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Functional Modeling of an Electric Machine Used on Road Vehicles

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Abstract
Recent years bring new European Union regulations concerning harmful emissions for road vehicles. The hybrid electric and electric mobility is a technology revolution for the automotive industry. In response to the stringent regulations and requirements enforced, vehicle manufacturers are developing new strategies, using hybrid electric or electric powertrain solutions. In order to obtain the goal of using alternative powertrain solutions, it is important to integrate from the early beginning different devices and to optimize their behavior. However, with a minimum of one electric motor architecture, a hybrid electric powertrain triggers more concerns about energy flows. During operation, there are energy losses caused by heat generation. Generated heat, emphasized as losses, is having a negative effect on motor efficiency. Using simulation, the electric motor, with both its functional model and its thermal model, were integrated in a mock-up virtual hybrid electric vehicle to study its behavior during a predefined cycle. The functional model is generating the data files, with regard to the voltage use and the torque generation. The functional behavior of the electric motor is the production of torque/rotational speed. The thermal model is using the data files in order to determine the energy losses. There will be possible to determine the electric motor efficiency, as part of the powertrain. Thereby, this paper aims to present the functional behavior of an electric motor in order to build the needed data files, which have to be used by the thermal model. An oriented electric motor was developed and the resulted data files were used by the electric motor that equips the virtual mock-up hybrid electric vehicle.

1. Introduction

New European standards will require auto manufacturers to reduce CO2 tailpipe emissions down to 130 g/km by 2015. For that it is need to predict and to minimize the harmful emissions from the model developing stage, by using a complete and detailed energy balance for a given powertrain configuration.

The automotive manufacturers are developing an array of other promising technologies. Hybrid vehicles are not the only answer to reduce harmful emissions and fuel consumption, but at this moment, they are a strong competitor for other solutions aiming this purpose. Hybrid vehicles are defined as having at least two different energy storage devices for vehicle propulsion, as the fuel tank – liquid chemical storage and the battery pack – electrical storage. A hybrid electric vehicle (HEV) stands out having at least one electric motor/generator, a battery pack and other components that every ordinary vehicle has [2].

The hybrid electric vehicle development process, within respect to energy management, contains more than one level for designing the model. The primary level may be used for developing and optimizing the control strategies, based on maps and data tables [2].

Another level may include only partial physical aspects, trying to find an optimal balance between maps and physical data. Using all the previous levels, it is mandatory to add a more developed level as a need for the detailed physical subsystems.

Many differences can be noticed between a conventional and a hybrid vehicle, but the most important ones are the powertrain architecture, the control and the different modes of operation.

The electric motors/generators are the most used solutions for the additional power sources/storage. There are many types of electric motors applied in hybrid powertrains. For all of them the concerns are regarding their power, functional behavior and lifetime. The electric motors/generators` efficiency may decrease while operating due to its thermal behavior. The electric motors/generators are generating heat that may reduce their lifetime and may lead to motors/generators failure [5].

The electric motor/generator used as a part of the powertrain architecture was a switched reluctance motor (SRM).

The result of this defined modeling approach is that design parameters for the motor can be linked to multiple vehicle performance parameters.

The paper will focus on modeling the electrical motor with respect to the functional behavior based on the motor operating characteristics.

2. Simulation of a Virtual Vehicle Model [5]

The HEV equipped with an electric motor/generator will be simulated using the AMESim software tool. The construction of the model for simulation, basically consists of linking sub-models from various software`s libraries. The sub-models are shown as icons. After linking the icons (which represent each component of the vehicle) in sketch mode and choosing the proper sub-model in sub-model mode, the parameters will be set. Each icon covers a fragment of C code, written using the specific equations for the system.

Using a pre-defined mission profile for setting the vehicle control speed with regard to the selected driving cycle, it is possible to input the ambient data (wind speed, density and ambient temperature) as real parameters. Acceleration control and brake control take into account the anticipation of the speed control.

The driver used in this model controls/calculates braking, acceleration and gear shifting using the vehicle speed. The driver is not able to calculate the gearbox ratio or clutch control.

The Hybrid Control Unit (HCU) performs regulations for idle speed and maximum speed. Also the HCU controls the batteries (the state of charge), analyzing them in order to minimize the energy consumption. The HCU contains two different functional modules/levels, based on power demand and the hybrid mode selection. The HCU estimates the load demand based on current load due to road conditions, mass, speed, inertia. The hybrid modes are selected from predefined operating modes, based on power demand, driver's request and vehicle state.

The model for the electric motor can be used as an electric motor and a generator, being independent from the technology of the machine and converter. It is using the torque reference, the battery voltage and the rotary velocity for being able to compute the efficiency tables. It is controlled by the HCU to deliver the motor torque and the losses.

The battery is an internal resistance model, which characterizes the battery with a voltage source and an internal resistance. The battery output voltage is calculated as follows V=V0-I*R, where V [V] is the output voltage, V0 [V] is the open circuit voltage, R [Ohm] is the equivalent internal resistance, I [A] is the input current. The battery consists of banks in serial and parallel arrangements; each battery bank consists of cells.

The transmission includes a continuous variable transmission to get the engine torque and to deliver it to the wheels.

The vehicle models a simple vehicle load when considering no longitudinal slip between the tire and the ground.

The hybrid powertrain architecture used in the simulation is a parallel configuration equipped with continuous variable transmission (Fig. 1).

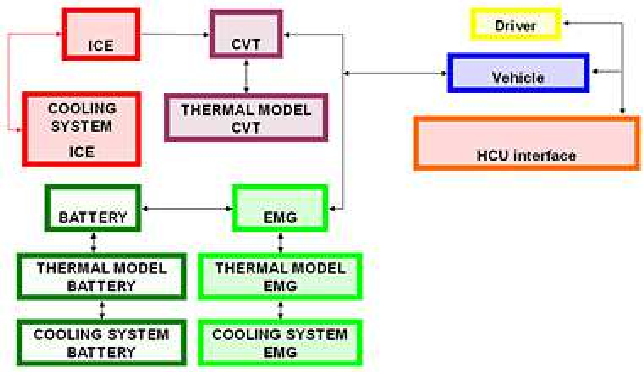


Fig. 1. *Model of the HEV equipped with the SRM [5].*

The electric motor/generator is connected to its thermal model, exchanging information about temperature and power losses.

The parameters used in the simulation are the benefit of existing vehicle and components. The most important are shown in Table 1.

Table 1. *The Most Important Parameters Used in Simulation.*

Sub-model	Parameter	Value / Unit
Electric motor	Type	SRM
	Maximum power	30kW
	Maximum torque	200 Nm
Battery	Voltage	~300 V
	Rated capacity	6.35 kWh
	Cells in series per battery bank	96
	Battery banks in parallel/series	1/1
Transmission	Type	CVT
	Efficiency	~ 0.85 - based on efficiency tables

3. Functional Modeling of the Electric Motor

The electric motor used in the simulation is a switched reluctance motor. It has simple design and dedicated control unit. It has stator and rotor poles, without having permanent magnets. To prevent blocking while operating, the stator poles number is different from the rotor poles number, the usual difference between the stator and the rotor being of two poles (SRM 8/6 – 8 stator poles and 6 rotor poles) (Fig. 2).

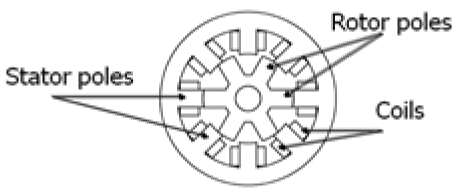


Fig. 2. *SRM 8/6 simplified design [2, 5].*

The SRM stator is similar to a brushless motor. The SRM rotor is made of rolled steel. The stator pole polarity does not affect the production of torque. The torque is produced as result of magnetic attraction between the rotor and windings. The windings are around each magnetic pole of the stator. The rotor is forming a magnetic circuit with the energized stator pole.

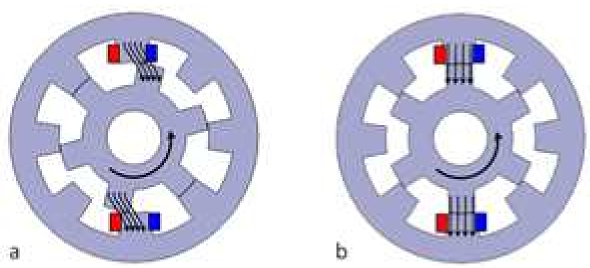


Fig. 3. *SRM 8/6 stator poles and rotor poles alignment [2].*

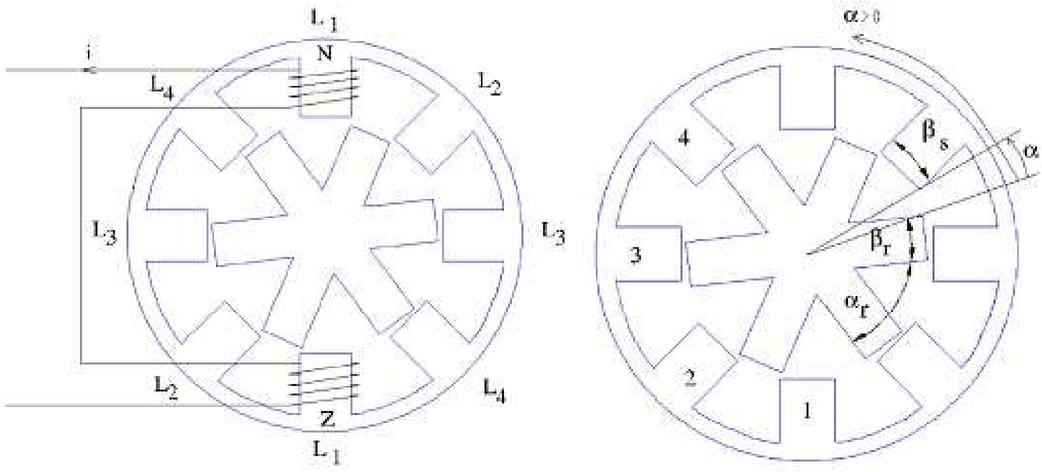
The SRM is operating by energizing the opposite stator coil. By exciting the stator poles, the rotor poles will align with the stator poles. When the two poles align (Fig. 3b), one from the stator and one from the rotor, the next set of stator coils are supplied with energy in order to change their position. The SRM is producing energy by consecutive excitation of the stator coils, which are surrounding the poles, resulting in rotor rotation. The torque is produced by the magnetic attraction between the rotor and the stator windings.

The motor is doubly salient with phase coils mounted around diametrically opposite stator poles. Energisation of a phase will lead to the rotor moving into alignment with the stator poles, so minimizing the reluctance of the magnetic path. This is the same principle of operation as the VR stepper motor. As a high performance variable speed drive, the motor's magnetic are optimized for closed-loop operation. Rotor position information is used to control phase energisation in an optimal way to achieve smooth, continuous torque and high efficiency. The theoretical equations governing the torque production mechanism have been published countless times in the literature, so below is a simple graphical explanation. The current waveforms are imposed on the angular unsaturated phase inductance. The maximum inductance corresponds to the minimum reluctance pole-aligned position. Positive torque is only produced at angles when the inductance gradient is positive.

The reluctance of the magnetic circuit is equivalent to an electric magnetic resistance and decreases when the rotor pole is aligned with the stator pole. During rotor and stator poles alignment, the distance between the rotor and the stator is very small, and therefore, the reluctance value is minimum. The winding inductance varies as long as the rotor is in motion. Between two consecutive alignments, the inductance is very low, and the current increases rapidly. The inductance increases when a rotor pole is aligned with a stator pole. These issues lead to difficult control of SRM.

The rotor relative position is able to be detected using two different procedures: with a position transducer or directly. The second procedure consists in the determination of the produced energy, without additional items needed, such as transducers. SRM electronic control unit decides to feed each stator windings only when useful torque can be produced. Therefore, following proper timing of stator excitation, the electrical machine can operate as a motor or as a generator, with exceptional performance in a wide speed and torque.

Rotor position is given by the angle α [^{0}], which has positive value in the opposite clockwise direction - counter-clockwise. The angle $\alpha=0^0$ is reached when the rotor pole is aligned with the stator pole. In figure 4b, the angle α is negative or less than 2π.



a b

Fig. 4. *SRM 8/6 magnetic description (a-$L_{1...6}$ magnetic windings, b-magnetic angles, α, β_s, β_r) [16].*

The SRM most important parameters are especially the geometrical ones, the maximum and minimum inductance and the torque constant. Stator inductance varies between a minimum and a maximum depending on the state of alignment of rotor and stator poles. Starting from the premise that the number of rotor poles is Nr, the stator inductance will be a periodic function that depends on the rotor position with a period of ($2\pi/N_r$) radians (Fig. 5).

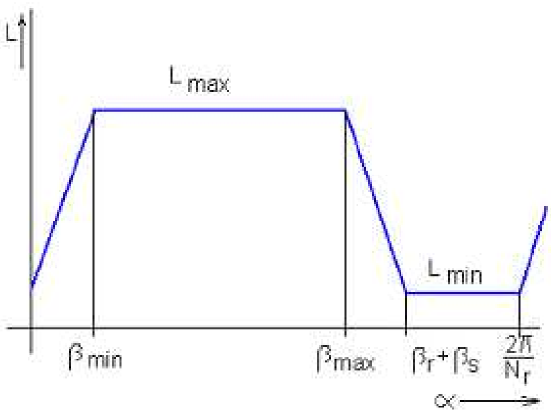


Fig. 5. *Inductance dependence with rotor position [16].*

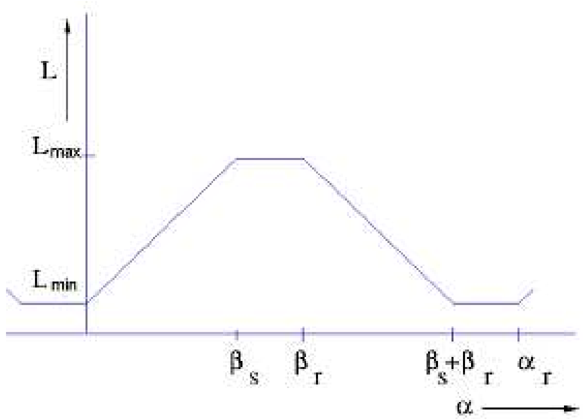


Fig. 6. *Inductance variation with regard to angular rotor to stator positions [16].*

The stator inductance varies between a minimum and a maximum value, L_{min} and L_{max}. When the rotor poles aligns with the stator poles, the inductance is maximum, and when none of rotor and stator poles are not aligned, the inductance is minimum (Fig. 6). The corresponding value to a phase inductance is given by the position of the rotor with regard to the position of the stator.

The SRM torque is produced only when a rotor pole is aligned with the stator pole. For this reason, the control is difficult to achieve. A command and control device (controller) must achieve optimum torque requirements using the rotor position.

SRM modeling is more complicated than an ordinary electric motor as a phase flow depends both on the rotor position and of all phases current.

Before simulation starts, it is mandatory to determine the electromagnetic variations curves. Therefore, the electrical machine will be developed using LMS. Imagine. Lab. AMESim in order to generate the electromagnetic variations curves.

Starting from the beginning, a basic electric motor model was chosen from the library. This model is a reversible electric machine, which can be used also as a motor and a generator. It is possible to determine output torque and power losses using data files. It has also a thermal port where it is able to receive temperature values and power losses that can be used for powertrain energy management.

The electric motor offers two different choices for modeling through data files and by setting parameters.

Data files can be built based on a matrix. The model allows the use of three data files to determine the maximum and the minimum torque and the power lost in a given operating point. To achieve data files used to determine the minimum and the maximum torque, a three-axis XYZ is used as follows: X axis values correspond to absolute values representative of the voltage received from the battery, Y axis values correspond to motor absolute velocity and Z axis values correspond to the minimum and the maximum torque values. Proper torque values can be both positive and negative, thus the maximum value is positive and the minimum value is negative.

The constant maximum power, the maximum torque, the efficiency and the maximum rotation speed are the parameters that have to be specified before the simulation starts. The model analytically determines the needed torque by taking into account the minimum and the maximum torque values. The supplied torque depends by the time constant. The efficiency is considered a constant value, while the motor power loss is determined taking into account the mechanical power delivered by the motor and its efficiency.

The SRM is possible to be used as motor or as generator. Taking into account the static operating conditions for the motor within the linear characteristics, it allows using the model in dynamic simulations. It is necessary to satisfy the condition that setting of the current time is sufficiently fast compared to the dynamics of the system.

The switched reluctance motor is a non-linear system, mainly due to its nonlinearity inductance profile [7, 8, 9], resulting in a non-linear torque equation. There are several available solutions for analytical modeling of the SRM [6, 13], but a detailed and accurate model can be developed using the data files. These data files contain non-linear inductance profile and other important magnetic characteristics [11]. In [14] there have been studied comparisons of non-linear analytical models and models that use data files. Using data files are given the best results. This is why this method was chosen for the design and the development of the modeled system for the SRM 8/6.

None of the existing models are satisfying the above mentioned demands. Therefore, a new oriented model was built in order to investigate the electromagnetic phenomena during operation.

The new model was develop by using geometric and energetic characteristics of the reversible electric machine, taking into account also the magnetic properties of materials and of the windings features. The SRM development interest is with regard to the number of windings, the magnetic flux and the torque that can be developed at a certain angular position of the rotor and at a certain values of the current. The challenge is to achieve a steady state, in which it is possible to determine the magnetic flux and the developed torque, for different values of the angular position of the rotor, and for different values for the current. Thus, this procedure can be repeated several times, to obtain a range of values for the current and for the angular position of the rotor in order to cover the entire range of the SRM 8/6 operation.

This model is used to determine the data files, which are underlying the functioning for the thermal model to determine the losses, being easily integrated into existing AMESim libraries with electric machines models (Fig. 7).

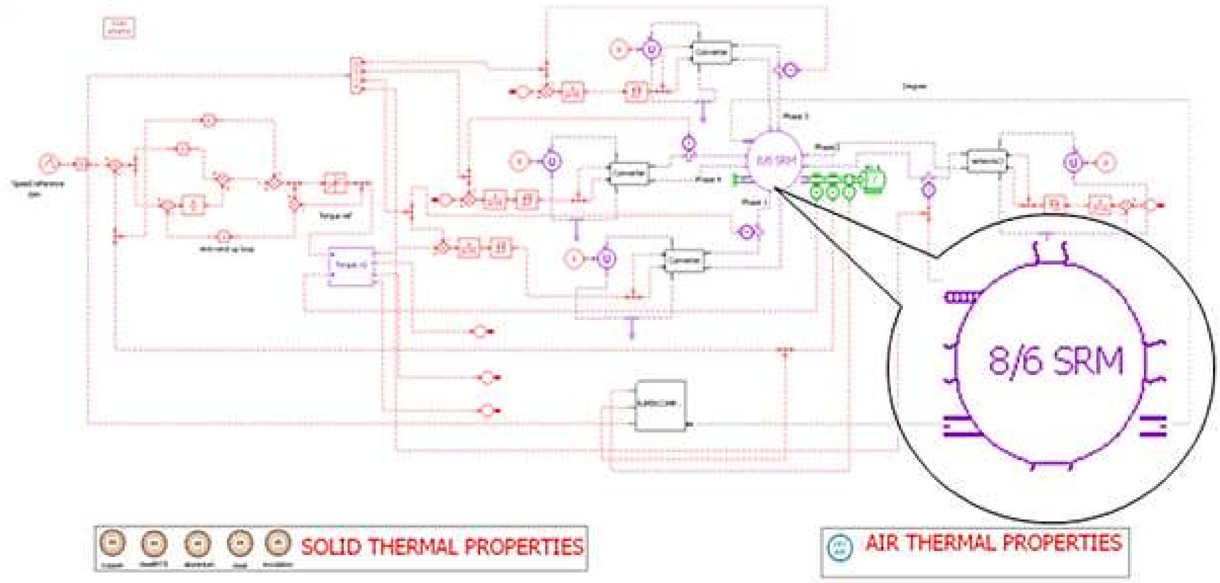


Fig. 7. *The oriented model designed to determine the data files [2].*

The data files shall be made taking into account the non-linear behavior of the SRM, in order to simulate the magnetic properties of the electrical machine (Fig. 8).

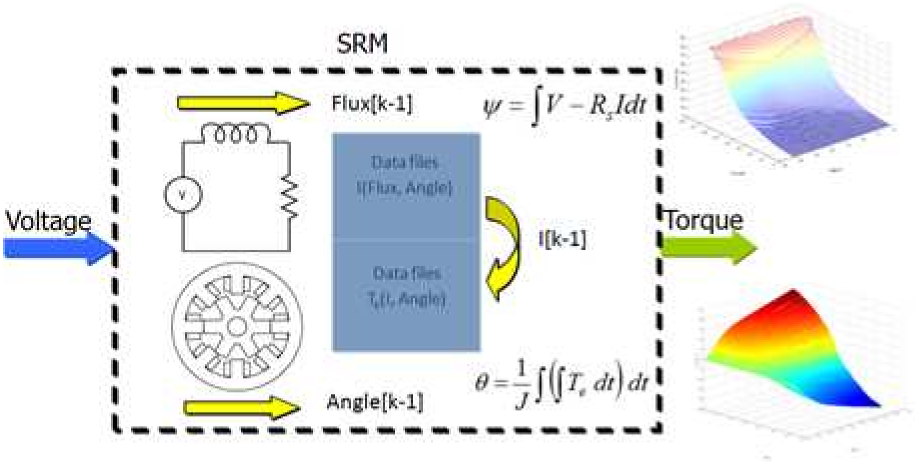


Fig. 8. The principle of making and using the data files [2].

It contains two variations of magnetic flux and current and torque depending on the rotor position (Fig. 9). The information about the current, the rotor position, the torque and the magnetic flux are stored and arranged in rows and columns to follow the directions to achieve data files. The information in the data files can be used only on a pair of poles, and then duplicates to other poles. In order to allow a correct and accurate operation of the model, there are selected only incremental values.

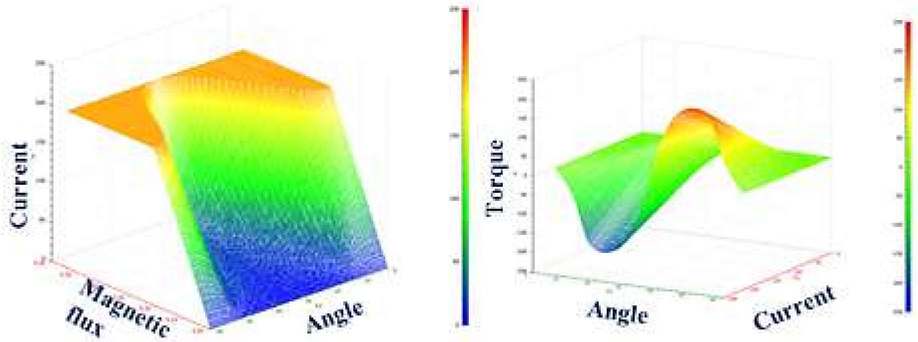


Fig. 9. Variations in (a) - magnetic flux and current and (b) - current and torque with rotor position [2].

The control for this model is characteristic to achieve the necessary data files. It is very important how to choose the angles at which the power supply is possible. Along with this choice, the control of the operating angular velocity and the current consumption can reduce torque ripple. Therefore, it is necessary to use transducers to determine the rotor position and its the angular speed and power transducers.

For the virtual mock-up hybrid electric vehicle, the previous model for the electric motor (that has been chosen from the beginning) was changed with another one that is able to use the resulted data files. The change is mandatory because it is needed to take into account all the operating phases while studying both the functional and the thermal behavior.

Given that, the SRM has several phases and using the first chosen model cannot investigate or use the information corresponding to several operation phases. The replacement occurred for modeling the thermal losses in order to achieve properly functioning during all the SRM phases. The substitute electric machine model is part of an optional library (library "Electric Motors and Drives"). It has many functional characteristics similar to the model previously used in the hybrid powertrain modeling. Additionally to the model used, this model allows the use of data files for several phases. The modeling will take into account the losses and the operating phases. The SRM 8/6 model especially designed will provide the needed data files. It uses certain parameters from the entire modeled system in order to proper functioning. The following values are used for the data files: the minimum and the maximum torque, the input voltage, the rotary velocity from the primary shaft and the temperature.

Even if it is not possible to use this last selected model for accurate modeling of the SRM dynamic behavior, this model allows modeling the energy behavior. This model is suitable for studying the electric machine behavior for different operating phases.

This model can only work if the interpolation types are established, the necessary data files are selected and the required standard values are properly defined: the voltage, the rotational speed, the temperature, the torque and the power losses.

The SRM torque is determined using data files or mathematical equations. The data files are using the range between the minimum and the maximum torque.

The power losses are determined by using the data files. They are presented as heat flow or operating generated heat.

The input voltage is determined starting from the minimum voltage. The maximum voltage is determined using graphical interpretation.

4. Modeling Results

The functional model (electromechanical) and the thermal model complete each other and help to ensure the correct operation for electric motor (Fig. 10).

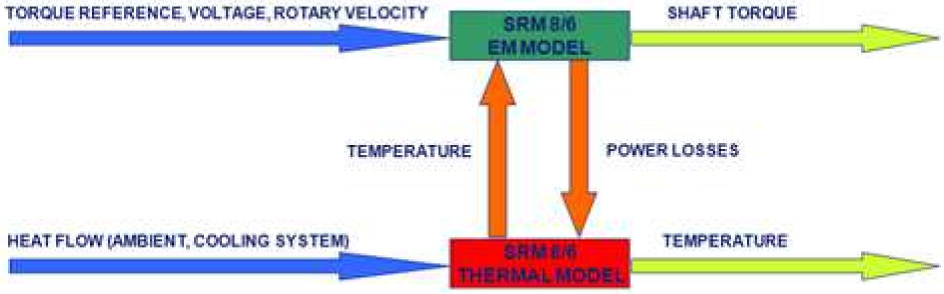


Fig. 10. *SRM modeling operation [2].*

The functional model uses torque reference, the battery voltage and the rotation speed, for being able to compute the efficiency tables, these information being sent by the hybrid control unit (HCU). The technology of the machine and converter do not influence the behavior of the SRM. The functional model also uses the temperature from the thermal model in order to provide the output. Power losses are taken from thermal model for necessary corrections and to be transmitted as required. The thermal model uses the ambient heat and from the cooling system. The thermal model receives the power from the electromechanical model. The thermal model will develop the temperature values during operation.

The main connection between the Electro Mechanical model and the Thermal model is that they are changing information about the temperature and the power losses.

The simulation results for the entire vehicle are available after modeling the mock up vehicle model, where the thermal model is also a part of it. After integrating the thermal model and linking it with some others components, it is possible to investigate the power losses evolution, the SRM efficiency and vehicle performances in terms of fuel consumption, the time to run the predefined simulation cycle, the maximum speed and the acceleration. The results were presented in [2, 5], the paper which refers to SRM thermal modeling as a hybrid electric vehicle powertrain component.

The results of SRM functional modeling consist of the data files for allowing the thermal model to provide the different types of losses based on temperature flows. The graphical representation of some data files can be seen in figure 9. The results of this modeling stage also consist in connecting electromechanical and thermal models. These two models were developed in order to exchange the necessary information with the entire powertrain system to obtain its correct operation.

5. Conclusions

A detailed electro-mechanical model was created by means of integrated approach that uses functional design for the electric motor/generator.

The intermediate electric machine model was special designed to determine the data files, being able to set the temperature reference and the windings resistance.

The paper shows the development need for a switched reluctance motor model, which cannot be found inside simulation software libraries. Without this SRM model, it would not be possible to connect the thermal model to the hybrid electric vehicle powertrain model and without which the investigation and evaluation of thermal phenomena would not be possible.

The new SRM model is developing data files that are needed for a predefined existing model. The existing electric machine model presents an electro-mechanical behavior which is similar to the electro-mechanical behavior of variable reluctance electrical machine, but which is not able to develop data files.

Using switched reluctance motors in the automotive industry has fast growing. It gaining popularity following the advantages it offers. Its usage is supported by strict fuel economy requirements, by the low emissions benefits and by the dynamic performances.

Many of the powertrain applications using electric machines for vehicle design represent challenges for the electrical drive systems that require high performance at low cost, the operation being able to run for mechanical and thermal environments, during many cycles at low voltages. These requirements extend existing power limits of machine. The SRM is considered an important candidate for equipping hybrids and electric cars electric [2, 5].

Due to its simplicity structural and functional, both mechanically and electrically, low cost and robustness, the switched reluctance electric motors represent a viable solution that can be used on vehicles' propulsion system.

Following the desired design, the SRM has a high efficiency in a wide range of loading conditions, outperforming conventional technologies in many applications, especially when are required high starting torque, high rotational speed and constant power within the high speed.

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