FIA 2018

XI Congreso Iberoamericano de Acústica; X Congreso Ibérico de Acústica; 49º Congreso Español de Acústica -TECNIACUSTICA'18-

24 al 26 de octubre

ELECTRO-VIBRO-ACOUSTIC ANALYSIS OF ELECTRIC POWERTRAIN SYSTEMS

PACS: 43.40.+s.

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KEYWORDS: NVH, electric drivelines, signature analysis, Permanent Magnet Synchronous Machine (PMSM), Switched Reluctance Machine (SRM)

ABSTRACT

To give an answer to the growing expectation of eco-friendly transport and more particularly of electric powered vehicles, a thorough investigation of electric powertrain systems is needed. The integration of electric powertrains in vehicles creates several new challenges. One concerns the NVH behaviour which is very different from conventional vehicles with combustion engine (ICE). The sound of an electric driveline features multiple pure and modulated high-frequency tones which, despite their low level, are perceived as unpleasant. This paper provides a comprehensive analysis of electric powertrains in the electric and vibro-acoustic domain based on experiments on different motor types and configurations.

INTRODUCTION

Nowadays, PMSM motors are the motor drive solution for most of the electric and hybrid vehicles. The future uncertainty of availability of rare earth materials, permanent magnet materials, is one of the major drawbacks of this type of electric motor. An alternative is a SRM drive. This type of motor has already proven its merits in a wide range of industrial applications which confirms its performance and reliability. From this point, SRM motors reflect a very attractive alternative to other electric motor types for automotive traction. Another advantage of the SRM motor is its simple design, which yields a cost-effective construction. The SR motor suffers, however, from a Noise, Vibration and Harshness (NVH) issue which has caused some concern in the automotive industry. The noise and vibration produced by SR motors is one of the most crucial problems to be solved before it will find its introduction into the automotive industry. The NVH properties of an SR motor depend on several factors such as machine dimensions, material properties and electromagnetic design. An NVH analysis may bring insight into the relation between these factors and the NVH performance. Therefore, an NVH analysis provides an essential value towards the challenges of designing SR motors in terms of ride comfort and acoustic comfort inside a vehicle. The typical noise generated by a PMSM motor will be first briefly discussed followed by a more in depth noise analysis of a SRM motor.

HYBRID VEHICLE WITH TWO PMSM'S TESTED IN ELECTRIC MODE

Today, most hybrid and electric vehicles are powered with PMSM (Permanent Magnet Synchronous Machine). In this paragraph, NVH analysis results are shown for this type of machines mounted in a hybrid car with two brushless PMSM's and one ICE. The PMSM's are 3-phase machines with a single layer topology (Fig. 1), four permanent magnetic pole pairs and a stator slot with distributed stator windings. The phase currents and magnetic flux in the air gap between rotor and stator show a sinusoidal profile. The car was tested in various driving conditions. The sections below exclusively present the results of measurements in pure electric vehicle mode (ICE switched off).

In electric machines, both the mechanical and electrical position are important parameters to be considered. The mechanical position is related to the rotation of the rotor shaft. When the rotor has completed 360 mechanical degrees, the rotor is back in its original start position. The electrical position of the rotor is related to the rotation of the rotor magnetic field. In the case of a PMSM with four magnetic pole pairs, the rotor has to rotate 90 mechanical degrees to reach an identical magnetic configuration.

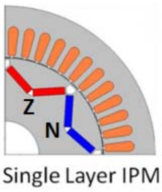
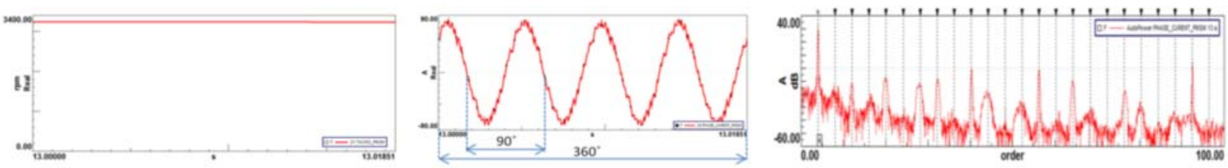


Fig. 1:Single layer topology (1)

Fig. 2 shows the measured phase current in the time and order domain at a constant speed of 3240 RPM (54 Hz). There exists a close relationship is shown between the fundamental harmonic, the rotor configuration and the rotation speed. This relation can be expressed as:

$$f = \frac{N_s * p}{60} = \frac{N_s * O_1}{60} \quad [1]$$

with f the fundamental frequency of the phase current (Hz), Ns the rotational speed (RPM) and p the number of magnetic pole pairs. In the current example, the PMSM consists of four pole pairs. This explains the dominant order 4 in the current spectrum in Fig. 2. The fourth order as well as some of its multiples can also be observed in the noise and vibration spectra. The spectra in the electric, vibration and acoustic domains are clearly linked and influenced by the physical rotor configuration.



(a) Rotational shaft speed (b) Phase current time signal (c) Phase current order spectrum

Fig. 2: Measured phase current in time- and frequency-domain of a 3-phase PMSM with 4 magnetic pole pairs running at constant speed

Next to the rotor harmonics, the phase currents, noise and vibrations show specific harmonic structures at higher frequencies as shown in Fig. 3. These harmonic structures are caused by the

PWM (Pulse Width Modulation) mechanism of the VSD (Variable Speed Drive). They are composed of central carrier frequencies surrounded by pairs of motor speed dependent sidebands. The first harmonic structure appears around 2.5kHz which is the switching frequency of the IGBTs. The second harmonic structure at 5 kHz is the dominating one in the acoustic signals. This frequency is very sensitive to the human ear and can be very annoying. Similar PWM phenomena are found in powertrain systems with induction motor. Tuning of the PWM switching frequency in the hearing range can highly affect the sound quality perception and can be considered as an important design consideration. This has been studied previously by experiments with different PWM switching frequency (3) and by listening tests using a dedicated sound synthesis tool (4).

ACOUSTIC NOISE GENERATION PROCESS OF A SRM MOTOR

A multi-phase SRM motor is a type of synchronous machine, but with particular features: field coil is wound around the stator poles, but no coil or magnetic material is presented on the rotor. The motor works by energizing opposite stator poles, thereby generating a magnetic field. This magnetic field forces the rotor poles to rotate to the position of minimum reluctance, aligning them to the closest stator poles. By energizing consecutive stator poles, continuous rotation is generated [7]. Fig. 4 shows the principle for a 12/8 SR motor, which has 12 stator poles and 8 rotor poles. Considering one phase, it can be observed that two main equilibrium position of the rotor exist. The rotor position illustrated in Fig. 4a is called the unaligned position in relation to phase AA'. The position with the smallest magnetic reluctance is called the aligned position (Fig. 4b). Typically, the number of rotor poles is lower than the number of stator poles, which prevents the poles from all aligning at the same time, such that, by switching the poles in an appropriate way a continuous rotary motion can be established.

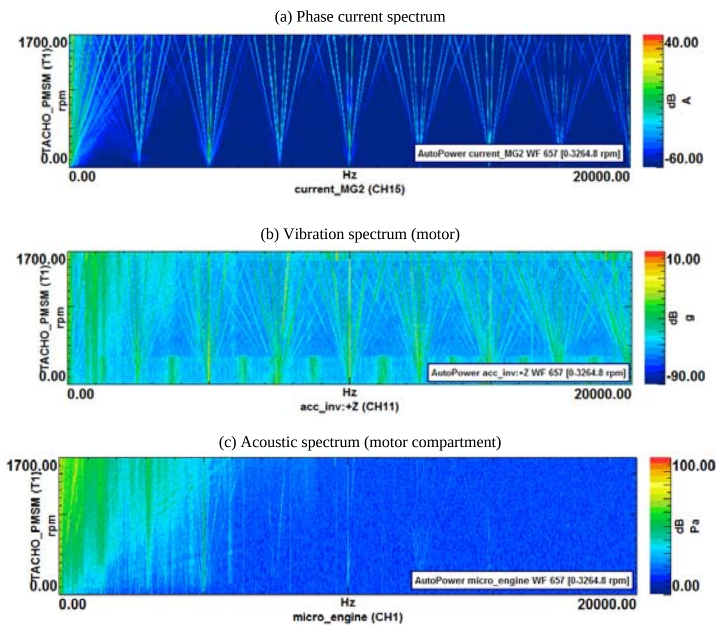
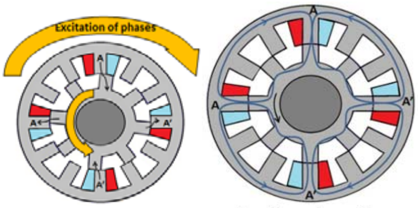


Fig. 3: Phase current (above), vibration (middle) and noise (below) time-frequency spectra during run-up



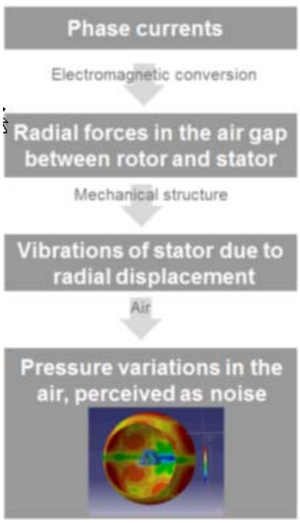
(a) unaligned position (b) aligned position

Fig. 4: Cross-sections of the analysed 12/8 SR motor and distribution of one coil group

In a 12/8 SR motor, each of the stator phases is activated eight times per revolution. As shown in Fig. 5, the acoustic noise generation process of an SR motor consists of three steps. Generally, the torque originating from the radial magnetic forces, which are determined by the phase currents, controlled by the switching pattern, plays a dominant role in the noise generation of a SR motor.

Each type of SR motor has its own unique acoustic and vibration signature which is defined by several factors such as the mechanical design, the electromagnetic design and the excitation pattern of the phase currents. It is expected that a 12/8 SR motor has better NVH properties than the 8/6 configuration. In general, the natural frequencies of the square mode are higher and the 'ovalization' mode is not expected because four poles are excited at the same time resulting in a symmetric distribution as shown in

Fig. 6. Finally, a lower noise contribution for a 12/8 configuration should be achieved in the most sensitive frequency area of the human ear.



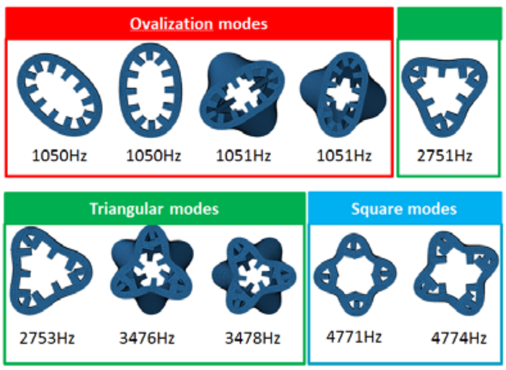


Fig. 5: Noise generation process of electric machine

Fig. 6: Simulated finite element model of the stator mode shapes [8]

EXPERIMENTAL TEST SETUP AND OBJECTIVES

The main objective of the measurement campaign is to evaluate a 12/8 SR motor in terms of NVH performance. More specific objectives are i) to verify with the help of operational deflection shapes that the square mode is the first excited mode, ii) to identify the dominant orders in different conditions. In total, sixty tri-axial accelerometers were mounted on the jacket and the side panels. Furthermore, four microphones were placed: two in the near-field, two in far-field.

To measure very accurately the rotational speed, an incremental encoder is used. Its output is measured in 2048 pulses per revolution which give a very detailed rotational speed profile.

The SR drive used a conventional control technique, hysteresis current control and is coupled to the induction motor with belts. Fig. 7 shows the principal parts of the test rig setup. The properties of the SR motor are described in Table 1.

An electric motor for vehicle applications should be able to operate in the four quadrants of the speed-torque plane. In this study, motor quadrant I and II (Fig. 8) are considered as they are the most used ones in automotive applications. Quadrant 1 indicates forward motoring since the torque is in the direction of motion. Quadrant 2 indicates forward braking since the torque is opposite to the direction of motion. In both quadrants, different torque levels from 0% to 49% were studied for this type of machine.

E-motor dimensions (LxD)	215x256mm
E-motor weight	50kg
E-motor inertia	21087kgmm^2
Nominal continuous power	45kW
Maximum speed	15000 min^{-1}

Table 1: Properties of the SRM

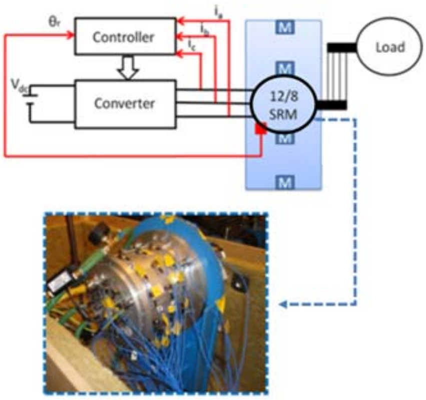


Fig. 7: Test rig with a SR drive system coupled to a two-pole induction motor

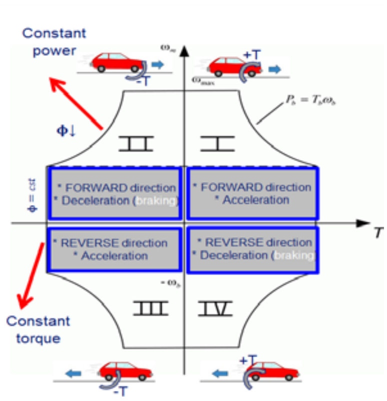


Fig. 8: Four quadrant motion control of an electric motor

VIBRO-ACOUSTIC STUDY BASED ON EXPERIMENTAL DATA

In this paragraph, both the results of a modal analysis and operational measurements in a speed range from 0 to 10000 rpm are studied in different load conditions.

A waterfall 3D-graph is a way to present acoustic noise and vibration data of rotating machines as function of time or rotational speed. It is a suitable tool to examine rotating machinery, like electric drives. Fig. 9 shows a waterfall spectrum of a phase current acquired during a run-up measurement between 0 and 10000 rpm. The corresponding time trace of the current waves is presented in Fig. 10.

With this kind of evaluation different characteristics can be examined. The oblique lines in Fig. 9 are motor harmonics, also called orders, which are rotational speed dependent. For the points on these lines, the relation between the frequency and the rotational speed is given by

$$f = \frac{h.N.RPM}{60} \quad (2)$$

where f is the frequency in Hz, N the number of rotor poles and RPM the rotational speed in revolutions per minute. [4] The number of the order h determines the slope of the line. As can be seen in Fig. 9, the 8th order is the most dominant order for a 12/8 SR motor. This is due to the fact that each of the stator phases is activated eight times per revolution in this type of SR motor.

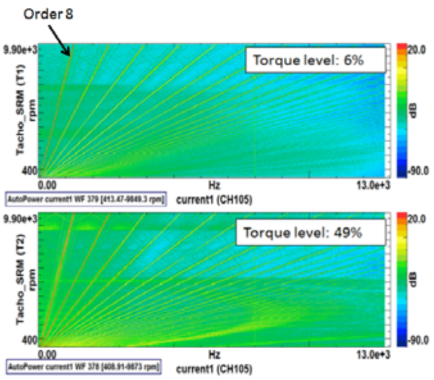


Fig. 9: Measured phase current during run-up operation

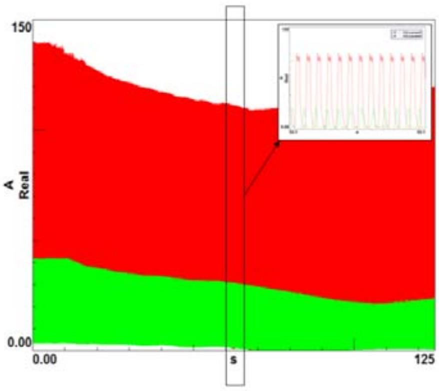
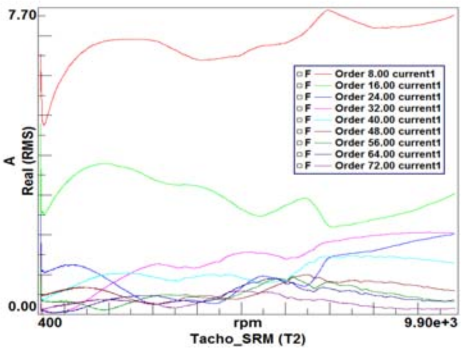
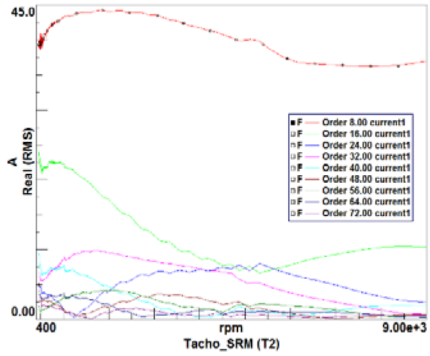


Fig. 10: Measured phase current time profile in different load conditions: 6% and 49%.



(a) Order sections by a torque level of 6%



(b) Order sections by a torque level of 49%

Fig. 11: Overview order section in different load conditions

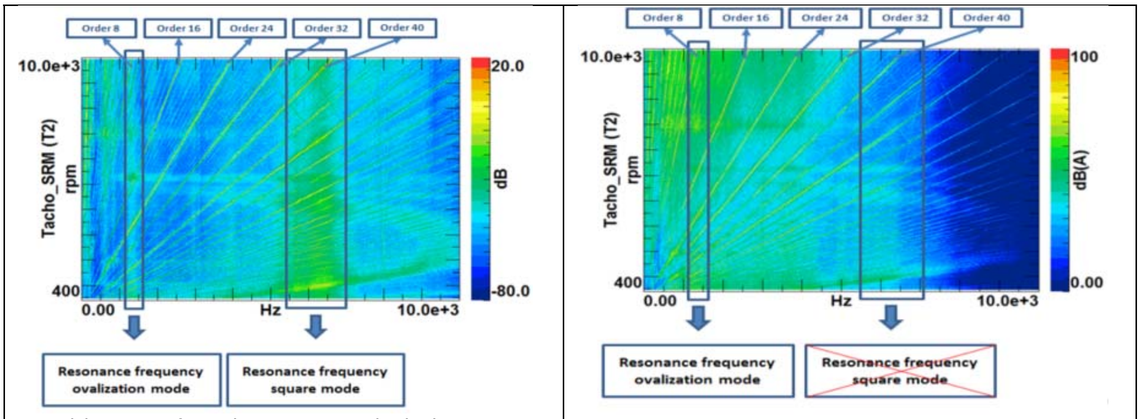
A next step is to go more in detail with an order analysis (

Fig. 11) by extracting the orders from the map. An order section allows inspecting the behaviour of single tonal components referring to the rotational speed of the motor itself. In this case the dominant order sections are calculated for torque level of 6% and 49%. As can be seen, the higher the harmonic number, the lower the amplitude for a specific order line is.

Fig. 12a shows a spectrogram of an accelerometer on the stator housing. Three phenomena can be recognized: i) 8th order harmonics, ii) resonances and iii) a kind of inverted C-shape. Fig. 12b shows the corresponding acoustic noise signature in the near-field.

In the proposed accelerometer signal, the resonance close to 6300Hz doesn't lead to increase of the acoustic power near this frequency. The same conclusion can be drawn from the order sections plotted in Fig. 14.

In fact, resonances of the stator amplify the excitation forces. The dominant resonance in this application is approximately 6300Hz with a corresponding square mode shape [4]. This is due to the fact that four stator poles are symmetrically loaded in a 12/8 SR motor. Another resonance at 1330Hz, an "ovalization" of the stator should not be excited in a 12/8 SR motor due to symmetry, but it is present probably due to manufacturing tolerances and rotor eccentricity [4].



(a) PSD of accelerometers on the jacket
(b) PSD of the microphone in near-field

Fig. 12: Spectrum analysis in function of the rotational SR motor speed and amplitude

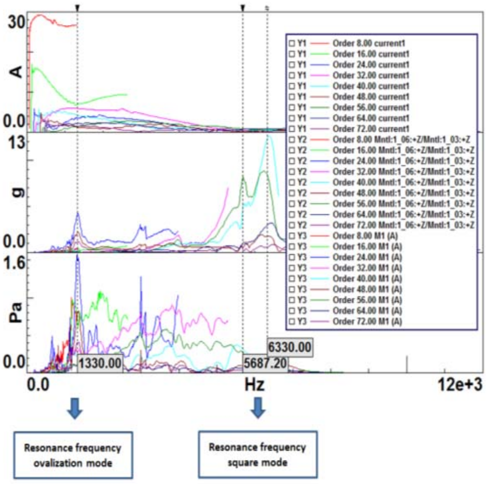


Fig. 13: Order sections of phase current (top), accelerometer (middle) and microphone (bottom)

The sound pressure level reaches its maximum when order 24 excites the 'ovalization' mode at 1330Hz. Hence, the claim that the 'ovalization' mode is not excited in a 12/8 SR motor and therefore does not contribute to the acoustic noise, is not fully consistent with the practice: excitation of the 'ovalization' mode is still a major source of acoustic noise (Fig. 13).

To verify the 'ovalization' mode shape, a modal analysis is carried out on the 12/8 SR motor, including, stator, rotor, end shields, cooling water, etc. Results can be found in Fig. 15. Consequently, this means that the measured mode frequencies (Fig. 14) are a little bit different from the calculated FEM structural mode shapes (

Fig. 6) because only the stator housing is there considered in free-free conditions.

Two 'ovalization' modes are presented (Fig. 14) at 1324Hz and 1425Hz. The 'ovalization' mode with out-of-phase of front/back is not presented due to the end shields. Measured resonance frequencies are higher and are more apart than simulated ones due to the end shields and clamping. The triangular modes at 2835Hz and 3135Hz are less visible because of the different boundary conditions between the measured and simulated modes. It was not possible to measure the square mode as the sampling frequency was too low during the modal analysis.

Finally, one resonance at 1330Hz in the frequency content of spectrograms in
Fig. 12 is confirmed by a modal analysis on the stator housing which visualizes the 'ovalization' mode at this frequency.

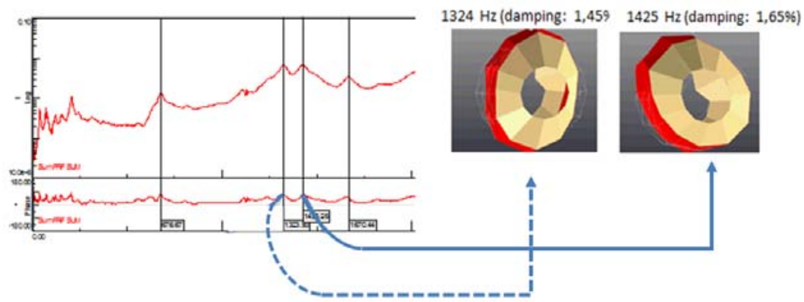


Fig. 14: Ovalization modes of mounted 12/8 SRM

CONCLUSIONS

The presented multi-physics approach utilizing combined electric measurements, noise and vibration data allows studying the NVH performance of electric motors, the differences between different types of motors PMSM versus SRM. An experimental investigation was done for two electric powertrains (SRM, PMSM) in various operating conditions. A clear relationship exists between the frequency spectra of the phase current excitations and the resulting noise and vibration spectra. The studied SRM and PMSM machines have a very different signature due to differences in motor type, configuration, working principle and motor control mechanism. The PWM control strategy, in particular, plays an important role. The hysteresis control of the SRM results in a broadband noise, while the sinusoidal PWM control of the PMSM yields high-frequency harmonic structures which affect the sound tonality and perception of annoyance.

AKNOWLEDGEMENT

The presented research was conducted within the Marie Curie IAPP project "DEsign, MOdeling and TESTing tools for Electric Vehicles (DEMOTEST-EV)", which is financial supported by the European Commission and the IWT research project "A new generation of NVH methods for Hybrid and Electric Vehicles (HEV-NVH)", funded by the Flemish government.

REFERENCES

[1] Urquhart I., Tanaka D., Owen R., Zhu Z.Q., Wang J.B., Stone D.A., "Mechanically Actuated Variable Flux IPMSM for EV and HEV Applications", EVS 27, Barcelona, Spain, November 2013
[3] Sarrazin M., Janssens K., Van der Auweraer H., "Influence of Inverter PWM Control Schemes on Noise Signature of Electric Powertrains", ICSV 20, Bangkok, Thailand, July 2013.
[4] Sarrazin M., Janssens K., Van der Auweraer H., "Virtual Car Sound Synthesis Technique for Brand Sound Design of Hybrid and Electric Vehicles", SAE Technical Paper 2012-36-0614, 2012, doi:10.4271/2012-36-0614.
[5] Lo W.C., Chan C.C., Zhu Z., Howe D., Chau K., "Acoustic Noise Radiated by PWM - Controlled Induction Machines Drives", IEEE Trans. Ind. Electr., vol. 47, no. 4, Aug. 2000, pp. 692-697.

[6] Dos Santos F.L.M., Anthonis J., Naclerio F., Gyselinck J., Van der Auweraer H., Sandoval Goes L., "Multiphysics NVH Modeling: Integrated Simulation of a Switched Reluctance Motor Drivetrain for an Electric Vehicle", IEEE Transactions on Industrial Electronics, 61(1), 469 – 476, 2014, DOI 10.1109/TIE.2013.2247012 .
[7] R. Krishnan. *Switched Reluctance Motor Drives: Modeling, Simulation*. CRC Press, 2001
[8] F.L.M. dos Santos, J. Anthonis, F. Naclerio, J. Gyselinck, H. Van der Auweraer, L. Sandoval Goes, *Multiphysics NVH Modeling: Integrated Simulation of a Switched Reluctance Motor Drivetrain for an Electric Vehicle*, IEEE Transactions on Industrial Electronics, 61(1), 469 – 476, 2014, DOI 10.1109/TIE.2013.2247012