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# Embedded Simple Excited Automotive Alternator Modeling using Magnetic Equivalent Circuits

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**ABSTRACT**

This paper presents the modeling by Magnetic Equivalent Circuit model (MEC) of a Simple Excited Automotive Alternator (SE2A) where DC-excitation winding is transferred from rotor side to statorone rather than in conventional automotive claw pole alternators, to overcome the disadvantages of the ring-brush system. Following the resolution of the MEC using Newthon-Raphson numerical method, the alternator performances at both no-load and under resistive load regimes is achieved considering the saturation effect. It has been found that alternator's performances carried out using the proposed MEC are with closed proximity to experimental records on a built prototype of the considered alternator.



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## 1. INTRODUCTION

Through the last years several works, [1-3], showed standing of claw pole structure adopted in conventional automotive alternators power generation. Due especially to its simplicity and low manufacturing costs, the claw pole alternator has the most popular electromechanical automotive source of electrical energy [4]. In reality, the hetero-polar structure of its rotor offering the integration a high pole pair number in a reduced volume, leading so to an interesting generation capabilities. Several claw pole alternators structures have been proposed and studied in bibliography and differ are mainly especially by their excitation forms [5], [6]. The disadvantage of this machine is a crucial maintenance problem as a result of brush-ring system [7], [8]. To discard this disadvantage, such approach consists in transmitting the field winding from rotor to stator.The removal of the brush-ring system makes it possible to achieve high reliability and crucial cost as well as it improves greatly the availability of the claw pole alternator.In this context, an embedded Simple Excited Automotive Alternator (SE2A) where the DC-excitation winding is located in the stator attracts currently an increasing attention and represents a fertile research domain [9].

The present work comes to append an analytical tool based on reluctant modeling of an embedded Simple Excited Automotive Alternator (SE2A). In what follows, a studied SE2A prototype is firstly described. After that, flux lines through SE2A's magnetic circuit are analyzed and magnetic equivalent reluctant network of this structure is elaborated. Finally, established model is resolved and obtained results are compared to experimental records performed on a test bench.

## 2. STRUCTURE AND DESCRIPTION OF FLUX LINKAGE OF THE SE2A

The SE2A prototype is a modified conventional claw pole alternator where DC-excitation winding is transferred from rotor to stator. Also, it is equipped by a three-phase armature winding and includes twelve claws leading to a six pole pair structure. The stator magnetic circuit is composed of two parts connected in series. The first part is the usual laminated cylinder consists of iron sheets and consecrated to the insertion of alternator armature. Though, the second one is a massive cylinder surrounding laminated part, committed to inductor flux's flowing and called "stator yoke" [10]. The described concept illustrated in Figure 1 is called Simple Excited Automotive Alternator (SE2A), because it has a single excitation source (only wound inductor).View that the inductor is placed in the stator, the field winding results from two ring shaped coils connected in series and introduced especially into both sides of the machine between the stator yoke and the armature end windings. Figure 2 illustrates flux paths between stator and rotor through the SE2A magnetic circuit. They are characterized by two kinds: useful and useless. In fact, described fluxes are:

a. A 2D flux, considered as leakage fluxes caused by homopolar linkage between rotor magnetic circuits and stator,
b. A 3D flux connecting two poles and crossing both stator and rotor magnetic circuits. It is dedicated to EMF generation in alternator's armature.

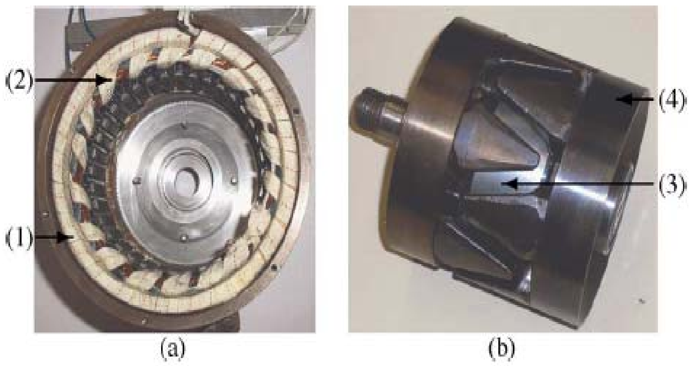



Figure 1.Structure of the SE2A. Legend: (a) stator, (b) rotor, (1) half of the statorDC-excitation ring winding, (2) armature en winding, (3) non-magnetic core

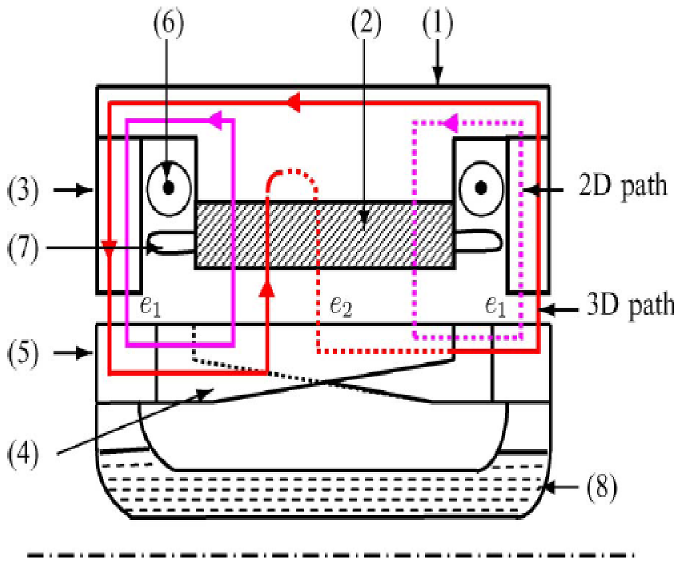



Figure 2. Flux paths through the magnetic circuit of the SE2A. Legend: (1) to (5) same as in Figure 1, (6): half of the stator DC-excitation winding, (7): armature end-winding, (8): non-magnetic core holding the two magnetic rings

## 3. MAGNETIC EQUIVALENT CIRCUIT OF THE SE2A

In literature, accuracy and calculation time are generally the main creterions adopted for the choice of an analytical modeling methodology among others. The magnetic equivalent circuit (MEC) modelingis a rapid analytical formulation mean that presents short calculation time with adequate precision, used for modeling of numerous machines [11]. Such amethod consists on the decomposition of machines structure to flux tubes. These flux tubes represent reluctances, MMF sources and, if available, permanent magnets sources. Also, the MEC approach is based on the magnetic Ohm law resulting from the analogy between magnetic circuits and electric ones.

In several works, as [12] and [13], flexible MEC models have been successfully investigatedand presented through detailed and synthetic description. In thepresent study, in order to prepare an accurate and rapid tool for the optimization of the proposed automotive alternator, the MEC method is adopted to estimate performances of the SE2A prototype.

### 3.1. No-Load Operation Model

Figure 3 shows the corresponding MEC of the SE2A at no-load regime, taking into account saturation effect. Considering Park's transformation, developed back-EMF can be decomposed in direct and quadrature components that correspond, respectively, to the polar and inter-polar axis elements, as expressed in Equation (1) and Equation (2):

$$\bar{E} = \overline{E_d} + \overline{E_q} \tag{1}$$

with:

$$\begin{cases} \|\overline{E_d}\| = E_d(I_f, I_d) \\ \|\overline{E_q}\| = L_q \omega I_q \end{cases} \tag{2}$$

Where Id is the direct component of armature's current, Iq is the quadrature component of armature's current, and If is alternator's field current.

In the case of no-load operation, alternator EMF is given only by direct flux component. As a result, the no-load EMF, can be calculated as in Equations (3) and (4):

$$E_q = 0 \text{ so } E = E_d \tag{3}$$

Then

$$E = \frac{1}{\sqrt{2}} N_a \omega \Phi_{\max} \tag{4}$$

Where $N_a$is the number of turns per armature phase, ω is the angular frequency, and $\Phi_{max}$ is the maximum flux crossing a phase which is obtained using the MEC.

Because of the nonlinear behavior of the SE2A, due to saturating materials, a numerical procedure based on Newton-Raphson method has been adopted in order to resolve proposed reluctance model and calculate needed value of flux crossing alternator's armature [14]. The number of Equations to be resolved is same as independent loops in considered magnetic circuit. In general, if a network includes: NR reluctances and NN nodes, it encloses: NIlp (= NR – NN + 1) independent loops. Let us consider our case, the proposed MEC includes 21 branches and 12 nodes which lead to 10 independent loops, as illustrated in MEC of the SE2A shown in Figure 3.

In the case of non-saturated magnetic circuit, obtained system is expressed by Equation (5).

$$\Psi = (SRS^T)^{-1}\mathrm{F} \tag{5}$$

The loop matrix S is built considering following values of each component: Sij is equal to:

a. -1: in the case where the flux of branch j is in the opposite direction of the orientation of loop i,
b. 0: in the case where the flux of branch j is not included in loop i,
c. 1: in the case where the flux of branch j is in the same direction of the orientation of loop i.

However, when materials are saturated, the inversion of matrix $(SRS^T)$ is not possible because reluctances depend on fluxes which are nonlinear.For that, the solution consists on defining a vector C expressed by Equation (6). So, the calculation process is stopped when C turns to be null.

$$C = F - (SRS^T)\Psi \quad (6)$$

Where F is loop m.m.f vector, S is the topological matrix and Ψ is loop fluxes vector, and R is a diagonal matrix containing the reluctances.
Reluctances are calculated using Equation (7):

$$R = \frac{L}{\Phi} H\left(\frac{\Phi}{S}\right) \quad (7)$$

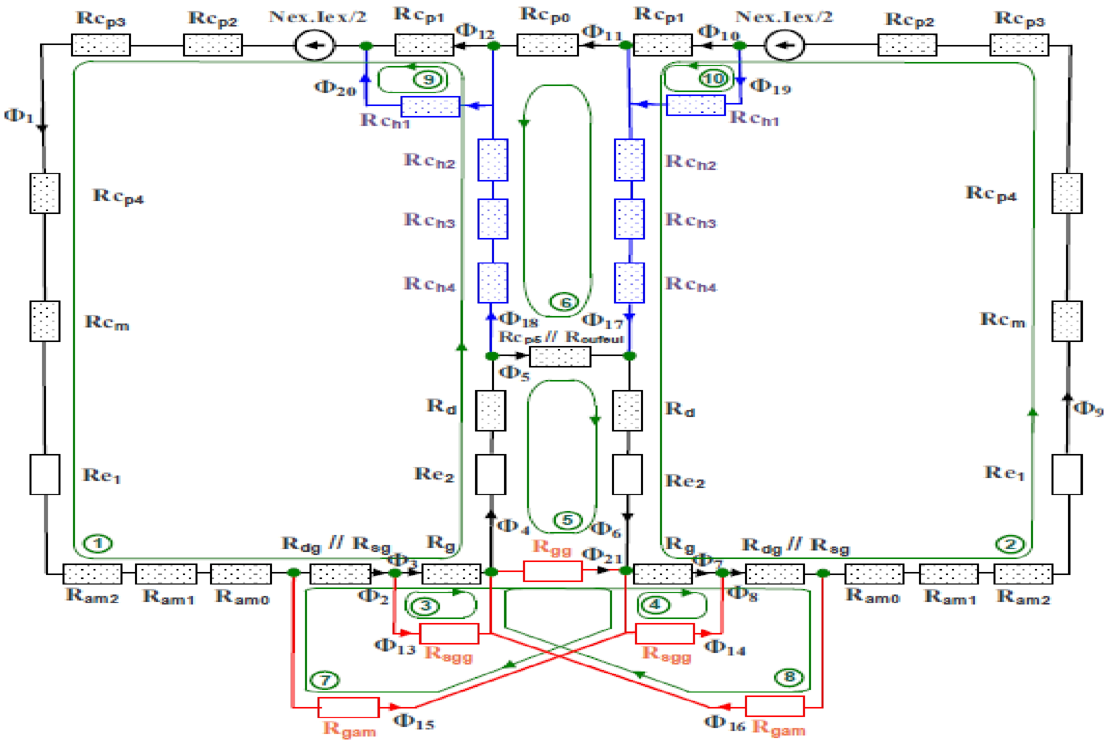



Figure 3. MEC of the SE2A where the orientations of the branches and the loops are indicated.

### 3.2. Load Operation Model

Under load operation, the proposed network is illustrated in Figure 4.It includes the effect of armature's magnetic reaction, in both d and q axis.Indeed, such a reaction is taken into account by the integration of an armature source named $AT_{arm}$ and expressed by Equation (8).

$$AT_{arm} = K_r N_c I_d \quad (8)$$

To take into account the effect of claws geometry on armature reaction Kr is replaced with a new coefficient: Kri [14], expressed by Equation (9):

$$K_{ri} = \frac{6R_{extr} l_n}{K_c e_2} \left( \frac{\cos\left(p\frac{l_{boutgriffe}}{2R_{extr}}\right) - \cos\left(p\frac{l_{basegriffe}}{2R_{extr}}\right)}{p^2\left(\frac{l_{basegriffe}}{2R_{extr}} - \frac{l_{boutgriffe}}{2R_{extr}}\right)} \right) \times \left( \frac{2K_c e_2}{l_s\left(l_{boutgriffe}+l_{basegriffe}\right)} + \frac{p\log\left(\frac{R_{intcm}}{R_{intcm}-e_1}\right)}{2\pi e_{cm}} \right) \quad (9)$$

Where $R_{extr}$ is the external rotor radius, $l_n$ is the claw length, $K_c$ is the Carter coefficient, $e_2$ is the thickness of the air gap between the claws and the stator teeth, $p$ is the pole pair number, $l_{basegriffe}$is the width of the claw base, $l_{boutgriffe}$ is the width of the claw tip, $l_s$ is the stator active length, $N_c$ is the number of conductors by slot, $e_1$ is the thickness of the air gap between the collector and the magnetic ring, $R_{intcm}$ is the internal magnetic collector radius, and $e_{cm}$ is the collector thickness.

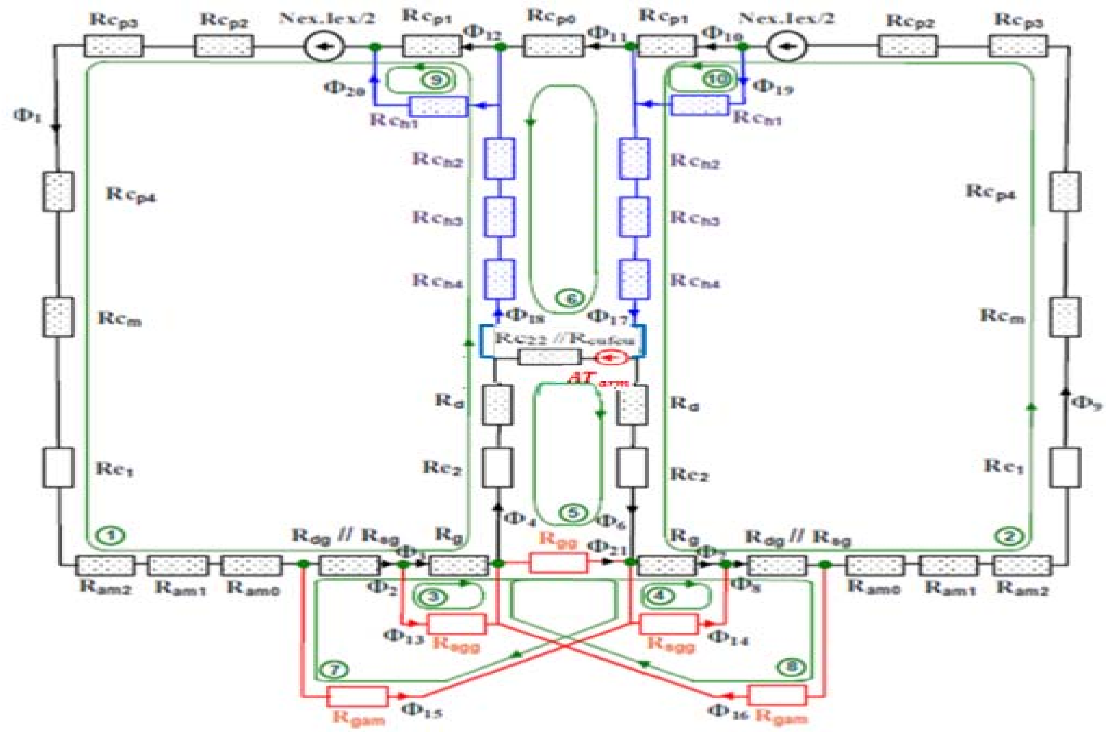


Figure 4. SE2A reluctance network within the d-axis accounting for the armature magnetic reaction and the saturation.

The direct component of alternator EMF ($E_d$) is obtained using the SE2A's reluctant model under load operation. Besides, quadrature component ($E_q$) is deduced using the phase diagram of Figure 5, corresponding to the single-phase scheme of a synchronous machine. In fact, referring to this diagram, the total EMF of the alternator can be calculated using Equation (10). Besides, referring to phase diagram of the SE2A, the projection of the EMF on d and q axis, leads to the expressions of needed components given by Equation (11).Finally, the bloc diagram for the resolution of the established MEC is illustrated in Figure 6.

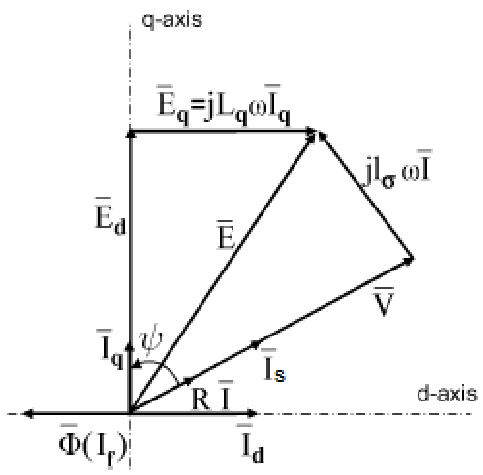



Figure 5. Phase diagram of the SE2A in the case of a resistive load

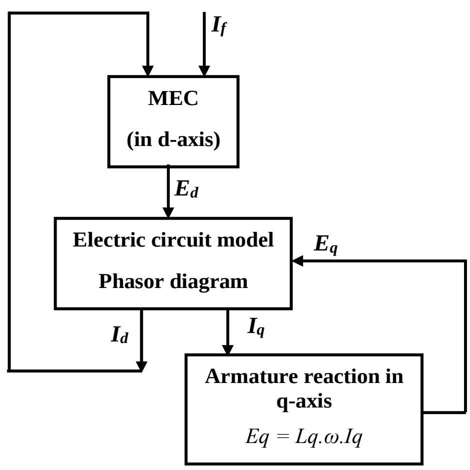



Figure 6. Block diagram of the numerical procedure developed for the resolution of the SE2A model

$$\bar{E} = R\bar{I_s} + \bar{V} + jl_\sigma\omega\bar{I_s} \quad (10)$$

$$\begin{cases} RI_s\cos(\Psi) + l_\sigma\omega I_s\sin(\Psi) - E_d = 0 \\ -RI_s\sin(\Psi) + l_\sigma\omega I_s\cos(\Psi) + E_q = 0 \end{cases} \quad (11)$$

Where Is is the armature's current, V is the phase's voltage, R is the phase's resistance, and $l_\sigma$ is the leakage inductance.

## 4. EXPERIMENTAL VALIDATION

In order to validate the proposed MEC, both accuracy and robustness of the elaborated model are targeted. Consequently, several tests have been managed and experimentally validated using a test bench built around an SE2A's prototype, illustrated in Figure 7. Operated tests are:

a. At no-load operation:
   1. Alternator's no-load characteristic at 1000 rpm (Figure 8(a)),
   2. EMF versus training speed for a field current of 5A (Figure 8(b)).
b. At short-circuit operation: armature current versus filed current, for a speed of 1000 rpm (Figure 9),
c. Under resistive load operation: armature voltage versus armature current, for a field current of 4A respectively at 1000 rpm and at 2800 rpm (Figure 10(a) and Figure 10(b)).

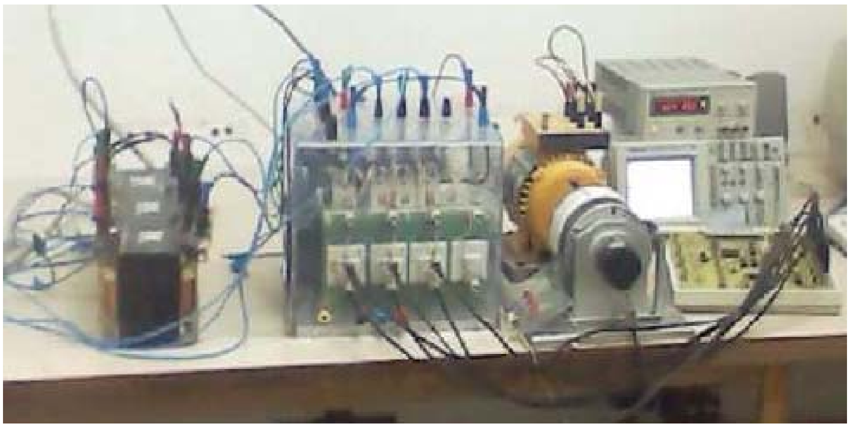


Figure 7. Experimental test bench of the SE2A.

Analyzing obtained curves, we summarized the error between model values and experimental ones in Table 1, using Equation (12).

$$Error(\%) = \frac{Model_{Value} - Experimental_{Value}}{Model_{Value}} \quad (12)$$

Table 1. Error rate for performed tests

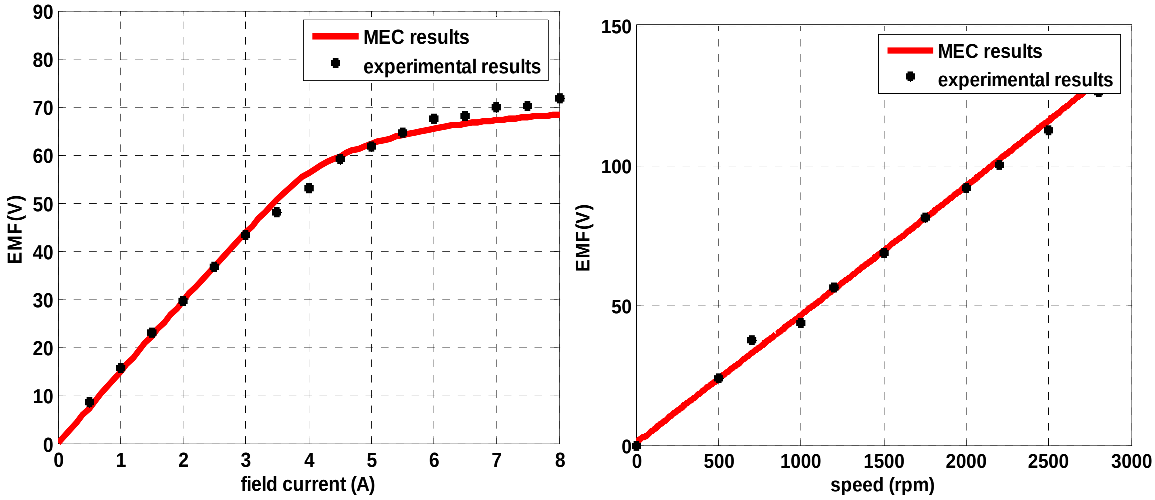
| No-load operation | | | | Short-circuit | | Resistive load (1000 rpm) | | Resistive load (2800 rpm) | |
|---|---|---|---|---|---|---|---|---|---|
| $I_F$(A) | Error (%) | speed (rpm) | Error (%) | $I_F$(A) | $I_S$(A) | $I_S$(A) | Error (%) | $I_S$(A) | Error (%) |
| 1 | 5 | 700 | 14.43 | 1 | 0.25 | 0.25 | 2.6 | 0 | 0.51 |
| 2 | 0.4 | 1000 | 5.83 | 1.5 | 0.4 | 0.4 | 0.4 | 0.83 | 1.74 |
| 3 | 1.8 | 1500 | 0.97 | 2 | 0.6 | 0.6 | 0.7 | 1.5 | 1.93 |
| 4 | 6.6 | 2000 | 1.01 | 2.5 | 0.95 | 0.95 | 3.5 | 1.75 | 0.05 |
| 5 | 1.4 | 2500 | 3 | 3 | 1.15 | 1.15 | 2.7 | 2.25 | 5.26 |
| 6 | 2.3 | 2800 | 3.15 | 3.5 | a1.66 | 1.66 | 1.8 | - | - |

Based on these results we can notice the following:

a. At no-load regime,for a constant speed(Figure 8(a)) error values do not exceed 7%. In addition, for a constant field current (Figure 8(b)) EMF error does not exceed 6%, except starting point.Furthermore, referring to Figure 8(a), magnetic circuit of the SE2A is saturated for a field current of 6A. However, in the case of the conventional alternator, saturation appears at field current of 3A. Consequently, modified alternator could be considered as serious candidate to for automotive generating applications.

b. At short-circuit regime,error on armature current is less then 2%.

c. Under load regime and for both considered speeds, error on armature voltage does not exceed 6%.




(a).$\Omega$ = 1000rpm (b). $I_F$ = 5A

Figure 8. EMF of the SE2A at no load operation regime.

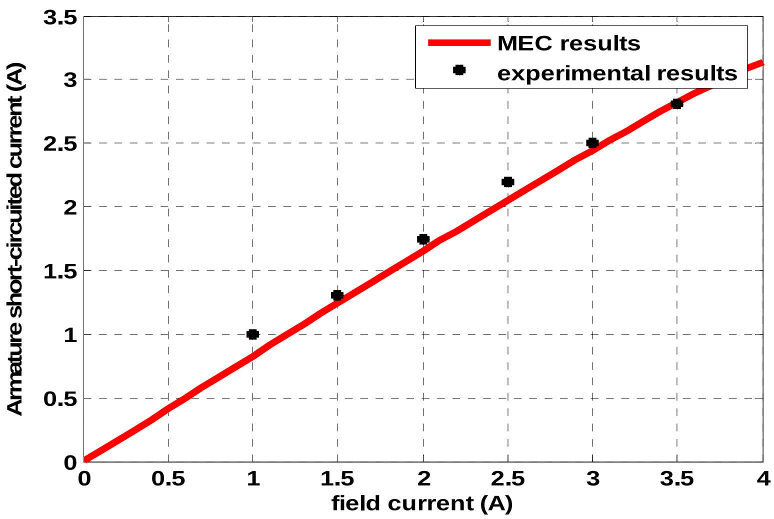
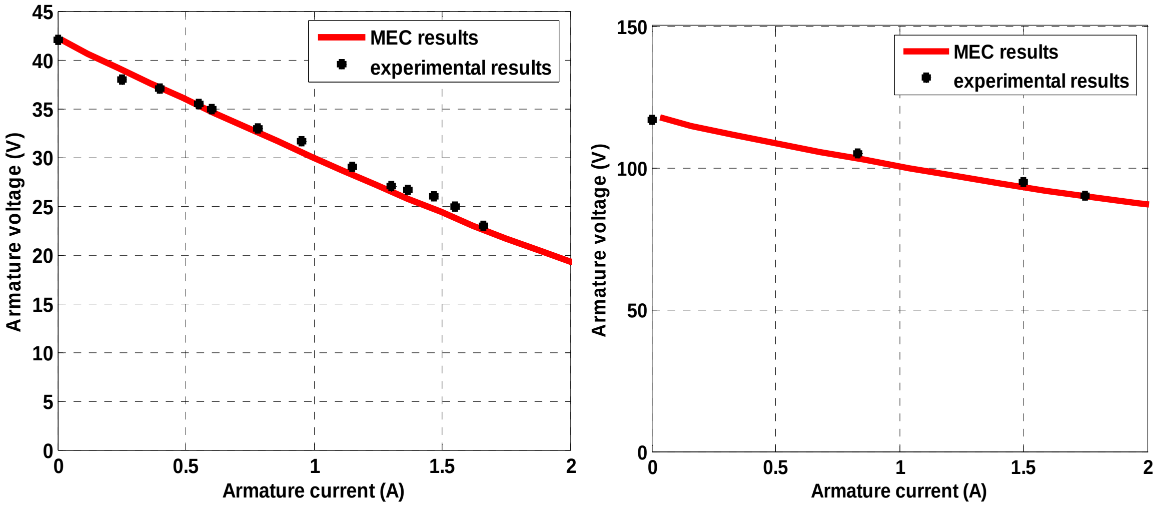



Figure 9. Armature short-circuited current versus the field current, for a speed of 1000 rpm.

As an issu of this comparison, we can conclude that the elaborated MEC provides values with closed proximity to experimental with a satisfying accuracy, under different operation regimes and excitation. Thus, rapidity of established model could be exploited to invest future works aimed to the optimization of the alternator’s performance and topology. Moreover, compared to conventional claw pole alternator, [15], in introduced SE2A the brush-ring system is eliminated leading to the improvement of alternator’s availability throughthe discard ofsystemic maintenance, [16].




(a). Ω = 1000rpm (b). Ω = 2800rpm

Figure 10. Armature voltage versus armature current for a field current of 4A (in the case of resistive load).

## 5. CONCLUSION

In order to improve the generation capabilities of automotive alternators, new concepts and designs of these machines are required. This paper was devoted to study analytically and experimentally a modified alternator with the aim of carry out a robust tool to predict electromagnetic behavior and performance of new enhanced structures. Established tool is a permeance network based on magnetic equivalent circuit method. It was applied on a Simple Excited Automotive Alternator (SE2A) where field winding is transferred from rotor to stator side rather than usual automotive alternators.

In first, based on flux paths through the magnetic circuit, SE2A reluctant network model was established at no-load and under load operations. After that, adopted numerical method based on the Newton-Raphson procedure for the resolution of obtained Equation system is provided. Finally, several tests have been managed and experimentally validated showing high satisfying precision and robustness of our model under different operation regimes and excitation. As an outcome of performed works, Authors plan to exploit established tool for the study and show that the SE2A can be enhanced to a hybrid alternator with high generation capabilities, making it a serious candidate to equip future automotives.

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