

FEM ANALYSIS OF A MOTOR-GENERATOR ASSEMBLY FOR A HYBRID ELECTRIC VEHICLE

Eng. Florin Lazar, Prof. Doc. Eng. Alecsandru SIMION PhD¹,
Lecturer Eng. Leonard Livadaru PhD¹, Eng. Sorin VLASCEANU, Eng. Daniel Irimia

¹“Gheorghe Asachi” Technical University of Iași, Faculty of Electrical Engineering,
Department of Electrical Machines, Iași, Romania.

REZUMAT. In prezent o multime de producatori auto produc autovehicule electrice si hibride. Un ansamblu motor-generator ce utilizeaza masini cu magneti permanenti poate fi o alternativa pentru construirea unui autovehicul hibrid. Motoarele electrice ofera o variatie mai lina a cupului si un raspuns mai rapid. Utilizarea configuratiei Halbach pentru amplasarea magnetilor permanenti in cazul generatoarelor prezinta avantajul eliminarii miezului feromagnetic si inducerea unor tensiuni cvasi-sinusoidale.

Cuvinte cheie: motor cu magneti permanenti, generator cu magneti permanenti

ABSTRACT. Currently a lot of car manufacturers come with new models of electric and hybrid vehicles. The motor-generator assembly using permanent magnet machines can be an alternative for a hybrid vehicle. The electric motors offer a more smoother torque and faster response. The Halbach array used for electric generator has the advantage of eliminating the iron core and producing a quasi sinusoidal voltage.

Keywords: permanent magnet motor, permanent magnet generator

1. INTRODUCTION

Currently a great accent is on the developing of non polluting technologies. One of these technologies is represented by the development of electric and hybrid electric vehicles. Along with the decrease of fossil fuels and the increase of fuel prices for normal vehicles, the electric and hybrid electric vehicles develop even faster than before.

Although the electric vehicle is considered to be the zero emission vehicle, the lack of infrastructure, batteries high cost to produce and replace combined with the low range and long times to reload, make the hybrid vehicle to be a better candidate, for now, as a „green” vehicle.

A hybrid vehicle uses a normal combustion engine coupled with an electric generator. The generator produces energy that is stored in the batteries, which power one or more electric motors. Three types of hybrid topologies are used today: series, parallel and power split. In this paper a split system is analysed. The system is composed from an synchronous motor and a synchronous generator. In the hybrid split topology the

combustion engine is not mechanically connected to the wheels. It drives the electrical generator that produces electrical power. The wheels are connected to an electrical motor fed either from the generator or from batteries through a rectifier-inverter system.

The system proposed in this paper uses an synchronous permanent magnet generator and a synchronous permanent magnet motor. This construction is different from normal cases. Generally the two machines are separate, but in this case they have the same rotor armature. The advantage of this construction is that it behaves like a speed reducer, reducing the rotating speed of the combustion engine in a ratio of 2:1. The system can be used without a gearbox, if the motor is properly controlled. It can also be used with a permanent continuously variable transmission (used on Toyota Prius). Thus, the training assembly can be reduced.

The two machines feature separated magnetic fluxes, although the rotor is common. This was achieved by using a Halbach array for the generator and a flux barrier in the rotor yoke.

2. OPERATING PRINCIPLE

The overall scheme of the motor-generator assembly is given in Figure 1. The constructive parts are:

- ■ Generator inner stator, connected to the combustion engine.
- ■ Electric motor stator.
- ■ Windings.
- ■ Permanent magnets.
- ■ Common rotor connected to gearbox
- ■ Slip rings

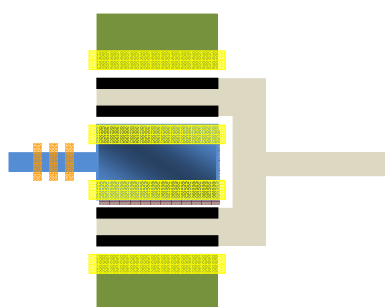


Fig. 1. Design of the motor-generator assembly

The combustion engine turns the generator interior stator until it reaches the synchronous speed. The common rotor is fixed in this period of time. The generator synchronous speed (1500 rpm) may match the combustion engine idle speed. Once the generator reaches the synchronous speed, the electric motor control can dictate its start up. The common rotor will have the same sense of rotation as the generator interior stator. The electric motor control can be made via a rectifier inverter with PWM signals, or a frequency converter. This type of control is required to maintain the generator speed close to synchronous, when the combustion engine increases the rotation speed. When this happens the electric engine will have to match its speed for the generator internal speed in relation to the speed of the rotor to be maintained close to synchronous.

The generator interior stator has permanent magnet excitation. The magnets are arranged in a Halbach array. Although this configuration requires a bigger permanent magnet volume, it has some advantages:

- The elimination of ferromagnetic material in the yoke.
- The elimination of iron losses.
- The induced voltages have a sinusoidal waveform.
- Lower inertia.

The elimination of ferromagnetic material from the yokes construction can compensate, in some manner, the increased cost caused by using a bigger volume of permanent magnet.

In this paper the no-load operation for the motor-generator assembly is analysed. The study is based on FEM analysis and uses the FLUX 2D package, produced by CEDRAT.

3. PERMANENT MAGNET SYNCHRONOUS MOTOR ANALYSIS

The synchronous motor used in this paper has a classical construction. The only difference from the normal case is the fact that it shares the rotor frame with the generator.

Table 1 shows the main constructive parameters of the permanent magnet synchronous motor.

Table 1

Main constructive parameters

Item	Value
Motor length	300 mm
Inner stator diameter	300 mm
Outer stator diameter	380 mm
Outer rotor diameter	299.6 mm
Air gap length	0.6 mm
PM width	2 mm
PM coverage angle	90°
Number of poles	4
Rated speed	1500 rpm
Number of slots	36

The motor has an output rated designed power of $P=75$ kW, the nominal voltage is $U=400$ V at a frequency of $f=50$ Hz.

Synchronous operation speed is considered to be 1500 rpm, the machine has a $2p=4$ number of poles.

The stator contains 36 oval shape slots with parallel wall teeth. The three phase stator winding is a single layer distributed type. Each stator slot is crossed by 16 wires with a cross-section diameter of 3.55 mm and a rated phase current of $I_n=54$ A.

Figure 2 shows the stator slot windings and the rotor magnet distribution.

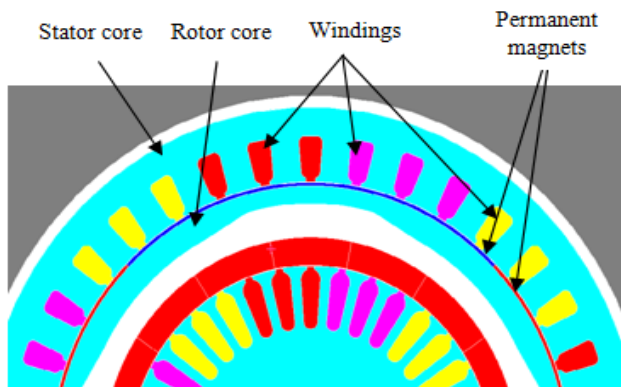


Fig. 2. Motor stator and rotor construction

The magnets used for the motor excitation system are NdFeB permanent magnets with remanent magnetic flux, $B_r = 1.1$ T, magnetic permittivity $\mu_r = 1.1$ and coercive force, $H_c = 871$ kA/m. In Figure 3 the flux line distribution and the flux density color maps are presented.

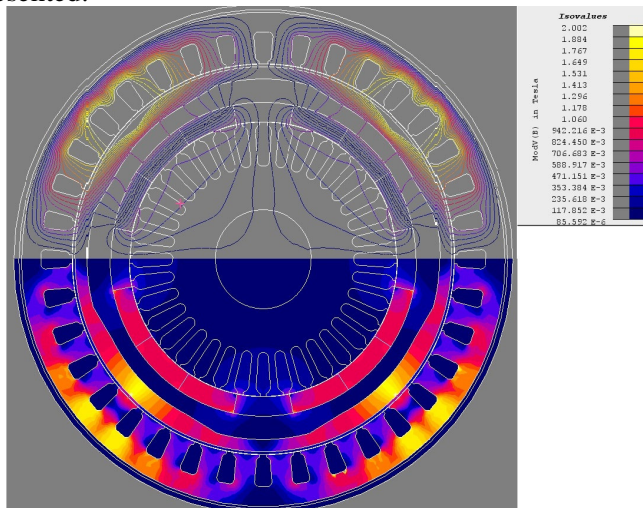


Fig. 3. Flux lines distribution and flux density color maps

As it can be seen the two machines have separate fluxes, the interference between the two generated fluxes is reduced. The flux density is close to the value of 2 T, in the stator and rotor yoke. This value can be achieved without any problems by the new materials used in laminated cores.

The FEM approach is based on a magnetostatic analysis and uses small changes in the rotor angle position, for each position the torque value is calculated. The resulting torque versus time waveform is given in Figure 4.

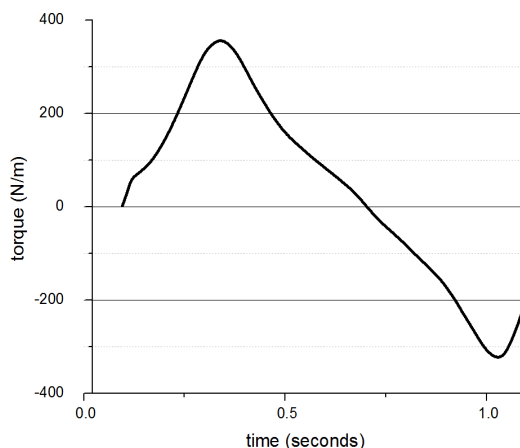


Fig. 4. Torque versus time

As it can be noticed the torque has a waveform close to a sinusoidal one, as expected. The maximum torque value is around 360 N/m.

The motor can be fed from an inverter-converter system with controlled power transistors, either by PWM technique or by a frequency converter. The second solution of feeding the motor would be easier to use because the phase voltage produced by the generator is perfectly sinusoidal.

4. PERMANENT MAGNET SYNCHRONOUS GENERATOR ANALYSIS

The generator used for producing the electric power in this assembly it's represented by a synchronous permanent magnet type. In this case the magnets are disposed in a Halbach array. The advantages of this array are:

- The generated voltage is sinusoidal
- The outside of the magnet pole is isolated from magnetic field lines.
- The yokes can be manufactured from non-ferromagnetic materials.

Although the Halbach array has some advantages, the major disadvantage for this array of permanent magnets, it's represented by the usage of bigger volumes of magnet.

The generator construction is reversed from classical topologies, the stator is placed inside the rotor, the two machines sharing the rotor armature.

Table 2 shows the main constructive parameters for the permanent magnet generator.

Table 2

Main constructive parameters

Item	Value
Generator length	300 mm
Inner stator diameter	75 mm
Outer stator diameter	210 mm
Inner rotor diameter	210.6 mm
Air gap length	0.6 mm
PM width	15 mm
PM coverage angle	22.5°
PM number	16
Number of poles	4
Rated speed	1500 rpm
Number of slots	36

The generator has an output rated designed power of $P= 65 \text{ kW}$, the generated voltage is $U= 300 \text{ V}$ at a frequency of $f= 50 \text{ Hz}$. The generator has a lower power than the motor due to limitations caused by space.

Synchronous operation speed is considered to be 1500 rpm, the machine has a $2p= 4$ number of poles. The operation speed for the generator is 1500 in respect to the rotor armature. It has been considered that if the thermal engine increases from idle rpm to a higher value, the motor will accelerate the rotor armature to a corresponding speed, thus the generator operating at speeds close to synchronism all the time.

The NdFeB magnets were used in this case too, the high value of the remanent flux causing higher values for the induced voltages.

The stator contains 36 oval shape slots with parallel wall teeth. The three phase stator winding is a single layer distributed type. Each stator slot is crossed by 31 wires with a cross-section diameter of 2.66 mm and a rated phase current of $I_n= 43 \text{ A}$. The generator construction can be seen in Figure 5.

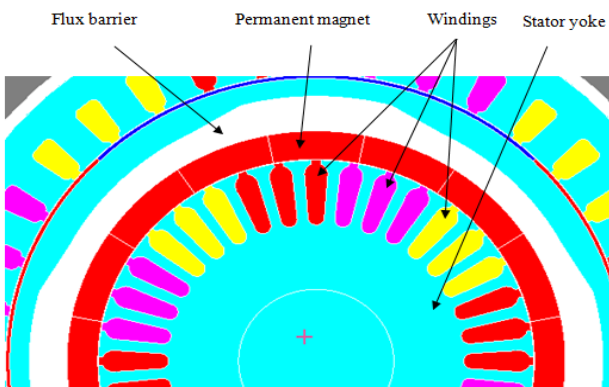


Fig. 5. Motor stator and rotor construction

The FEM approach in this case is based on a transient analysis. The motor stator winding is fed in such manner

that the established magnetic field is static, used only to determine if the two magnetic fields come in contact.

In Figure 6 the field lines and the flux density color maps are presented.

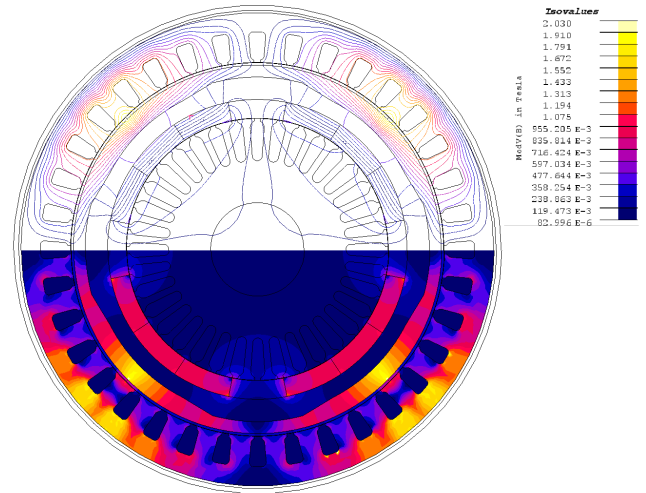


Fig. 6. Flux lines distribution and flux density color maps

As it can be seen the two generated fluxes interact due to the magnets displaced at 90° , but this interaction is reduced. The stator yoke and the flux barrier are constructed from non ferromagnetic material. As expected the flux density in the generator is lower than in the motor.

The phase induced voltages are presented in Figure 7.

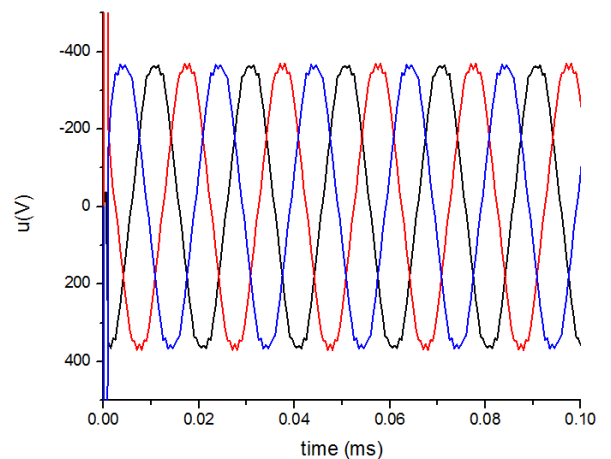


Fig. 7. Three phase induced voltages

As it can be seen from Figure 7 the tension waveform is almost sinusoidal, and has a maximum value of approximately 365 V.

5. CONCLUSIONS

- ✓ The presented construction has the advantage of using the same space and the same rotor for the two machines.
- ✓ The combustion engine no longer drives the wheels, it runs the generator that powers the electric motor.
- ✓ The motor-generator system can be used without a gearbox reducing the drivetrain assembly.
- ✓ The motor needs proper control in order to maintain the generator speed close to synchronous.
- ✓ The drive system must contain a battery in order to supply the motor with the required power, due to the fact that the generator has a lower rated power.

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About the authors

Assoc. Prof. Eng. **Leonard LIVADARU**, PhD.
Technical University „Gheorghe Asachi” of Iași, Romania
email: livadaru@ee.tuiasi.ro

Leonard Livadaru received the B.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Iași, Romania, in 1985 and 2003, respectively. He is currently an Assoc. Prof. with the Department of Electrical Machines at Electrical Engineering Faculty from the Technical University of Iași, Romania. He has published over 150 papers in conference proceedings and 5 books. His technical interests are electric machines, design and optimization based on FEM.

Prof. Eng. **Alecsandru SIMION**, PhD.
Technical University „Gheorghe Asachi” of Iași, Romania
email: asimion@ee.tuiasi.ro

Alecsandru Simion received the B.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Iași, Romania, in 1968 and 1976, respectively. He is currently a Professor with the Department of Electrical Machines from the Technical University of Iași. He has published over 230 papers in conference proceedings and 10 books. His technical interests are electric machines and drives, simulation and design. He is the holder of 12 patents.