DYNAMIC ANALYSIS OF A NOVEL SYNCHRONOUS RELUCTANCE MOTOR WITH A SINUSOIDAL ANISOTROPIC ROTOR

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ABSTRACT

This paper deals with the dynamic analysis of a Novel Synchronous Reluctance Motor (NSynRM) having a sinusoidal rotor shape in the axial direction, without changing the flux-barriers design variables. Due to the non-self-starting characteristic of a Synchronous Reluctance Motor (SynRM), the motor is started by means of an industrial drive of ACS880 type. The motor is a 4-pole, 5.5 kW with a base speed of 1500 rpm. The practical tests are performed at three different speeds in order to analyze the dynamic responses when there is a sudden change in mechanical load characteristics. The measured results of the NSynRM are compared with those of a Standard Synchronous Reluctance Motor (SSynRM).

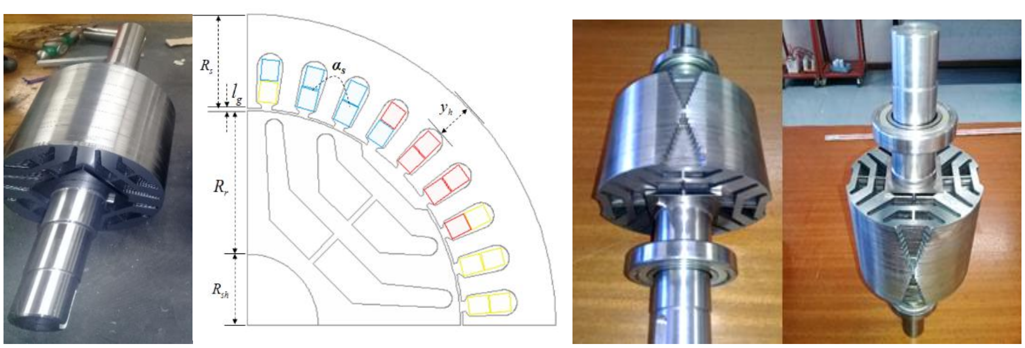
I. INTRODUCTION

Synchronous reluctance motors (SynRMs) are good competitors in AC drives due to their compact design and high power density. They have also become an interesting choice, being used as small power motors in various applications [1]. One of these applications is a small electric scooter, commonly used by people with physical disabilities. In [2] the in-wheel switched reluctance motor driving system for future electric vehicles (EVs) has been reported. A mechanical robust rotor with transverse-laminations for a SynRM for electric traction application is discussed in more detail in [3]. The novel lamination concept for transverse flux machines suitable for direct drive application to EVs is presented in [4]. The design optimization of SynRM drives for Hybrid Electric Vehicles (HEVs) power train application is analyzed in [5].

However, the interaction between spatial harmonics of the electrical loading and the rotor anisotropy of SynRMs causes a high torque ripple that is intolerable in most applications [6], [7]. A good number of previous work intended to reduce the torque ripple contents in SynRMs was mostly focused on a suitable choice of the number of flux-barriers in respect to the number of stator slots per pole per phase [8], [9]. It also focused on the optimization and asymmetry of the flux-barriers geometry and so on [7], [10], [11], [12], [13]. In 2014, Zhao proposed and analyzed the material-efficient Permanent Magnet Synchronous motor with a sinusoidal magnet shape [14]. The analysis was performed on a fraction of Horse power permanent magnet surface-mounted motors used in automotive actuators. For medium and high power motors to be used in traction, electric vehicles and hybrid electric vehicles, where less torque ripple and high torque density are required, the magnet volume will be intolerably high. The Novel SynRM with sinusoidal rotor shape in the axial direction, without changing the flux barrier geometry, has positioned itself as an alternative in applications that require high torque density and less torque ripple. The novel motor was first reported in 2016 [15]. The study was done on a 1.5 kW, six-pole machine and it was only limited to Finite Element Analysis (FEA) [15]. A based 3D FEA of a 4-pole, 5.5 kW SynRM with sinusoidal rotor shape was recently reported [16]. In the latter, the FEA results have shown that the SynRM with sinusoidal rotor shape provided better performance as far as torque characteristics are concerned. The traction in EVs require less torque ripple contents, high ratio torque/mass, high efficiency and good overload performance under the limited battery capacity condition. The Novel SynRM presented in [15] and [16] is a good candidate in such traction applications. Nothing is yet to be reported on the dynamic responses of the Novel SynRM. Therefore, this paper evaluates the dynamic responses of the Novel SynRM with a sinusoidal rotor lamination shape in the axial direction and compared to the standard SynRM of the same ratings.

II. NOVEL MOTOR GENERAL SPECIFICATIONS

Fig.1 (a) shows the photograph of the prototype for the standard SynRM rotor without cut-off on the *q*-axis, while Fig. 1 (b) illustrates the cross-section of a basic SynRM with cut-off on *q*-axis. Table 1 depicts the general design specifications for a 4-pole, 5.5 kW SynRM with 36 stator slots. The photographs of the prototype novel rotor with sinusoidal rotor shape are shown in Fig.1 (c). The details of the design criteria of the novel rotor are well presented in [15].



(a) (b) (c)

Figure 1: (a) photograph of the standard rotor without cut-off on the *q*-axis, (b) cross-section of the standard rotor with cut-off on the *q*-axis, (c) photographs of the prototype novel rotor with sinusoidal shape.

Table 1: General design specifications

Description	Values
Stator slot pitch $\boldsymbol{\alpha_s}$	10º*mech*
Airgap length $\boldsymbol{l_g}$	0.88 *mm*
Stack length	160.00 *mm*
Number of barriers per pole	2
Number of pole pairs	2
Number of stator slots	36
Rotor radius $\boldsymbol{R_r}$	48.80 *mm*
Stator radius $\boldsymbol{R_s}$	31.62 *mm*
Shaft radius $\boldsymbol{R_{sh}}$	24.00 *mm*
Yoke height $\boldsymbol{y_h}$	12.87 *mm*

III. ANALYSIS OF RESULTS

The experimental setting comprises of the three-phase Novel SynRM coupled to a MAGTROL torque transducer and a WB 115 Series Eddy-Current Powder Dynamometer current brake. The brake cooling is provided by a water circulation system, which passes inside the stator to dissipate heat generated by the braking power. A MAGTROL DSP6001 high speed programmable dynamometer controller is used to provide the desired mechanical load. Fig. 2 shows the experimental setup rig photo. Fig.3 (a) to (l) shows the measured NSynRM and SSynRM transient torque and current characteristics, while Table 2 gives the time responses and the speed variations during transient load torque changes.

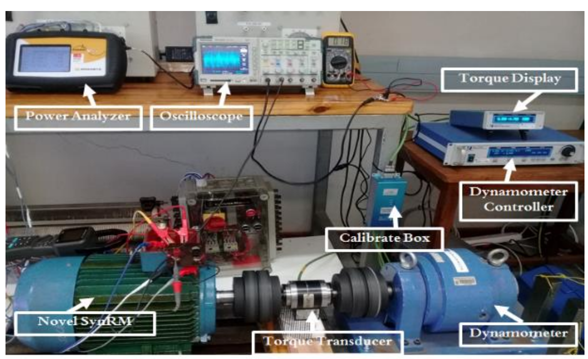


Figure 2: experimental setup rig photo

Table 2: Comparison of transient behavior from no-load to different load torque

		10.5 Nm			21 Nm			28 Nm		
SynRM Type	Speed (rpm)	*RT* (μSec)	*FT* (μSec)	ΔN (%)	*RT* (μSec)	*FT* (μSec)	ΔN (%)	*RT* (μSec)	*FT* (μSec)	*ΔN* (%)
NSynRM	1500	594	124	± 0.200	448	180	± 0.312	488	200	± 0.400
	1000	564	224	± 0.267	431	324	± 0.312	464	348	± 0.400
	750	560	229	± 0.200	416	352	± 0.333	408	350	± 0.400
SSynRM	1500	900	224	± 0.267	902	216	± 0.467	910	210	± 0.667
	1000	740	248	± 0.400	868	474	± 0.467	500	400	± 0.600
	750	600	336	± 0.333	464	522	± 0.467	462	464	± 0.600

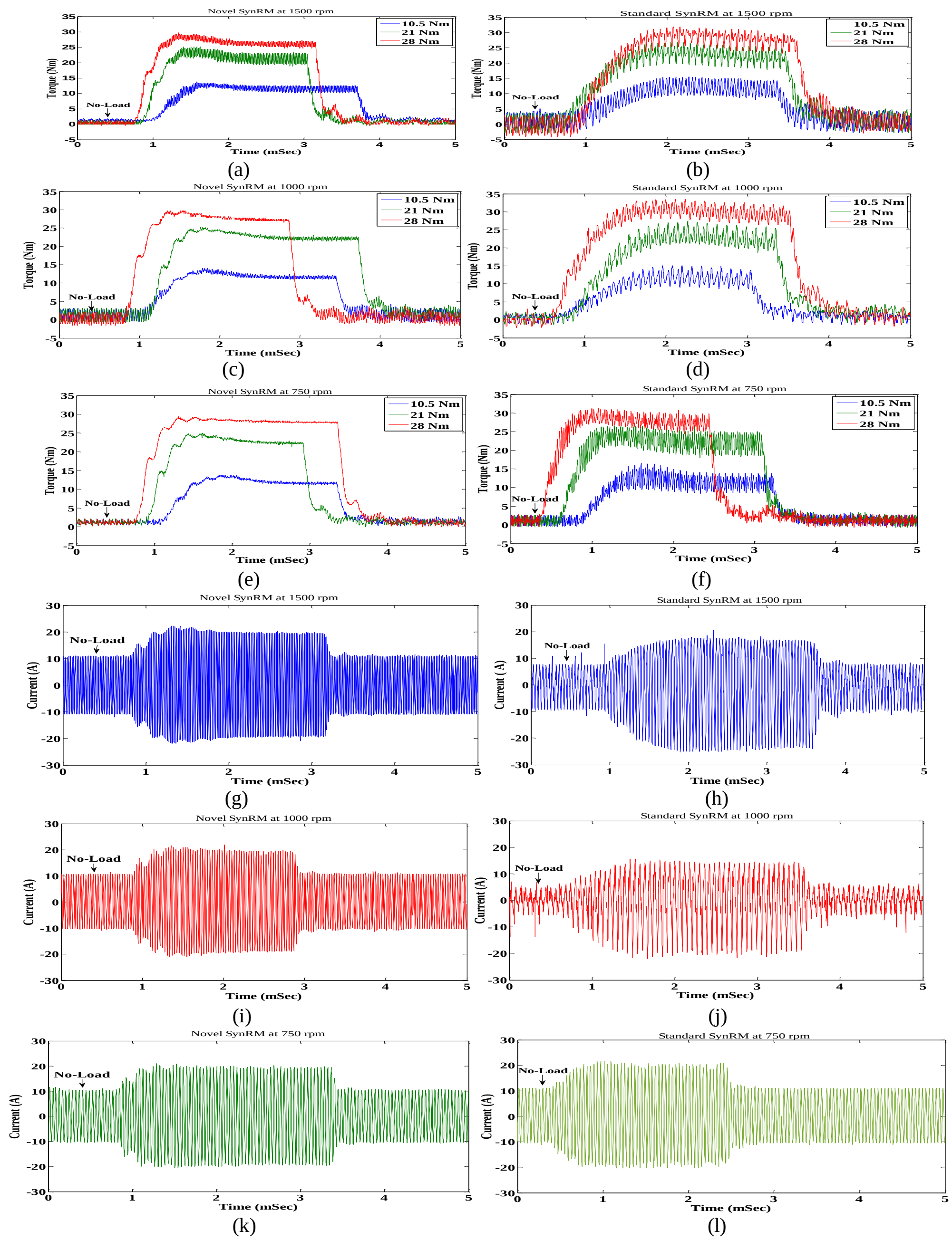


Figure 3: Comparison of dynamic responses between the NSynRM and SSynRM, (a) torque of NSynRM at 1500 rpm, (b) torque of SSynRM at 1500 rpm, (c) torque of NSynRM at 1000 rpm, (d) torque of SSynRM at 1000 rpm, (e) torque of NSynRM at 750 rpm, (f) torque of SSynRM at 750 rpm, (g) current of NSynRM at 1500 rpm, (h) current of SSynRM at 1500 rpm, (i) current of NSynRM at 1000 rpm, (j) current of SSynRM at 1000 rpm, (k) current of NSynRM at 750 rpm, (l) current of SSynRM at 750 rpm

Both SynRMs operated on no-load for a short time and suddenly load torques of 10.5 Nm, 21 Nm and 28 Nm were applied and removed at a certain time in order to analyze the motors' dynamic responses. The rising time (RT) is observed to be 595 μSec $\leq$ 488 μSec at 1500 rpm, 564 μSec $\leq$ 464 μSec at 1000 rpm and 560 μSec $\leq$ 408 μSec at 750 rpm, while the falling time (FT) with the same speed pattern is noted to be 124 μSec $\geq$ 200 μSec, 224 μSec $\geq$ 348 μSec and 229 μSec $\geq$ 350 μSec when a load torque of 10.5 Nm or 21 Nm or 28 Nm is applied and removed respectively in the NSynRM. The change in speed (ΔN) is ± 0.2 % ≥ 0.4 % for the NSynRM and ± 0.21 % ≥ 0.667 % for the SSynRM. The signs (-) and (+) refer to when the load torque is applied and removed respectively. The NSynRM responds faster than the SSynRM due to a lesser moment of inertia. The mass of the novel rotor is less compare to the standard rotor because of cut-offs on the *q*-axis.

IV. CONCLUSIONS

This paper has presented the dynamic responses of a Novel Synchronous Reluctance Motor with sinusoidal rotor shape. The analysis has been carried out through practical measurements. The practical results of the Novel SynRM were compared with those of the Standard SynRM of the same ratings and specifications. From the results, it is evident that the Novel SynRM has exhibited quicker time responses when the load torque is suddenly changed. The Novel SynRM's sudden change in speed during transient condition is observed to be minimal compared to the Standard SynRM. This has positioned the Novel SynRM with sinusoidal rotor shape to be a good contender in traction, electric vehicles and hybrid electric vehicles applications. More analysis, including Finite Element Analysis results, will be provided in the final paper. Future work on the Novel SynRM will include the use of ferrite on the rotor to improve the field weakening capability, efficiency and power factor.

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