Simulation and Analysis of a Switched Reluctance Machine for Flywheel Replacement

Daniel S. Cardoso and Paulo O. Fael

***Abstract* — This work presents the analysis of results obtained through a simulation presented previously in ICEUBI 2017. The simulation was built for obtaining results that will be analysed on the present work. With these results it is intended to show the feasibility of the study and development of a switched reluctance machine capable of replacing the flywheel on the internal combustion engines. This system will improve the efficiency in terms of consumption and dynamic parameters.**

***Index Terms* — Internal combustion engine, flywheel, switched reluctance motor**

I. Introduction

The combustion engine is, nowadays, the most widely used source of mechanical energy for vehicle locomotion. Although combustion engines are in decline due to the evolution of electric vehicles, there is still a long way to go in order for this technology to go obsolete. The research and development of more efficient internal combustion engines is still a challenge that has strong support from the transport industry [1]. Several technologies have emerged in recent years to reduce emissions from internal combustion engines and to increase their efficiency. Advancements such as the introduction of cylinder deactivation systems, valve opening time variation systems, exhaust gas recirculation systems, turbocharger systems, among many others are the proof that these engines still have a long way to go [1].

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This paper presents the results obtained through a simulation that analysed the viability of a system that replaces the flywheel of the internal combustion engines. This flywheel can be found on combustion engines and its purpose is to accumulate energy while the engine produces work, to release it later when no work is being produced and energy is required to continue the engine.

This study simulates a system composed by a Switched Reluctance Machine (SRM) connected to the crankshaft of the combustion engine. The SRM acts as a generator during the time that work is produced by the combustion engine, converting mechanical energy into electrical energy that is stored on a supercapacitor. This energy is then used, by the SRM, acting as a motor when work is not produced by the combustion engine.

The aim of this system is to adapt and adjust the load when acting as a generator to the required power demand when acting as a motor, in the traditional inertia flywheel system this adaptation is not possible. This is due to the fact that with higher rotations the flywheel could be reduced significantly, which in conventional systems is not possible. A further goal is to reduce vibrations by stabilizing the combustion engine. In the latter case, the motor / generator system would act as a damper: at positive work spikes this will consume much of that work and, on the contrary, will provide work on the negative torque peaks.

However, there are other advantages in implementing this system, such as: using energy harnessed from other parts of the vehicle to assist the combustion engine's operation by giving it the ability to increase speed more quickly or by compensating for times when load applied to the combustion engine is higher.

This simulation was performed using the programming tool SIMULINK®, and the complete explanation about the construction of the simulation can be found on [2].

II. Simulation

On Fig. 1, it is possible to see all blocks and connections that make the configuration of the system introduced posteriorly.

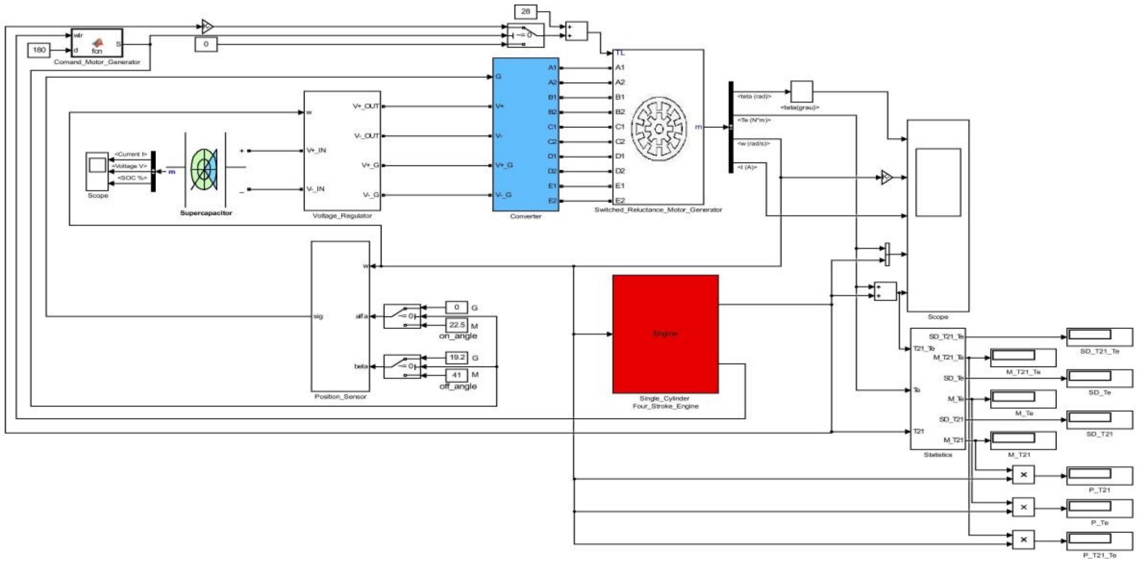

Fig. 1. Layout of all simulation

The principal two blocks are *Single Cylinder Four Stroke Engine* and *Switched Reluctance Motor Generator*. The first block represents the internal combustion engine and the output from this block is the torque produced in function of the characteristics attributed to the engine in the inputs. The second block represents the electric machine and one of the inputs of this block is the signal that indicates the position of the internal combustion engine.

According to the strokes of the engine, the electric machine will act as a motor and a generator. If the electric machine works as a generator, the torque output will be negative and compensate the higher torque produced by the combustion engine. On the other hand, when the electric machine produces positive torque this will increase the low or negative torque from the engine. All the other blocks, such as *Converter*, *Voltage Regulator*, *Position Sensor* and *Command Generator Motor* have function as control of the whole the system.

III. Operating Parameters

The simulation takes into account many parameters that can be changed so as to simulate different engine sizes and different configurations for the electric machine. Some of these can be obtained from other references or arbitrated to test and discard some doubts that can occurred.

A. Internal Combustion Engine

To obtain the present results, the geometric parameters from the *Honda® GX 160* were used. This is an engine known from many experiments due to its simplicity and versatility.

Table I
Geometric parameters from the engine

Geometric Parameters *Honda® GX 160*	
Bore	0.068 m
Stroke	0.045 m
Compression ratio	9:1
Connecting rod length	0.084 m
Piston mass	0.201 kg
Connecting rod mass	0.0483 kg

B. Switched Reluctance Machine

The parameters for the switched reluctance machine are chosen differently from the combustion engine parameters.

This is due to the fact that the electric machine needs to be adapted to the engine in order to correct the torque produced by this. The parameters have suffered a long process of optimization with the aim of improving the results in terms of torque correction and to adapt the interference of the electric machine along the increase of the rotation [3-4].

Table II
Switched Reluctance Machine Parameters

Electric machine configuration	10/8	
Power of electric machine	10 Kw	
Switching Angles		
	On	Off
Motor	22.5º	41º
Generator	0º	19.2º
Supply Voltage		
RPM	Voltage	
600	87 V	
1600	217 V	
2600	296 V	
3600	353 V	
4600	400 V	
Operating angle as generator		
During expansion stroke	180º	

IV. Obtained Results

The simulations as an optimization process were performed in 5 steps of rotation. The first step is 600 RPM. This was chosen because it is the lowest speed at which the *Honda® GX 160* engine works properly. After that, the simulations were performed with an increase of 1000 RPM until we reach the 4600 RPM.

After the presentation of the results from the 5 steps, it is presented a graph with an evolution of the correction of the standard deviation of the combustion engine torque in function of the analysed rotation ranges.

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The standard deviation measures the dispersion of the individual values around the media, i.e. a low value of standard deviation tells us that the data are close to the mean values. On the other hand, a high standard deviation indicates that the data are further from the mean values. When analysing the values of the torque, if we take in consideration the standard deviation of the values obtained, we can perceive the dispersion and consequently the irregularities present in the torque of the engine.

The values obtained for the standard deviation of the torque resulting from the sum of the torque of the electric machine with the combustion engine, the electric machine torque and the combustion engine torque will be presented as followed.

The simulation time has been always adjusted as a function of the speed of rotation of the system, so that each simulation is carried out at 720 ° rotation required to complete a complete combustion engine cycle.

Table III
Results to 600 RPM

Resultant standard deviation	57 N.m
Standard deviation electric machine	45 N.m
Standard deviation combustion engine	76 N.m
Resulting average torque	26 N.m
Average electric machine torque	0 N.m
Average combustion engine torque	26 N.m
Simulation time	0.2s

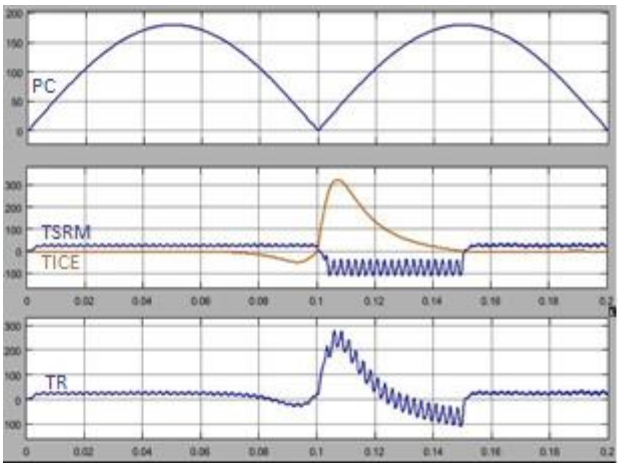

Fig. 2. Results obtained for 600 RPM, in this order: Position of the crankshaft (PC in degrees), Electric machine (TSRM) and combustion engine (TICE) torque (N.m), Resultant torque (TR) (N.m).

Table IV
Results to 1600 RPM

Resultant standard deviation	55 N.m
Standard deviation electric machine	44 N.m
Standard deviation combustion engine	75 N.m
Resulting average torque	26 N.m
Average electric machine torque	0 N.m
Average combustion engine torque	26 N.m
Simulation time	0.075s

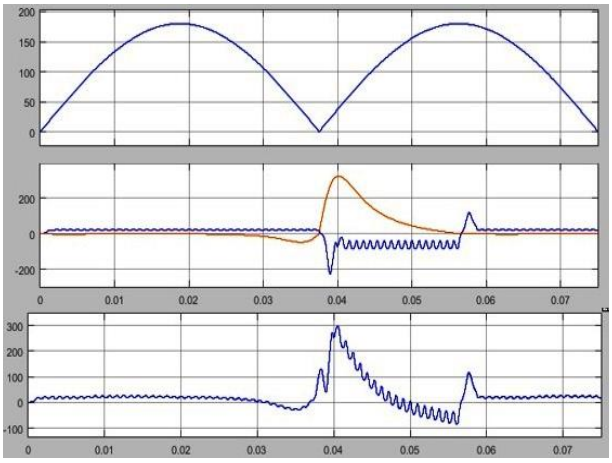

Fig. 3. Results obtained for 1600 RPM, in this order: Position of the crankshaft (degrees), Electric machine and combustion engine torque (N.m), Resultant torque (N.m).

Table V
Results to 2600 RPM

Resultant standard deviation	60 N.m
Standard deviation electric machine	31 N.m
Standard deviation combustion engine	75 N.m
Resulting average torque	26 N.m
Average electric machine torque	0 N.m
Average combustion engine torque	26 N.m
Simulation time	0.046s

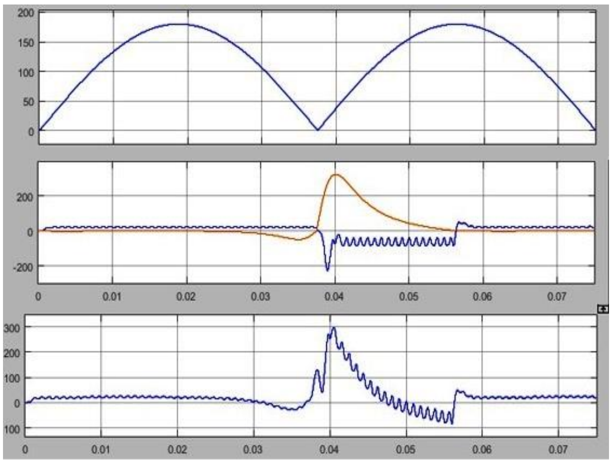

Fig. 4. Results obtained for 2600 RPM, in this order: Position of the crankshaft (degrees), Electric machine and combustion engine torque (N.m), Resultant torque (N.m).

Table VI
Results to 3600 RPM

Resultant standard deviation	62 N.m
Standard deviation electric machine	24 N.m
Standard deviation combustion engine	74 N.m
Resulting average torque	26 N.m
Average electric machine torque	0 N.m
Average combustion engine torque	26 N.m
Simulation time	0.033s

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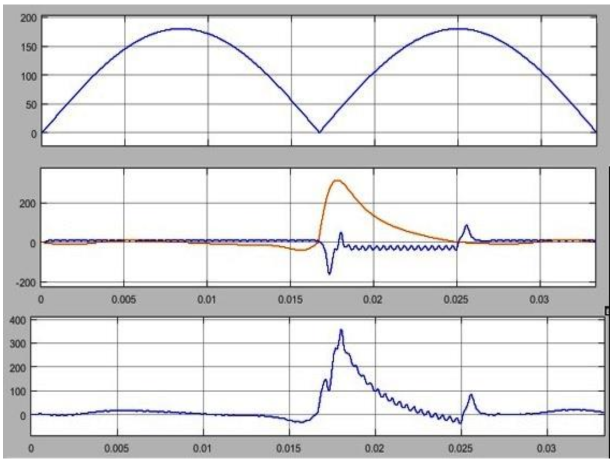

Fig. 5. Results obtained for 3600 RPM, in this order: Position of the crankshaft (degrees), Electric machine and combustion engine torque (N.m), Resultant torque (N.m).

Table VII
Results to 4600 RPM

Resultant standard deviation	64 N.m
Standard deviation electric machine	19 N.m
Standard deviation combustion engine	73 N.m
Resulting average torque	26 N.m
Average electric machine torque	0 N.m
Average combustion engine torque	26 N.m
Simulation time	0.0.026s

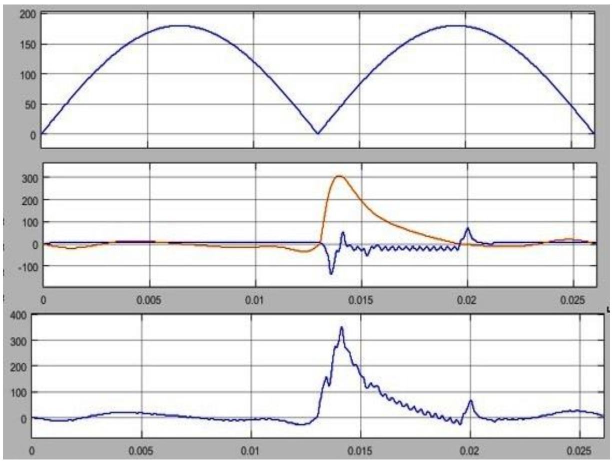

Fig. 6. Results obtained for 4600 RPM, in this order: Position of the crankshaft (degrees), Electric machine and combustion engine torque (N.m), Resultant torque (N.m).

V. Discussion of Results

The standard deviation of the resulting torque relative to the combustion engine torque reveals improvements in all the ranges of rotation and are more significant at lower rotations. In some cases, as can be seen in Fig. 7, there are improvements in the order of 20 Nm. This progress of the machine in relation to the combustion engine was carried out keeping in mind that with the increase of the rotation the combustion engine will lose the need for help to fill the strokes in which it does not produce torque.

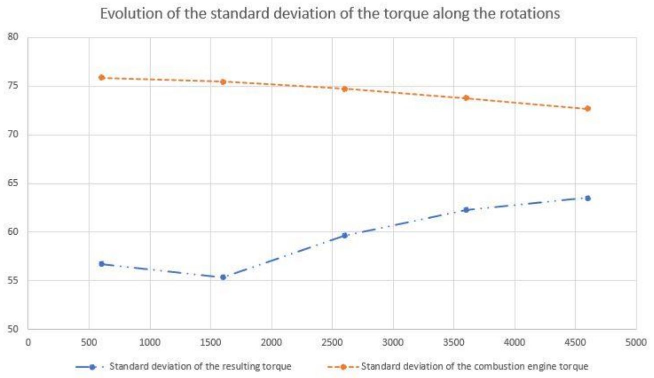

Fig. 7. Evolution of the standard deviation along the rotations

Another important point is that it has been possible to keep the average torque from the electric machine slightly below 0 Nm, since this implies a zero energy balance between the energy produced as a generator and consumed as a motor, which was also desirable since the objective was to cancel the inertia flywheel and not generate more than necessary power as this would imply a reduction of the available torque at the output of the combustion engine and the torque with a larger standard deviation value. The average torque of the combustion engine has been also maintained without changes. This fulfils the initial goal, since the goal was to correct this and not make changes in their mean value. Therefore, the results are as initially intended.

VI. Conclusions

From the research it was still noticeable that a system like the one proposed would cover some flaws in developing technologies and triggering a series of advances necessary for modern technologies to emerge [5]. This type of system is part of the development lines that the largest manufacturers of combustion engines tend to follow by making the means of transport increasingly efficient and environmentally friendly.

The option to build the simulation proved to be an asset for the future development of the project, since it saved a considerable amount of resources that could be wasted if the feasibility of the idea of this system was not verified.

All the simulation performed as expected, the fact that it was performed using magnetization curves obtained by means of finite elements, came to bring more support to the whole simulation since one of the main doubts would be the behaviour of the electric machine in its switching from motor to generator. On the other hand, the fact that the combustion engine is modelled using theoretical cycles suggests that there may be improvements in terms of results, there is still an endless number of variations and combinations of factors that could be performed to seek better results.

With this work it was possible to fulfil the proposed objectives, since the results point out that the initially proposed system is viable, which gives good indications in the continuation of the study and development of this system.

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