CONTRIBUTION AND COMPARISON STUDY FOR TORQUE RIPPLE REDUCTION IN VARIABLE RELUCTANCE GENERATOR USING THREE-DIMENSIONAL FE ANALYSIS AND WINDING FUNCTION THEORY

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The aim of this study is to overcome the major drawback of the SRM (synchronous reluctance machine) which is torque ripple to be used as a wind generator or traction motor. In this work we are interested to enhance and improve the torque ripple of variable reluctance machine and find the better torque evaluation for multiphase machine, tow different machines of the same power order are compared (three phases machine, five phases machine). This comparison is focused on geometry parameters study for the important parts of the SRM, which proved that they have a direct impact on the reluctant torque (slots, winding, rotor geometry), which represents the inductance variation. For the geometry parameters effect we used winding function theory which have approved it effectiveness in case of complex geometry study, this method is compared to finite elements analyses (two and three dimensional), and a VSI is used for the alimentation source. The VSI is used as feeding source only for the reluctance machines, the interrupter switching command for 120° electrical angle.

Keywords: Variable Reluctance Generator, torque ripple, winding, rotor topology, Winding Function Theory, Finite Elements Method, Voltage Source Inverter

1. Introduction

In the presence of a variable magnetic field with a ferromagnetic asymmetric structure, the last one can create a motion, this motion is the original phenomena for reluctance variation, and this phenomenon has been developed to create the SRM. The SRMs are an electromagnetic converter which are particularized by the simplicity in structure construction (there is no winding or permanent magnets magnetic in the rotor) and easy in operating principle as it is showing in “Fig. 1”. The old studies prove that the SRM present two big remaining advantages when it operated as automotive motor: ability to product a big torque [1], and their robustness which allows them a high-speed operation [2]. Regarding these advantages, the SRM is more used in all technology fields as automotive motors [3], renewable energy [4] nave application [5], etc. However,

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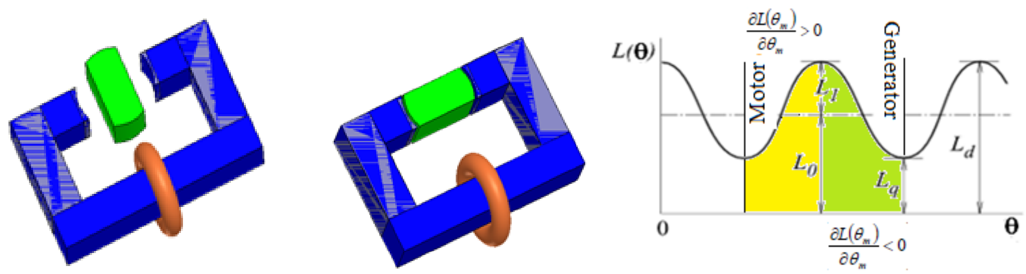
there are still drawbacks in all these applications. The most two major disadvantages fond in this machine are a very less puissance factor and a high torque ripple [6][7]. To resolve these problems, many researchers proposed the use of the development of power electronics compounds to improve the optimal forms of power wave [8], or by using the developing in numerical calculation methods to optimize the machine dimensional parameters [9]. Too many methods to reducing torque ripple were developed. In [10], it uses the winding chording. In [11] propose the using the rotor altering layers, and in [12], they suggest the use the stator sluts' optimization. To use the SRM as generator the rotor position is the most important part because of the inductance variation will create the torque which it can be a motor or generator dependent on it. To improve the torque protected quality and to see the advantages of multiphase's machines on the torque and the torque ripples, we will compare a three phases machine to five phases machine with the same power and construction conditions. The use of a three-dimension modalization gives the advantage of the very good precision in the obtained results which are approached from the real one when we compared experimental produced torque to the simulation ones. The winding function theory (WFT) is used to calculate the torque variation because in SRM the torque is produced from the reluctance (magnetic energy calculation like reluctance network [13] [14]) the variation which it directly the image of the inductance (electrical energy calculation) and in this theory the torque calculated directly from the inductances variation that give as a idea about the relation between inductance value and torque ripple. The result is compared with 3D final element method using software FLUX 3D produced by the company CEDRAT [15].

2. Study of Torque Ripple By FEA And WFT:

The basic Elementary VRG or SRM geometry is shown in "Fig. 1".



(a)Unaligned position (b) Aligned position (c)Inductance variation

Fig. 1. Elementary VRG or SRM example

The motion of rotatif part present tow particulate positions, this are obtained for the maximum inductance value cooled Ld in the lined position and the minimum inductance value cooled Lq for unaligned position. In this case the torque is calculated by (1):

$$Cem(\theta) = \frac{1}{2} i^2 \frac{\partial L(\theta)}{\partial \theta} \qquad (1)$$

where $L(\theta)$ is given by (2):

$$L(\theta) = L_0 + L_1 \cos(2\theta) \qquad (2)$$

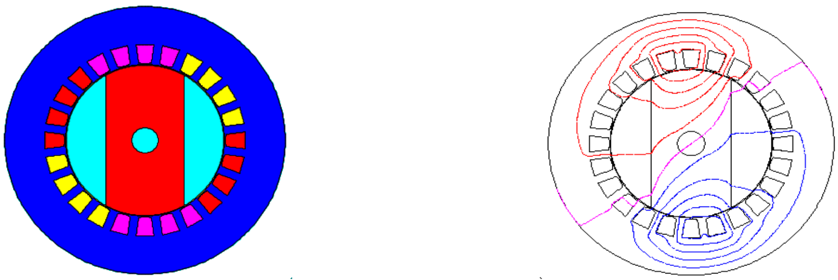
Where:

L_0 and L_1 are given in "Fig.1" and define as the average inductance value and the maximal inductance value respectively. In Table 1, the geometric data for three and five phases machines design parameters, the geometry is drowning in tow dimension, and the problem is defined as magneto static problem.

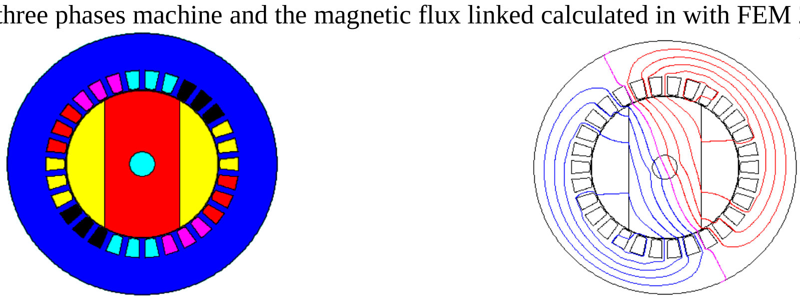
Table 1

Design Parameter

Design Parameter	Three Phase VRG(mm)	Five Phase VRG(mm)
Number of stator slots	24	30
Stator outer diameter	160	160
Stator inner diameter	92.7	92.7
Axial length	100	100
Rotor outer diameter	91.9	91.9
Air gap	0.8	0.8
Stator slot opening	2	2
Stator slot height	16.8	16.8
Minimum width of stator slot	4.5	4.5
Maximum width of stator slot	6.7	6.7
Number of slots in phase and pole	4	3



(a) The three phases machine and the magnetic flux linked calculated in with FEM 2D .



(b) The five phases machine and the magnetic flux linked calculated in with FEM 2D.

Fig. 2. 2D FEM geometry and flux linked

In case of multiphase's machine the torque is dependent on all the inductances and the electrical equations are given by matrices in order of the machine phases number (n x n dimension) , in case of three phases the metric equation (3) , all so in case of five are given in (4).

$$[L_{ij}]_3 = \begin{bmatrix} L_{aa}(\theta) & L_{ab}(\theta) & L_{ac}(\theta) \\ L_{ab}(\theta) & L_{bb}(\theta) & L_{bc}(\theta) \\ L_{ac}(\theta) & L_{bc}(\theta) & L_{cc}(\theta) \end{bmatrix} \quad (3)$$

$$[L_{ij}]_5 = \begin{bmatrix} L_{aa}(\theta) & L_{ab}(\theta) & L_{ac}(\theta) & L_{ad}(\theta) & L_{ae}(\theta) \\ L_{ab}(\theta) & L_{bb}(\theta) & L_{bc}(\theta) & L_{bd}(\theta) & L_{be}(\theta) \\ L_{ac}(\theta) & L_{bc}(\theta) & L_{cc}(\theta) & L_{cd}(\theta) & L_{ce}(\theta) \\ L_{ad}(\theta) & L_{bd}(\theta) & L_{cd}(\theta) & L_{dd}(\theta) & L_{de}(\theta) \\ L_{ae}(\theta) & L_{be}(\theta) & L_{cd}(\theta) & L_{de}(\theta) & L_{dd}(\theta) \end{bmatrix} \quad (4)$$

Where:

$L_{i=j}$: are the propre phases inductances .

$L_{i\neq j}$: are the mutual phases inductances .

The main key of WFT model is to get the electromagnetic torque using the inductances formulas in terms of rotor angular position. Referring to [16], the machine torque formulas can be written as (3), (4) and (3) in case of three phases, the same formulas are used in case of five phases machine the windings are displaced by 72° as in [17] [18].

$$L_{aa}(\theta) = \mu_0 RL \int_0^{2\pi} \frac{1}{E(\theta-\alpha)} N_{aa}^2(\alpha)\, d\alpha \quad (5)$$

$$L_{ab}(\theta) = \mu_0 RL \int_0^{2\pi} \frac{1}{E(\theta-\alpha)} N_a(\alpha) N_b(\alpha)\, d\alpha \quad (6)$$

Where μ_0, R, L are vacuum magnetic permeability, machine air gap radius, and the machine active length respectively.

The mechanical angel θ is associate to the stator, the angle α is defined associate to the rotor.

$$C_{em} = \left(\frac{\partial W_c}{\partial \theta_m}\right) = C_{em} = \frac{1}{2}\, [i]^t \frac{d[L_{ij}]}{d\theta_e} [i] \quad (7)$$

The current wave forms used in WFT to calculate the electromagnetic torque are represented in Fig. 3 for three and five phases.

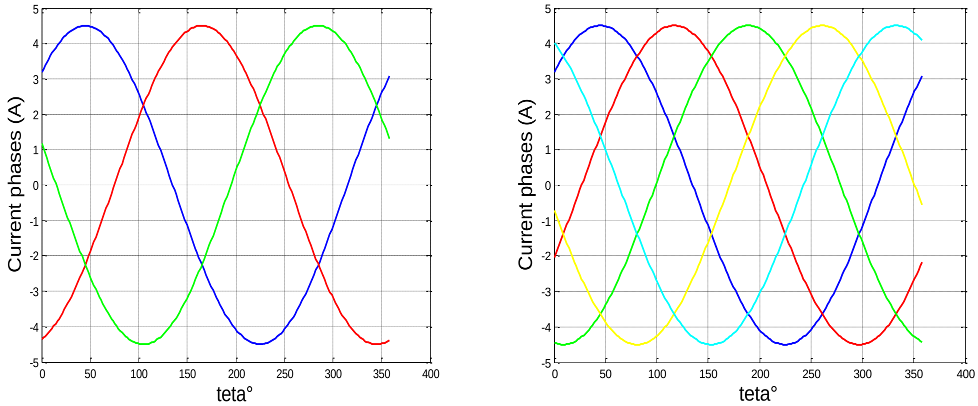


Fig.3.(a)The current for three phases a, b and c (b)The current for five phases and a, b, c, d and e.

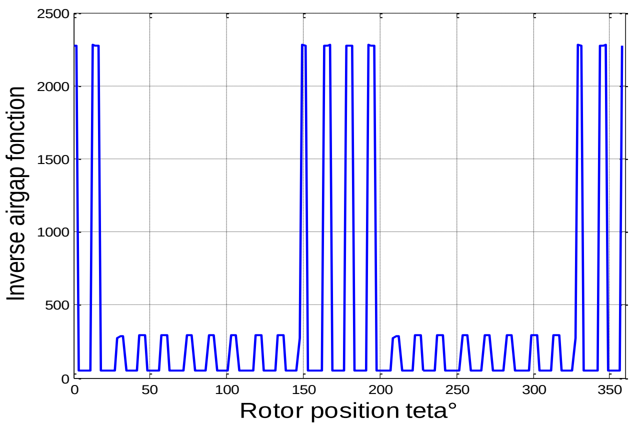


Fig. 4. The inverse air gap function

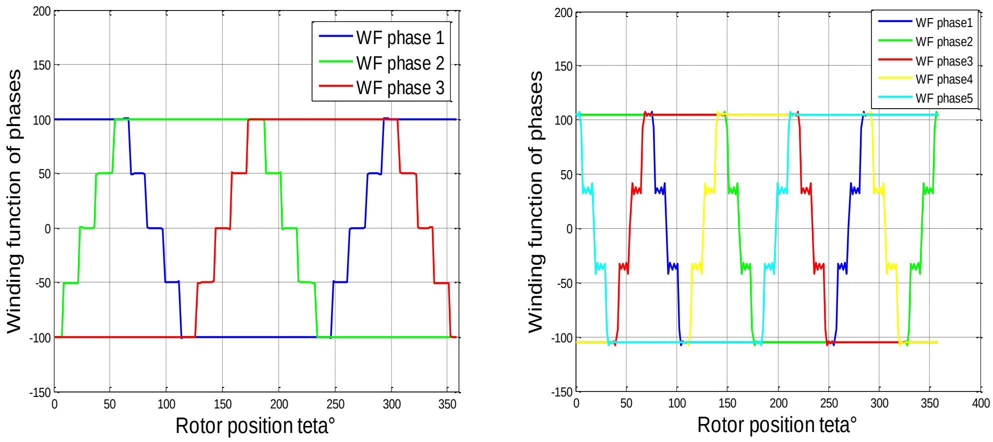


Fig. 5. (a) The winding function for three phases a, b and c (b) The winding function for five phases and a, b, c, d and e

The VRG study by FEM is proved that it defined as magneto static problem without eddy current, so using Maxwell equations give the equation that to be resolved is (8)

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}(\vec{A})\right) = J \tag{8}$$

Where:
μ: is the metal magnetic permeability.
A: magnetic potential vector.
J: current surface density.

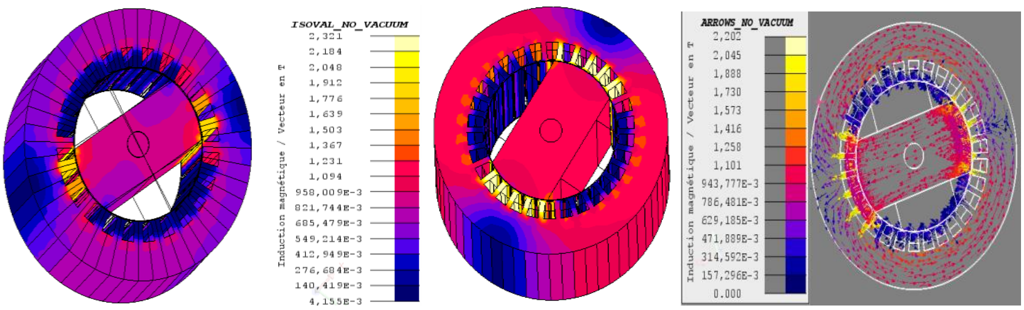
Referring to [15] the general FEM expression for proper and mutual inductance analysis between two windings “a” and “b” is given by (9) and (10). The electromagnetic torque is giving by (11)

$$L_{aa}(\theta) = \frac{1}{i_a^2}\iiint_v AJdv \tag{9}$$

$$L_{ab}(\theta) = \frac{1}{2i_a\, i_b}\left(\iiint_v AJdv - L_a(\theta)i_a^2 - L_b(\theta)i_b^2\right) \tag{10}$$

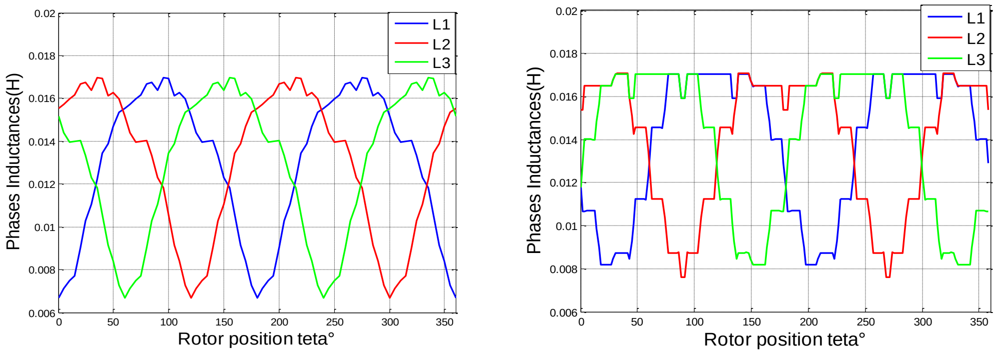
$$C_{em}(\theta) = \frac{R^2L}{\mu_0}\int_0^{2\pi} B_{normal}(\theta)B_{tangential}(\theta)d\theta \tag{11}$$

Where:
i_a : The current flowing through the winding ‘a’.
i_b : The current flowing through the winding ‘b’.
$B_{normal}(\theta)$: The normal magnetic induction vector.
$B_{tangential}(\theta)$: The tangential magnetic induction vector.



(a) (b) (c)

Fig. 6. (a) The magnetic flux density 3D for three phases a, b and c (b) The magnetic flux density 3D for five phases and a, b, c, d and e (c) The magnetic flux links for five phases machine

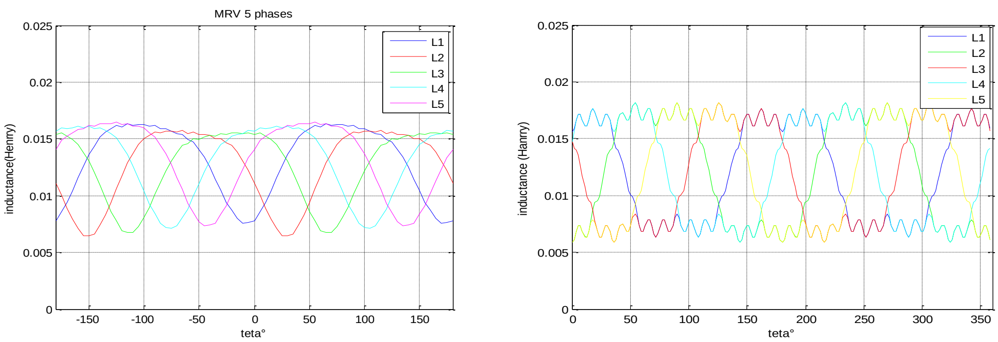


(a) (b)

Fig.7.(a) The three phases indecencies variation obtained by FEM (b) The three phases indecencies variation obtained by WFT .

The magnetic flux density “Fig. 6 “in all cases are showing two magnetic poles in the machines and the maximal value of flux density is in the sluts and teeth face of the rotor, but with five phases the flux is more intensive, we obtained the value 2.32 T in case of five phases machine.

The machines inductances “Fig .7” and “Fig .8” are on the same order and they don’t have a sinusoidal form and that the case of the torque ripple.

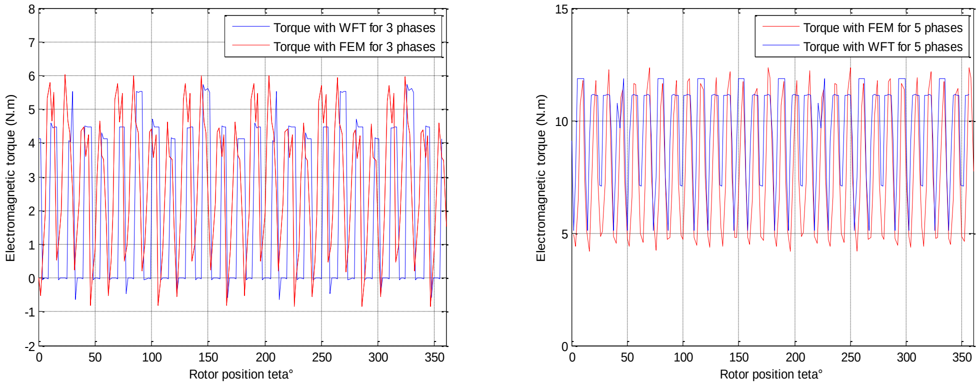


(a) (b)

Fig.8:(a) The Five phases indecencies variation obtained by FEM (b) The three phases indecencies variation obtained by WFT

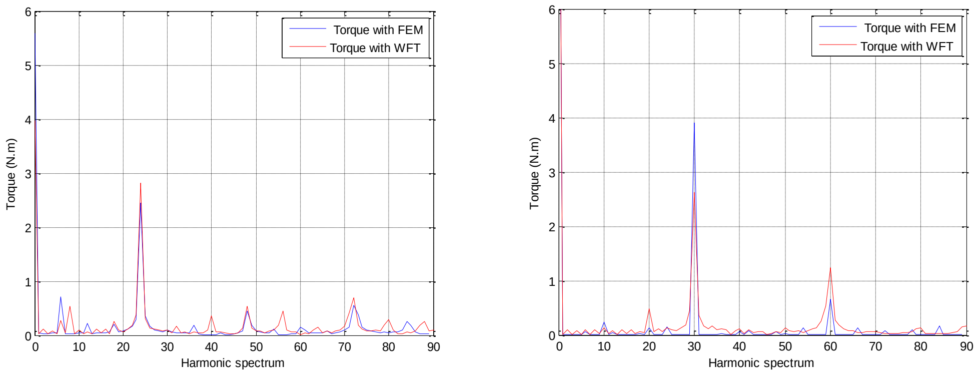
The electromagnitic torque variation obtined by WFT in and FEM for three phases machie “Fig. 9 (a)” showing that the torque have ripple the maen value for the same ceurrent is 3 N.m, the harmonic analises by using FFT (Fast Fourier Transform “Fig. 10 (a)” the must harmonique is 24 which is the sluts nomber and than in the same order is 48 and 72 they are a multiplies of 24,one more space

For five phAse machine “Fig. 9 (b)”, we compared these results, the torque have the same variation form like in the first case , but with a mean value of 8 N.m , the FFT analises “Fig.10(b)” show that the must important harmonique is 30 which is the sluts nomber ,than a multipie 60 , and the space harmonic also for the inductances 10 and 20 .



(a) (b)

Fig.9. (a) The electromagnetic torque calculated by WFT and FEM for three phases (b) The electromagnetic torque calculated by WFT and FEM for five phases.



(a) (b)

Fig.10.(a) Harmonic space analyses for electromagnetic torque calculated by FEM and WFT for three phases machine (b) Harmonic space analyses for electromagnetic torque calculated by FEM and WFT for five phases machine.

3. Alimentation with SVI (Voltage Source Inverter) :

The Basic Construction of three phases VSI in [18] we use coupled system FEM3D-Electrical circuit, to create this system the logical FLUX3D give this function of coupling, so the electrical compound (inductances and resistor) are infected to the geometry parts in 3D, than the VSI is programmed in the workspace (see [15]).

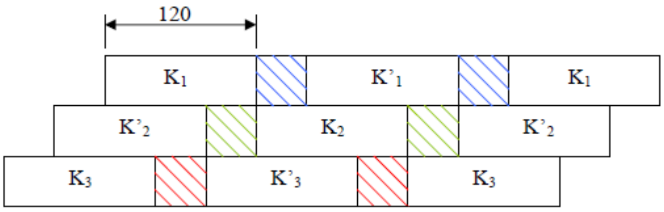
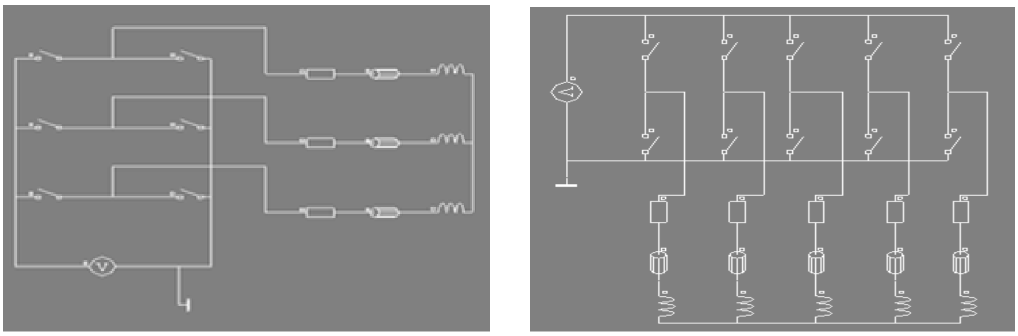


Fig. 11. Switches conducts for 120°

The switches operation interval for each case is fixed to 120. In this conduction mode, each switch conducts for 120° time period or 2π/3 radians. At any instant of time, two switches will conduct simultaneously. After every 60° or π/3 radians, one of the conducting switches is turned off and some other switch will start conducting” Fig. 11”.

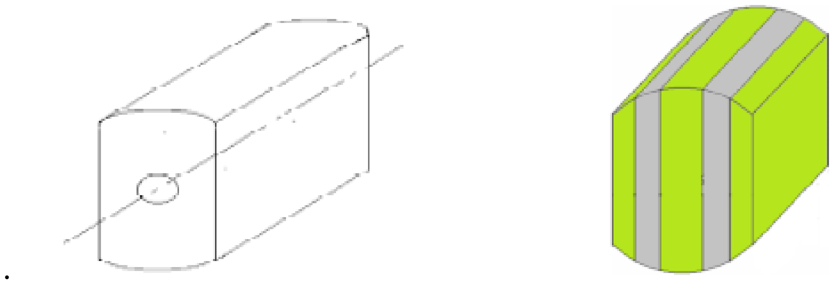
In “Fig. 12 (a)” the three phases machine is coupled to three phases VSI which is alimented from a DC source, and in “Fig. 12 (b)” the five phases machine coupled to five phases VSI which is alimented from a DC source as per [19] .



(a) (b)

Fig.12. (a) The three phases VSI and connecting schema. (b)The five phases VSI and connecting schema

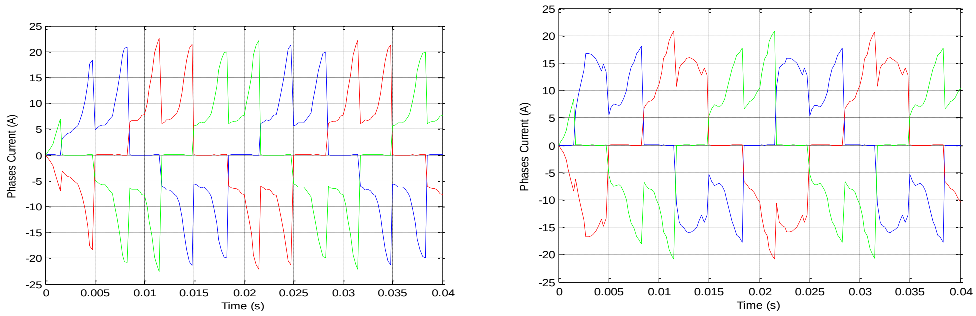
Two different rotors are used, massive rotor Fig.13. (a) and the second with alternating layers rotor Fig.13. (b), and for the five phase we use only the massive rotor.



(a) (b)

Fig.13. (a) Massive rotor and (b) Alternating layers rotor

The use of VSI for the three phases machine the torque have a big ripple, more less by using the rotor with alternating layers, the current wave form with the massive rotor “Fig. 14 (a)” and alternating layers rotor “Fig. 14(b)” are not sinusoidal and this is the cause of the torque ripple, but we can see that the rotor construction have a direct impact on the torque wave.



(a) (b)

Fig.14. (a) The current for three phases a, b and c with massive rotor (b) The current for three phases a, b and c with alternating layers rotor

The torque has tow part positive and negative, that because of the rotor starting angel as we prove in experimental test. With five phases we can see “Fig. 15” that the current are enhanced and all most sinusoidal that has enhanced the torque Fig. 16 with fewer ripples.

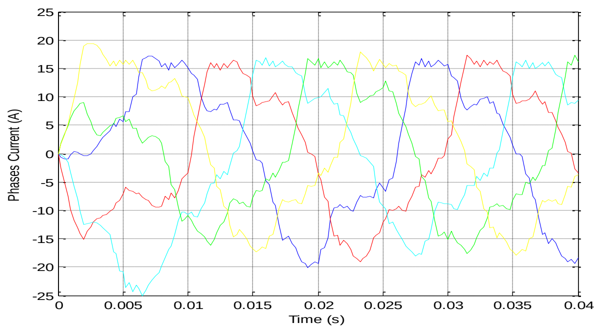


Fig.15. The current for five phases and a, b, c, d and e with massive rotor

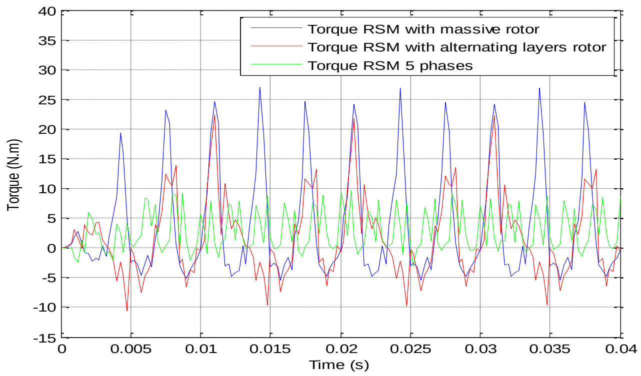


Fig.16. The electromagnetic torque calculated by FEM 3D

4. Conclusions

3D FE Analyses offered a very precise result where the behavior of reluctance machine geometry design is clearly showing in all extracted results and it is represented by torque ripple.

By using the 2D FE analyses and WF theory on three phases GRV and five phases GRV, the torque has been calculated and the relation between the torque ripples and the inductances variation and number prove that the torque ripple harmonics are multiples of the inductance space harmonic and stator slut number, and it is lower by using five phases (five inductances) also the torque can be enhanced by the use of rotor with alternating layers. The changing of rotor structure has a direct impact on the machine generated torque. The use of VSI as alimentation, the torque has less ripples in five phase machine, and this because of the current wave enhancement. From the other hand the rotor start position is very important to operate as motor or generator, and for that a position sensor is indispensable for the reluctance machine.

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