SIMULATION OF A TIME DEPENDENT 2D GENERATOR MODEL USING COMSOL MULTIPHYSICS

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ABSTRACT

COMSOL Multiphysics is designed to be an extremely flexible package applicable to virtually many areas of research, science, and engineering. A consequence of this flexibility is that it becomes necessary to set up COMSOL Multiphysics for a specific modeling task. It familiarizes with the modeling of generator (2D) in the AC/DC Module and illustrates different aspects of the simulation process. It steps through all the stages of modeling, from geometry creation to post processing. The program must mesh the geometry of the generator model before it can solve the problem. The powerful visualization of COMSOL Multiphysics tools is accessible in the program's post-processing mode. With this visualization time varying flux distribution and corresponding voltage output of the generator is possible to represent. Reliable output voltage of the generator depends upon the number of flux lines cut by the stator winding that depends on material property of stator and rotor. The materials may be magnetic or non-magnetic. With various combinations of these materials corresponding output voltage and flux distribution are shown here with the process of modeling, defining, solving, and post processing using the COMSOL Multiphysics graphical user interface. The purpose of this modeling is to find out best material combination which would produce significant amount of output voltage with least harmonic.

KEYWORDS: *Multiphysics, Magnetic material, non-magnetic material, Permeability, Mesh.*

I. INTRODUCTION

COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems based on partial differential equations (PDEs). With this software we can easily extend conventional models for one type of physics into multiphysics models that solve coupled physics phenomena and do so simultaneously.
Accessing this power does not require an in-depth knowledge of mathematics or numerical analysis. Thanks to the built-in physics modes it is possible to build models by defining the relevant physical quantities—such as material properties, loads, constraints, sources, and fluxes—rather than by defining the underlying equations. COMSOL Multiphysics then internally compiles a set of PDEs representing the entire model. It is possible to access the power of COMSOL Multiphysics as a standalone product through a flexible graphical user interface, or by script programming in the COMSOL Script language or in the MATLAB language.
As noted, the underlying mathematical structure in COMSOL Multiphysics is a system of partial differential equations. We provide three ways of describing PDEs through the following mathematical application modes:

- Coefficient form, suitable for linear or nearly linear models
- General form, suitable for nonlinear models
- Weak form, for models with PDEs on boundaries, edges, or points, or for models using terms with mixed space and time derivatives.

Using these application modes, we can perform various types of analysis including:

•Stationary and time-dependent analysis
•Linear and nonlinear analysis
•Eigen frequency and modal analysis

When solving the PDEs, COMSOL Multiphysics uses the proven finite element method (FEM). The software runs the finite element analysis together with adaptive meshing and error control using a variety of numerical solvers. Here Software version- Comsol multiphysics Module3.3; Module /DC_Module/Motors_and_Drives/generator has been used [1].

II. MODELING IN COMSOL MULTIPHYSICS

- Partial differential equation

The COMSOL Multiphysics model of the generator is a time-dependent 2D problem on a cross section through the generator. 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. Thus, there is no Lorentz term in the equation, resulting in the PDE

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

(where the magnetic vector potential only has a z component)

- 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

$$\begin{bmatrix} x_{rot} \\ y_{rot} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} x_{sat} \\ y_{sat} \end{bmatrix} \qquad (2)$$

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). The rotor problem is solved in a rotating coordinate system where the rotor is fixed (the rotor frame) [1].

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].

- Choosing of Material

The material in the stator and the center part of the rotor has a nonlinear relation between the magnetic flux, **B** and the magnetic field, **H**, the so called B-H curve [3]. This is introduced by using a relative permeability, μ_r which is made a function of the norm of the magnetic flux, |**B**|.It is important that the argument for the permeability function is the norm of the magnetic flux, |**B**| rather than the norm of the magnetic field, | **H**|. In this problem **B** is calculated from the dependent variable **A** according to

$$\mathbf{B} = \nabla \times \boldsymbol{A} \qquad (3)$$

H is then calculated from **B** using the relation

$$\boldsymbol{H} = \frac{\boldsymbol{B} - \boldsymbol{B}_r}{\mu_0 \mu_r} \qquad (4)$$

Resulting in an implicit or circular definition of μ_r had |**H**| been used as the argument for the permeability function.

In COMSOL Multiphysics, the B-H curve is introduced as an interpolation function; see Figure 1. This relationship for μ_r is predefined for the material **Soft Iron** in the materials library that is shipped with the AC/DC Module, acdc_lib.txt.

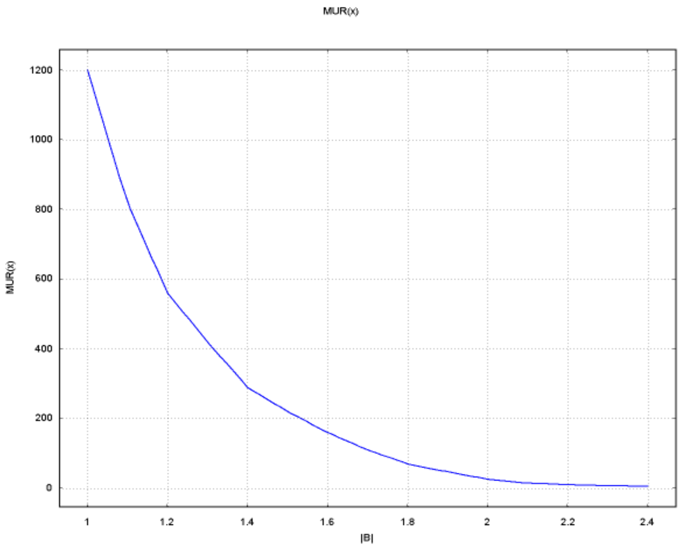


Figure 1: The relative permeability versus the norm of the magnetic flux, |**B**|, for the rotor and stator materials.

- Generated Voltage

The generated voltage is computed as the line integral of the electric field, **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 **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 [4].

$$V_i = NN \sum_{winding} \frac{L}{A} \int E_z dA \quad (5)$$

III. MAGNETIC & NON MAGNETIC MATERIAL

Table 1: Sub domain configuration for magnetic & non magnetic material

Sub domain	20,23,24,27	21,22,25,26	2,28	All others
Constitutive relation	$B = \mu_0\mu_r H + B_r$	$B = \mu_0\mu_r H + B_r$	$B = \mu_0\mu_r H$	$B = \mu_0\mu_r H$
Material	Samarium cobalt (Radial, inward)	Samarium cobalt (Radial, outward)	Chromium(Cr)	

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 .45 V for a single turn winding; which indicates in Figure 2.

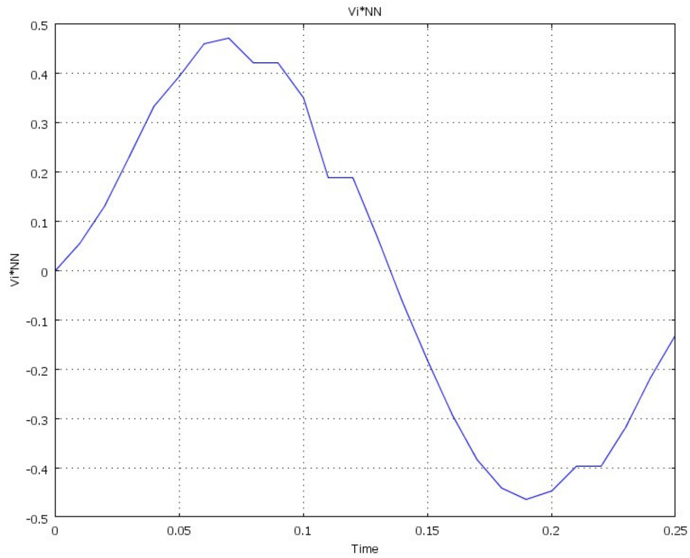


Figure 2: The generated voltage over one quarter of a revolution.

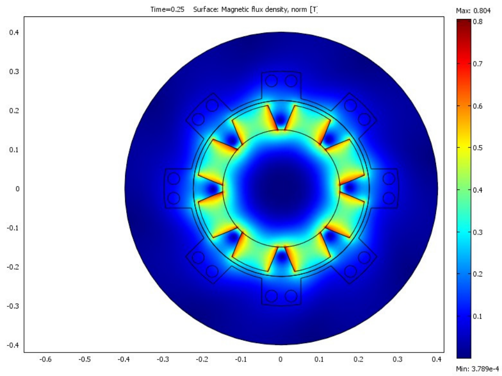


Figure 3-Static solution of time–dependent simulation

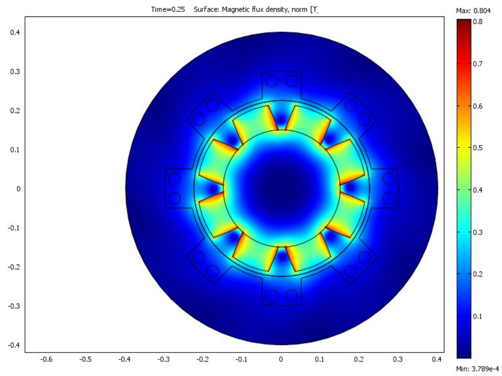


Figure 4-Static solution of time–dependent simulation

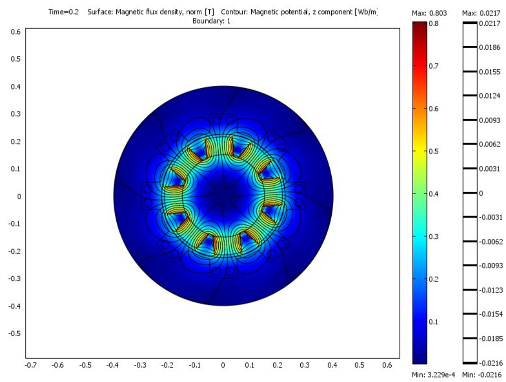


Figure 5: The norm and the field lines of the magnetic flux after 0.2 s of rotation.

Note the brighter regions, which indicate the position of the permanent magnets in the rotor

IV. MAGNETIC COPPER

Table 2: Sub domain configuration for magnetic Copper

Sub domain	20,23,24,27	21,22,25,26	2,28	All others
Constitutive relation	$B = \mu_0 \mu_r H + B_r$	$B = \mu_0 \mu_r H$	$B = \mu_0 \mu_r H$	$B = \mu_0 \mu_r H$

Material	Samarium Cobalt (Radial, inward)	Copper	Soft Iron	

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 .225 V for a single turn winding; which indicates in Figure 6.

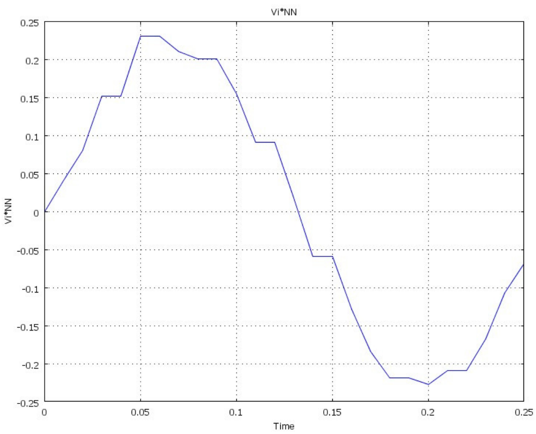


Figure 6: The generated voltage

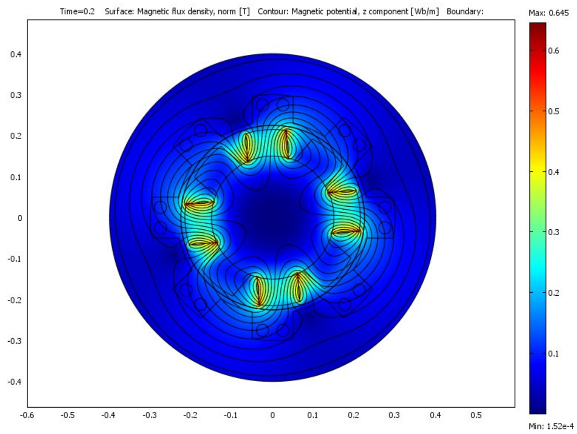


Figure 7: The norm and the field lines

V. MAGNETIC QUARTZ

Table 3: Sub domain configuration for magnetic Quartz

Sub domain	20,23,24,27	21,22,25,26	2,28	All others
Constitutive relation	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} + \boldsymbol{B}_r$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$
Material	Samarium Cobalt (Radial, inward)	Quartz	Soft Iron	

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; which Indicates in Figure 8.

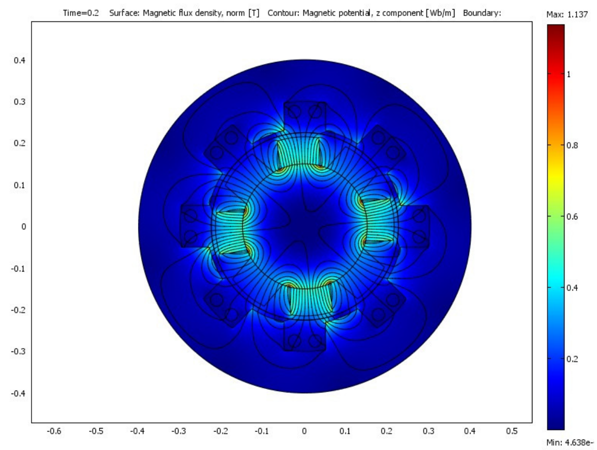


Figure 8: The norm & the field lines

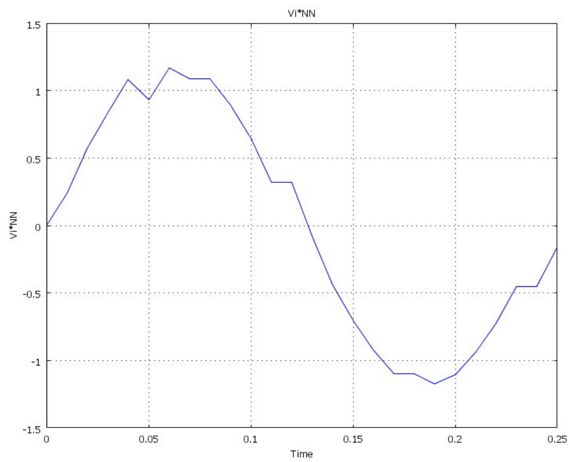


Figure 9: The generated voltage

VI. Magnetic Aluminium & Magnesium

Table 4: Sub domain configuration for magnetic Aluminum & Magnesium

Sub domain	20,23,24,27	21,22,25,26	2,28	All others
Constitutive relation	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} + \boldsymbol{B}_r$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} + \boldsymbol{B}_r$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$
Material	Samarium cobalt (Radial, inward)	Samarium cobalt (Radial, outward)	Aluminum(Al)	

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 0.35 V for a single turn winding; which indicates in Figure 10.

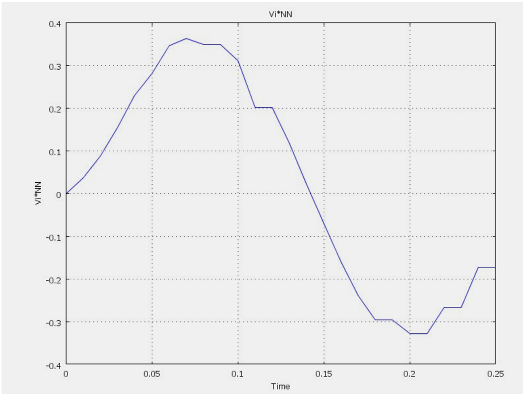


Figure 10: The generated voltage over one quarter of a revolution.

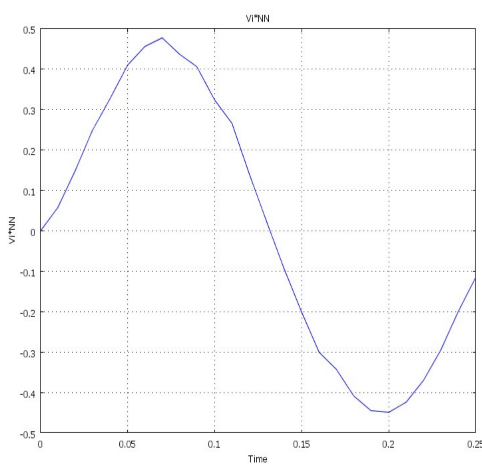
This simulation used a single-turn winding.

- Magnesium

Table 5: Sub domain configuration for Magnesium

Sub domain	20,23,24,27	21,22,25,26	2,28	All others
Constitutive relation	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} + \boldsymbol{B}_r$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H} + \boldsymbol{B}_r$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$	$\boldsymbol{B} = \mu_0\mu_r\boldsymbol{H}$
Material	Samarium cobalt (Radial, inward)	Samarium cobalt (Radial, outward)	Magnesium(Mg)	

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 0.48 V for a single turn winding; which indicates in figure 11.



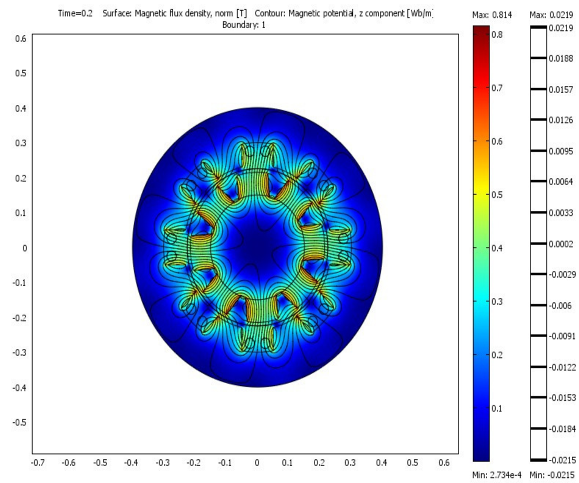


Figure 11: The generated voltage **Figure 12:** The norm and the field lines

VII. RESULT & DISCUSSION

For non magnetic material it is seen that the flux lines are not confined around the stator winding pole so the number of flux cut by the stator winding is very small and the output voltage is approximately zero. This is because the material Antimony used for sub-domain 20-27 and Indium for 2,28 is non-magnetic.

But for magnetic & non magnetic material case, in spite of using non-magnetic material Chromium for sub-domain 2,28 a reasonable output voltage of 0.45 V 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.

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

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=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.

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=5.998e ^7 [4]

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

- Relative permeability MUR(normB_emqa) is predefined by the material library
- Electrical conductivity σ=0.

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

Next the material of sub-domain 21.22,25,26 is changed from Copper to Quartz having

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=1e^-12 p [4]

As a result, the output voltage has changed from 0.225 V (Figure-5.1) to 1.25 V (Figure-6.1) 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.

Later the material of sub-domain 2, 28 is Aluminum having

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=3.77e^7 [4]

Then the material of sub-domain 2, 28 is Magnesium having

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=1.087e^7 [4]

Comparing magnetic material Aluminum & Magnesium it is found that, the output voltages are almost equal 0.35 V & 0.48 V. But for Magnesium the voltage shape is almost distortion less than Aluminum due to sinusoidal flux distribution.

Now the material of sub-domain 2, 28 is Iron having

- Relative permeability μ_r =4000
- Electrical conductivity σ=1.12e^7[4]

Next the material of sub-domain 2, 28 is Soft Iron having

- Relative permeability μ_r =1 (isotropic)
- Electrical conductivity σ=0 [4]

Here though the magnitude of the output voltages are almost equal 0.35 V to 0.48 V, but Soft Iron is more preferable than Iron in practical case due to low eddy current loss.

VIII. CONCLUSION

Independent of the structure size, the AC/DC Module of COMSOL Multiphysics accommodates any case of nonlinear, inhomogeneous, or anisotropic media. It also handles materials with properties that vary as a function of time as well as frequency-dispersive materials. Applications that can successfully simulate with the AC/DC Module include electric motors, generators, permanent magnets, induction heating devices, dielectric heating, capacitors, and electrical machinery. The simulation of the generator model can be used to design small power generator with high efficiency, compactness and low wait to torque ratio. This simulation experiment clearly demonstrate the output voltage characteristics for different material under rotating condition and also shows the strong effect of permeability and conductivity on output voltage magnitude.. In future experiment Neodymium–Iron-Boron (NdFeB) is likely to be used instead of Samarium Cobalt due to its High remanent flux density & low cost [6].

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