper is to show the performance of generated voltage of a machine made by magnetic and non-magnetic materials and whose voltages are calculated as a function of time during the rotation. It also shows the influ-

ence on the voltage from rotation velocity and number of turn in the winding.

2 MODELING IN COMSOL MULTIPHYSICS

2.1 Partial Differential equation

The COMSOL Multiphysics model of the generator is a time-dependent 2D problem on a cross section through the generator [3]. This is a true time-dependent model where the motion of the magnetic sources in the rotor is accounted for in the boundary condition between the stator and rotor geometries (Fig. 1). Thus, there is no Lorentz term in the equation, resulting in the PDE

$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{0} \quad (1)$$

where the magnetic vector potential only has a z component.

2.2 Geometry Separation

Rotation is modeled using a deformed mesh application mode (ALE), in which the center part of the geometry, containing the rotor and part of the air-gap, rotates with a rotation transformation relative to the coordinate system of the stator. The rotation of the deformed mesh is defined by the transformation [3]

$$\begin{bmatrix} \mathbf{x}_{rot} \\ \mathbf{y}_{rot} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} \mathbf{x}_{sat} \\ \mathbf{y}_{sat} \end{bmatrix} \quad (2)$$

The rotor and the stator are drawn as two separate geometry

objects, so it is possible to use an assembly. This has several advantages: the coupling between the rotor and the stator is done automatically, the parts are meshed independently, and it allows for a discontinuity in the vector potential at the interface between the two geometry objects (called slits).

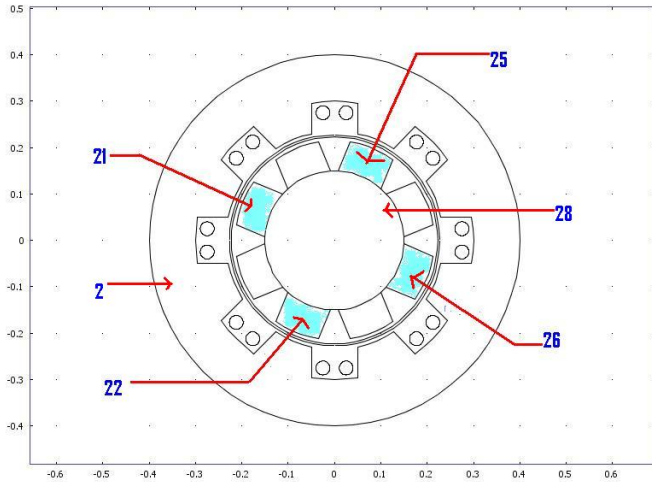


Fig. 1. Generator Geometry

The rotor problem is solved in a rotating coordinate system where the rotor is fixed (the rotor frame), whereas the stator problem is solved in a coordinate system that is fixed with respect to the stator (the stator frame). An identity pair connecting the rotating rotor frame with the fixed stator frame is created between the rotor and the stator. The identity pair enforces continuity for the vector potential in the global fixed coordinate system (the stator frame).

2.3 Choosing of material

The material in the stator and the center part of the rotor has a nonlinear relation between the magnetic flux, \mathbf{B} and the magnetic field, \mathbf{H} , the so called B-H curve. This is introduced by (Fig. 2) using a relative permeability, μ_r which is made a function of the norm of the magnetic flux, $|\mathbf{B}|$.

It is important that the argument for the permeability function is the norm of the magnetic flux, $|\mathbf{B}|$ rather than the norm of the magnetic field, $|\mathbf{H}|$. In this problem \mathbf{B} is calculated from the dependent variable \mathbf{A} according to $\mathbf{B} = \nabla \times \mathbf{A}$

\mathbf{H} is then calculated from \mathbf{B} using the relation

$$\mathbf{H} = \frac{\mathbf{B} - \mathbf{B}_r}{\mu_0 \mu_r} \quad (3)$$

In COMSOL Multiphysics, the B-H curve is introduced as an interpolation function (Fig. 2). This relationship for μ_r is pre-defined for the material **Soft Iron** in the materials library [3].

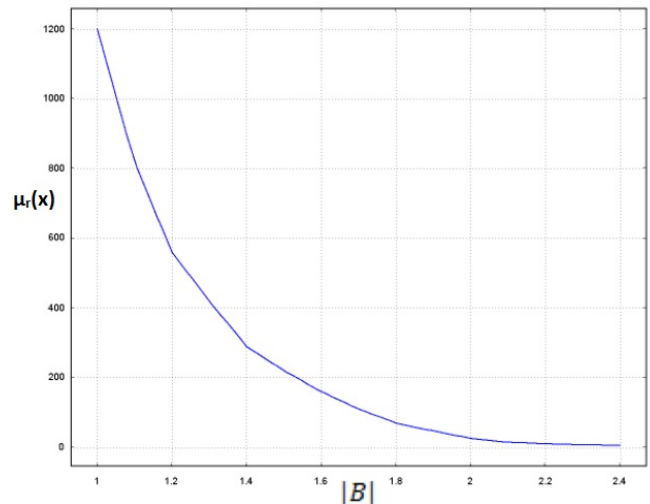


Fig. 2. Relative permeability, μ_r is made as a function of the norm of the magnetic flux, $|\mathbf{B}|$

2.4 Generated Voltage

The generated voltage is computed as the line integral of the electric field, \mathbf{E} , along the winding. Since the winding sections are not connected in the 2D geometry, a proper line integral cannot be carried out. A simple approximation is to neglect the voltage contributions from the ends of the rotor, where the winding sections connect. The voltage is then obtained by taking the average z component of the \mathbf{E} field for each winding cross-section, multiplying it by the axial length of the rotor, and taking the sum over all winding cross sections.

$$V_i = NN \sum_{winding} \frac{L}{A} \int E_z dA \quad (4)$$

Where L is the length of the generator in the third dimension, NN is the number of turns in the winding, and A is the total area of the winding cross-section.

3 SIMULATION AND RESULTS

The methods presented above are applied to the analysis of flux distribution and generated voltage of a generator by varying stator & rotor materials. The generated voltage simulated here is over one quarter of a revolution having a single-turn winding. Generator geometry with sub-domains is indicated in (Fig. 1). We have changed the material of sub-domain 21, 22, 25 & 26; sub-domain 20,23,24,27 and sub-domain 2, 28 collectively. Different types of magnetic and non magnetic materials are considered as 6 different cases. The brighter regions in the simulated magnetic flux figure indicate the position of the permanent magnets in the rotor for each case.

TABLE I
 Sub Domain Materials & Constitutive Relation for Different Generator Geometry

Type	Sub domain	Constitutive relation	Material
Non Magnetic Material	20,23,24,27	$B = \mu_c \mu_r H$	Antimony (Sb)
	21,22,25,26	$B = \mu_c \mu_r H$	Antimony (Sb)
	2,28	$B = \mu_c \mu_r H$	Indium (In)
Magnetic & Non-magnetic Material	20,23,24,27	$B = \mu_c \mu_r H + B_r$	Samarium cobalt (Radial, inward)
	21,22,25,26	$B = \mu_c \mu_r H + B_r$	Samarium cobalt (Radial, outward)
	2,28	$B = \mu_c \mu_r H$	Chromium(Cr)
Magnetic Copper Material	20,23,24,27	$B = \mu_c \mu_r H + B_r$	Samarium Cobalt (Radial, inward)
	21,22,25,26	$B = \mu_c \mu_r H$	Copper
	2,28	$B = \mu_c \mu_r H$	Soft Iron
Magnetic Quartz Material	20,23,24,27	$B = \mu_c \mu_r H + B_r$	Samarium Cobalt (Radial, inward)
	21,22,25,26	$B = \mu_c \mu_r H$	Quartz
	2,28	$B = \mu_c \mu_r H$	Soft Iron
Magnetic Iron Material	20,23,24,27	$B = \mu_c \mu_r H + B_r$	Samarium Cobalt (Radial, inward)
	21,22,25,26	$B = \mu_c \mu_r H + B_r$	Samarium cobalt (Radial, outward)
	2,28	$B = \mu_c \mu_r H$	Iron(Fe)
Magnetic Soft Iron Material	20,23,24,27	$B = \mu_c \mu_r H + B_r$	Samarium Cobalt (Radial, inward)
	21,22,25,26	$B = \mu_c \mu_r H + B_r$	Samarium cobalt (Radial, outward)
	2,28	$B = \mu_c \mu_r H$	Soft Iron

Case 1: For non-magnetic material at a rotation speed of 60 rpm the voltage will have negative amplitude for a single turn winding; see Fig. 3(a). The norm of the magnetic flux, $|B|$, and the field lines of the B field are shown below in Fig. 3(b) at time 0.20 s.

Case 2: For Magnetic & Non-magnetic Material the generated voltage in the rotor winding is apparently a sinusoidal signal. At a rotation speed of 60 rpm the voltage will have amplitude around 0.45 V for a single turn winding; see Fig. 4(a). The norm of the magnetic flux, $|B|$, and the field lines of the B field are shown below in Fig. 4(b) at time 0.20 s.

Case 3: For Magnetic Copper Material the generated voltage in the rotor winding is apparently a sinusoidal signal. At a rotation speed of 60 rpm the voltage will have amplitude around 0.225 V for a single turn winding; see Fig. 5(a). The norm of the

magnetic flux, $|B|$, and the field lines of the B field are shown below in Fig. 5(b) at time 0.20 s.

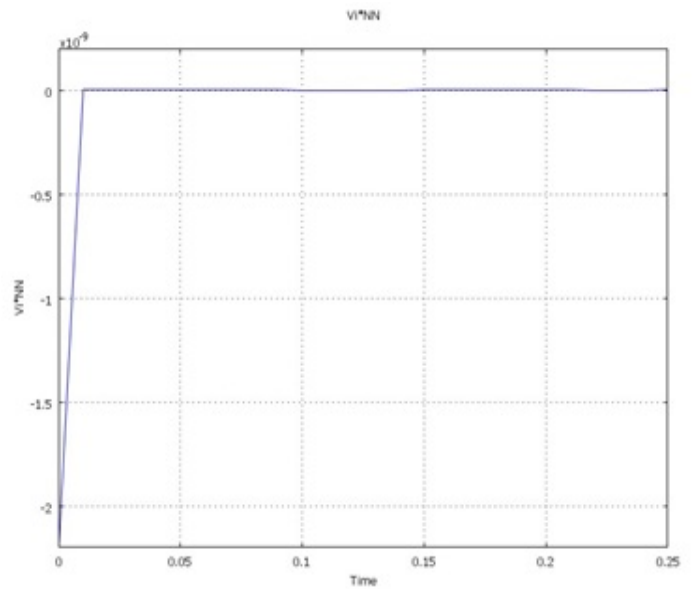


Fig. 3(a). Generated voltage over one quarter of a revolution

Case 4: For Magnetic Quartz Material the generated voltage in the rotor winding is apparently a sinusoidal signal. At a rotation speed of 60 rpm the voltage will have amplitude around 1.25 V for a single turn winding; see Fig. 6(a). The norm of the magnetic flux, $|B|$, and the field lines of the B field are shown below in Fig. 6(b) at time 0.20 s.

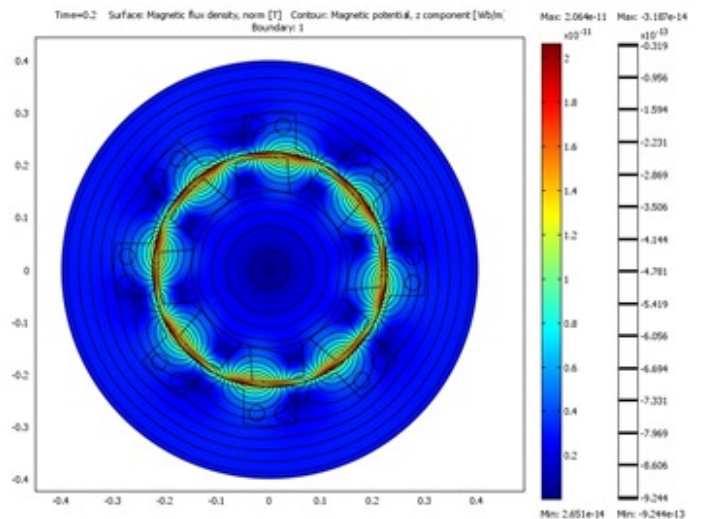


Fig. 3(b). The norm and the field lines of the magnetic flux

Case 5: For Magnetic Iron Material the generated voltage in the rotor winding is apparently a sinusoidal signal. At a rotation speed of 60 rpm the voltage will have amplitude around 2.25 V for a single turn winding; see Fig. 7(a). The norm of the magnetic flux, $|\mathbf{B}|$, and the field lines of the \mathbf{B} field are shown below in Fig. 7(b) at time 0.20 s.

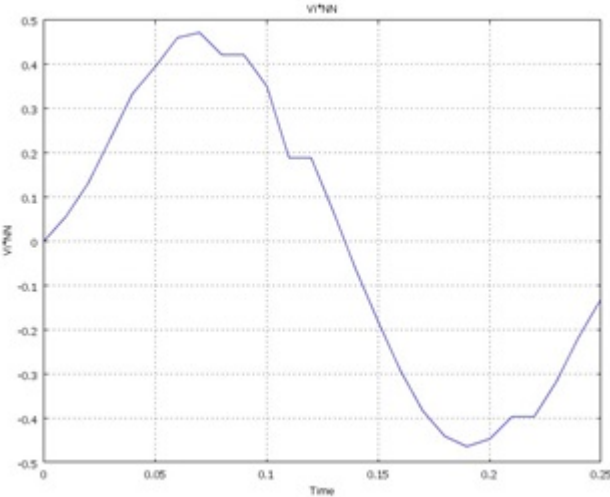


Fig. 4(a). Generated voltage over one quarter of a revolution

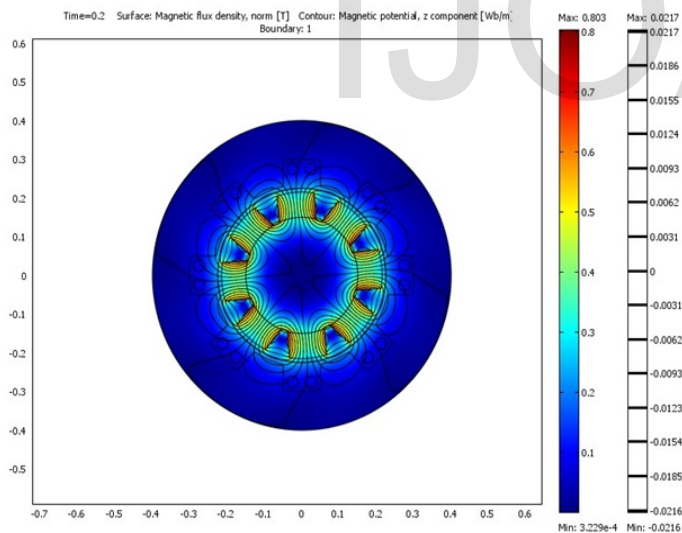


Fig. 4(b). The norm and the field lines of the magnetic flux

Case 6: For Magnetic Soft Iron Material the generated voltage in the rotor winding is a sinusoidal signal. At a rotation speed of 60 rpm the voltage will have amplitude around 2.3 V for a single turn winding; see Fig. 8(a). The norm of the magnetic flux, $|\mathbf{B}|$, and the field lines of the \mathbf{B} field are shown below in Fig. 8(b). at time 0.20 s.

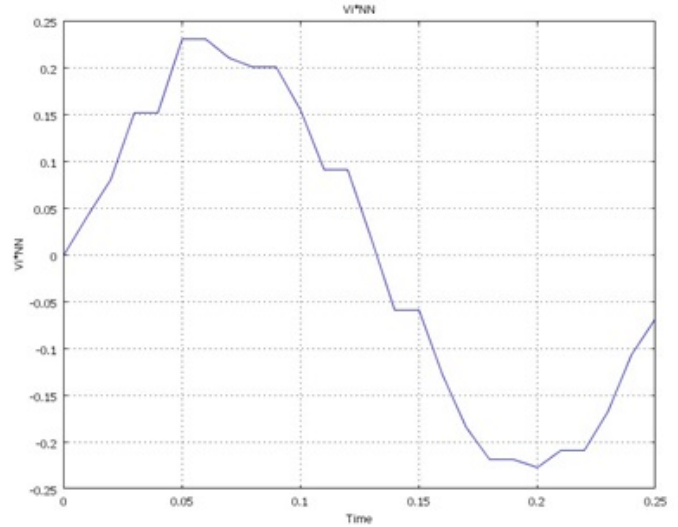


Fig. 5(a). Generated voltage over one quarter of a revolution

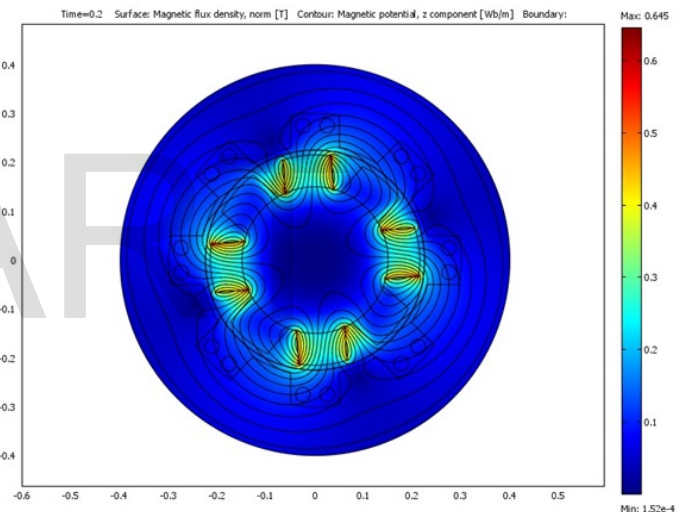


Fig. 5(b). The norm and the field lines of the magnetic flux

4 ANALYSIS & DISCUSSION

In **case-1**, it is seen that the flux lines are not confined around the stator winding pole (Fig. 3(b)). So the number of flux cut by the stator winding is very small and the output voltage is approximately zero (Fig. 3(a)). This is because the material Antimony used for sub-domain 20-27 and Indium for 2,28 is non-magnetic.

But for **case-2**, in spite of using non-magnetic material Chromium for sub-domain 2,28 a reasonable output voltage of 0.45 V (Fig. 4(a)) is found due to use of magnetic material Samarium Cobalt in sub-domain 20-27.

Which implies that the material used for model must be magnetic to get fair amount of output voltage. That is why for all of the preceding case magnetic materials are used.

- Relative permeability $\mu_r = 1$ (isotropic)
- Electrical conductivity $\sigma = 5.998e^7$

Soft Iron is used for sub-domain 2, 28 for which

- Relative permeability μ_r is predefined by the material library
- Electrical conductivity $\sigma = 0$.

Due to magnetic material, flux confined around the stator pole (Fig. 5(b)) is so enough to produce a small amount of 0.225 V (Fig. 5(a)). But the voltage shape is not so smooth due to non uniform flux distribution between stator and rotor.

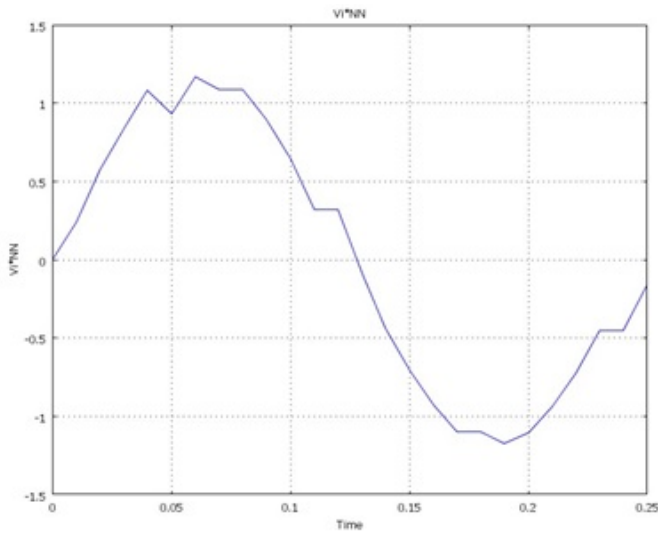


Fig. 6(a). Generated voltage over one quarter of a revolution

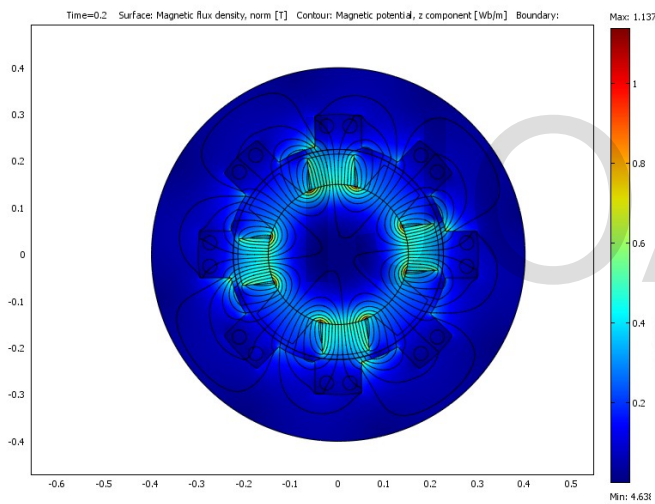


Fig. 6(b). The norm and the field lines of the magnetic flux

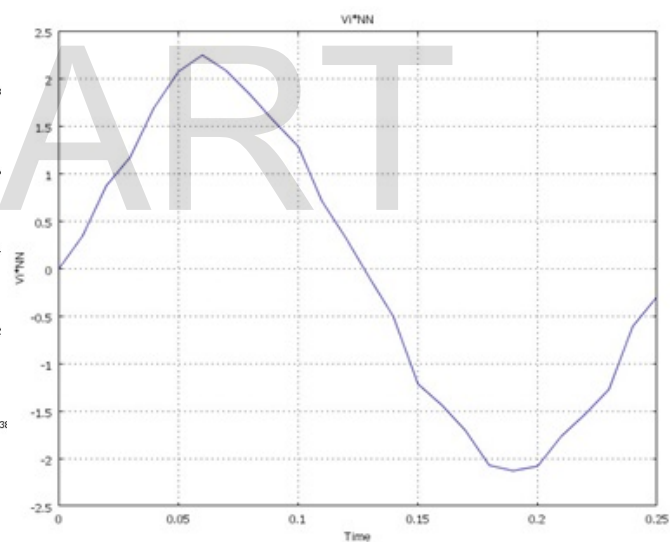
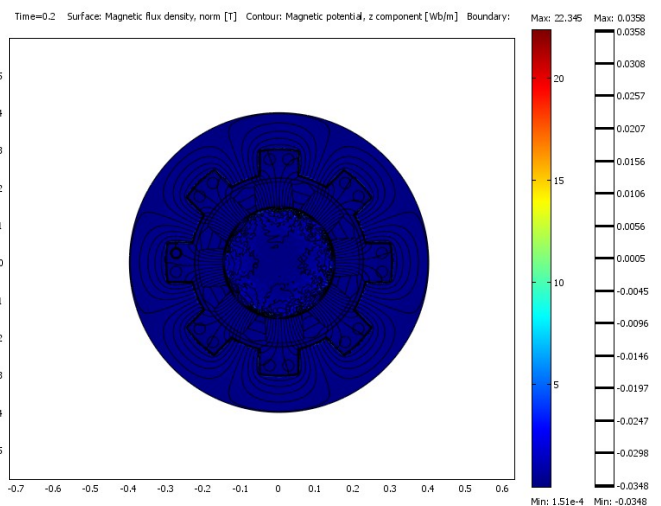


Fig. 7(a). Generated voltage over one quarter of a revolution

In case-3, the material Samarium Cobalt (Radial, inward) used for sub-domain 20,23,24,27 which has the following properties.

- Relative permeability $\mu_r = 1$ (isotropic)
- Electrical conductivity $\sigma = 0$.
- Remanent flux density $B_r = (-0.84) * x / \sqrt{x^2 + y^2}$ or $(-0.84) * y / \sqrt{x^2 + y^2}$.

For sub-domain 21,22,25,26 copper is used whose properties are as follows.



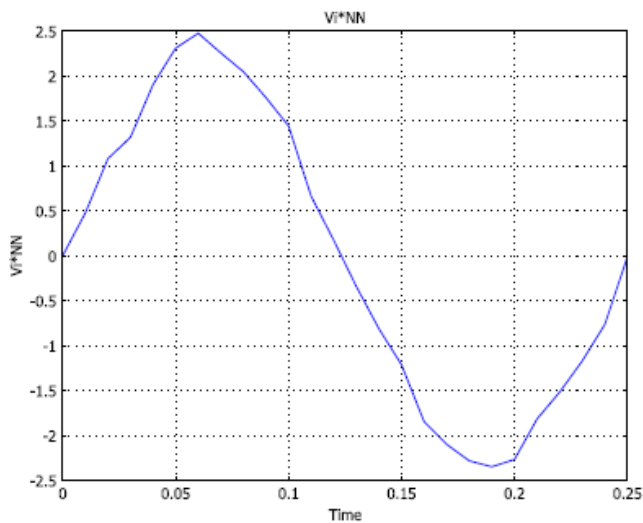


Fig. 8(a). Generated voltage over one quarter of a revolution

For **case-4**, the material of sub-domain 21,22,25,26 is changed

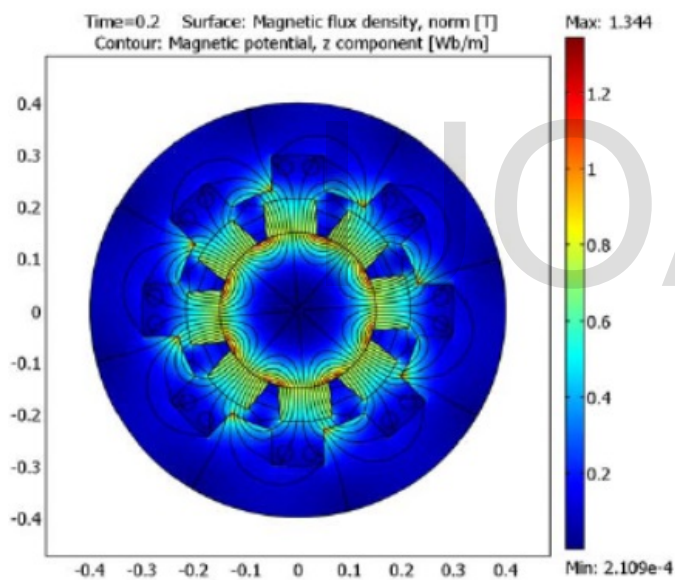


Fig. 8(b). The norm and the field lines of the magnetic flux from Copper to Quartz having

- Relative permeability $\mu_r = 1$ (isotropic)
- Electrical conductivity $\sigma = 1e^{-12}$.

As a result, the output voltage has changed from 0.225 V (Fig. 5(a)) to 1.25 V (Fig. 6(a)) due to large amount of flux confinement around the stator winding.

For the rest of the case only the material of sub-domain 2, 28 is changed keeping the sub-domain 20-27 unchanged with Samarium Cobalt.

For **case-5**, the material of sub-domain 2, 28 is Iron having

- Relative permeability $\mu_r = 4000$

- Electrical conductivity $\sigma = 1.12e^7$.

For **case-6**, the material of sub-domain 2, 28 is Soft Iron having

- Relative permeability $\mu_r = 1$ (isotropic)
- Electrical conductivity $\sigma = 0$.

Here though the magnitude of the output voltages are almost equal (2.25 V (Fig. 7(a)) to 2.3 V (Fig. 8(a))) but Soft Iron is more preferable than Iron in practical case due to low eddy current loss.

5 CONCLUSION AND FUTURE WORK

This paper presented the simulation of the generator model that can be used to design small power generator with high efficiency, compactness and low wait to torque ratio. It is also effective for generating less distorted output voltage with different combination of material in the stator and rotor.

In our work we just tried to analysis various aspects of 2D generator model. The knowledge of this work leads us for better analysis of 3D generator model having static, quasi-static, transient, and time-harmonic simulations with graphical representation. Due to its high remanent flux density and low cost Neodymium–Iron-Boron (NdFeB) can be used instead of Samarium Cobalt in our future work.

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