Investigation on PMSM for electric vehicle applications using co-simulation of MATLAB and magnet software

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Abstract. Transportation plays an important role in all our day to day life. Advancements in technology have uplifted the transportation system into the next level by the introduction of E-Vehicle. E-vehicles are the replacement of gasoline vehicles which are the major reason for depletion of ozone layer. The main component of the E-vehicle is the motor which basically decides the efficiency of the vehicles. The design of the machine has a great impact on the efficiency and as well as on the engines output. Due to the poor analysis of electromagnetic properties of the motor, undesired fluctuations and pulsations would occur causing harmonics to take place thereby there is a huge increase in iron loss. This will also affect the control over the vehicle at low speed. A reasonable method to avoid such issues is to introduce an additional step of analyzing the electromagnetic properties before prototyping the machine. Analysis of the machine is done on the perspective with the integration of the motor and the other components. A new design phase where multi-domain analysis defines these phenomena will assist in the task of achieving an optimal design. A specific simulation tool for each domain is needed for analysis of the entire system. The co-simulation is carried out on a 10-pole, 12-slot interior Permanent Magnet Synchronous Motor (PMSM) in this paper to do finite element analysis in order to achieve the necessary efficiency.

Keywords: E-vehicle, harmonics, multi analysis, co-simulation, PMSM

1. Introduction

Energy and climate have a major role to play in the creation of human society. The oil prices of recent years continue to increase, variations are also growing intense, defense of the environment for public opinion. The respective rules are exponentially increasing with many strict laws for reducing the pollution due to conventional power plants. Lesser usage of energy becomes the need of the hour. New energy use and pollution reduction technologies have become an important technological path for automotive technologies. There’s no question that pure EV has become one of the most appealing energy-saving solutions and cutting emissions.

The architecture of EVs is different from the Internal Combustion Engine vehicles. EVs are the outcome of the interdisciplinary fields of automobile and Electrical. This makes the integration of the system to obtain good performance and cost effective. A new method of analysis of the design is
required to satisfy the constraints. This solution was unlikely just a few years ago due to the restrictions in computational facilities and integration difficulties between varieties of software’s. However, at present scenario the deployment of new powerful tools made possible for complex problem analysis and investigation through co-simulation.

In [1] authors discussed the need the essentiality of battery eco-system which is the major part of EVs. In [2] authors estimated the control strategies for PMSM motor for EVs. [3] focused on the review of various technologies involved in the EVs, management of battery, charging issues. [4] discussed the effect of PMSM motor for EV application rather than induction motor. [5] presented the application of the Finite element method to understand the fundamental theoretical aspects of rotating electrical machines. [6] provided the analysis of the battery to improve the performance of EV. [7] modeled the three types of interior PMSMs with different PM arrangements by the finite element method (FEM) and commented on the better model.[8] evaluated the optimization procedure based on Matlab and FEM software. [9] reviewed the trend, effects and the opportunities in the growth of EV development. [10] analyzed the torque of Permanent Magnet Synchronous Motor (PMSM) of electric vehicle by finite element analysis. [11] presented co-simulation which is a method which to study the electric machine for EV design.[12] introduced a coupled simulation structure which includes the control, the power electronics and also a permanent magnet synchronous machine. [13] proposed a co-simulation tool for analysis and design of electrical machines. The co-simulation that exists between the system software and FEM are used for evaluation of losses at different voltages.

Many researches are going on in the field of PMSM motor for EV application. Few are surveyed and listed above. No extensive study was reported on co-simulation and that is the motivation of the present work.

2. System design

In variable speed drives, the power converter controls the motor speed by making variations in the supply voltage frequency, called PWM. The phenomenon induced by the reciprocal regulation between the power converter and the terminal machines of the computer is overvoltage. The high dv / dt characteristic of PWM waveforms causes this overvoltage and can appear too long when wires are linked between the power converter and the computer. In the worst case, this effect can irreversibly destroy stator winding insulation.

This paper discusses the incorporation into a single simulation method of the MAGNET finite-element analysis programme and the MATLAB device simulator-SIMULINK. The electrical device is developed in conjunction with MAGNET software, while MATLAB-SIMULINK implements the power, electrical elements and mechanical structures.

It is important to pair the FEM software MAGNET with the device simulator MATLAB SIMULINK through Magnet Plug-in interface. Sheela et al(2020) [14] have verified the PMSM machine for EV application using magnet software for the required speed.

3. Magnet plug in properties for simulink interface and reference model

For the plug-in interface, the factors to be used are MagNet time phase, MagNet solve type, Transient or Transient with Motion solver, voltage and current scale factors, Average time interval. The above factors are consistent because whether or not the solution is stored, that is needed for post-processing MagNet fields or global quantities, other than voltage and current, and also the magnetic fields in the circuit simulation are insensitive to high-frequency components. The co-simulation is done for the model 10P-12S interior PMSM motor. The design specifications and the dimensions of the interior PMSM model are given in table 1 & 2 respectively.
Table 1 Specifications of PMSM Model

| Operating Points | Speed (rpm) | Torque (Nm) | Power (kW) |
|------------------|-------------|-------------|------------|
| A                | 1000        | 22          | 2.3        |
| B                | 4100        | 7           | 3.4        |
| C                | 7500        | 7           | 5.5        |

Table 2 Dimensions of the PMSM Model

| Dimensions       | Design    |
|------------------|-----------|
| Length (mm)      | 72        |
| Stator Details   |           |
| Stator OD (mm)   | 120       |
| Slots            | 12        |
| Turns for each Phase (ohm) | 2.5 |
| Resistance at each phase (ohm) |           |
| Rotor Details    |           |
| No.of.poles      | 10        |
| Magnet Grade     | N45UH     |
| Br,bHc,iHc       | 1.33T,1003kA/m,1990kA/m |
| Cu Weight (kg)   | 1.1       |
| Magnet Weight (kg) | 0.275   |

The Permanent Magnet Synchronous Motor in figure 1 was designed using Magnet Software. It is a 10 pole 12 slot interior PMSM with 12 turns per phase.

Figure 1 10P-12S interior PMSM Design

4. Field oriented control in co-simulation

Field Oriented Control (FOC) of PMSM is implemented in this co-simulation, wherein the stator currents of a are recognized as two orthogonal components that can be visualized with a vector.
The two components are the magnetic flux and the torque. Equivalent current references are estimated from the flux and the torque. Controllers are used to maintain the current value at their normalized values, by generating suitable PWM pulses. The PMSM FOC design couples the dq frame of the torque and flux. The figure 2 shows the overall structure and the corresponding Simulink block diagram is shown in figure 3. Here, the control is implemented without the PWM Generator and Power Converter.

The design of the machine is done using MAGNET software and the equivalent algorithms for controlling the machine are implemented using Matlab. Magnet plug-in interface is used to import the file from magnet to MATLAB. The factors such as magnet time step, voltage and current scale factor and solver options are given in plug-in properties. The rated speed and torque are given as input in Simulink. The Simulink parameters such as speed, torque, input voltage and input current act as input for this co-simulation. This also includes the factors such as magnet time step, voltage and current scale factor and solver options as plug-in properties. The Simulink parameters for this respective interface is shown below in the table 3

![Figure 2 FOC Control of PMSM in MATLAB SIMULINK](image-url)
Table 3 Simulink Parameters of project model

| Parameters       | Value | Unit     |
|------------------|-------|----------|
| Speed (N)        | 104.7 | rad/sec  |
| Torque (T)       | 22    | Nm       |
| Input Voltage (V)| 28    | V        |
| Input Current (I)| 217   | A        |
| Simulink End Time (t) | 0.5 | s        |
| Magnet Time Step  | 0.0002| s        |
| Voltage Scale Factor | 2   | Nil      |
| Current Scale Factor | 1  | Nil      |

The controller parameters such as proportional constant Kp and integral constant Ki for current controllers (d-axis and q-axis) and speed controller are represented below in the table 4.

Table 4 Controller Parameters of project model

| Parameters          | Value   |
|---------------------|---------|
| Id Controller       |         |
| Constant of proportional controller (Kp) | 0.021   |
| Constant of Integral controller (Ki)    | 2.93    |
| Iq Controller       |         |
| Constant of proportional controller (Kp) | 0.065   |
| Constant of Integral controller (Ki)    | 2.93    |
| Speed Controller    |         |
| Proportional Constant (Kp)              | 21.56   |
| Integral Constant (Ki)                   | 287.47  |
5. Co-simulation results

The waveforms obtained from MATLAB SIMULINK for speed, position, input voltage, output current, voltage in dq axis, current in dq axis and torques are shown respectively in the figures 4-10.

![Speed](image1)

Figure 4 Speed

![Position](image2)

Figure 5 Position

![Input Voltage](image3)

Figure 6 Input Voltage

![Output Current](image4)

Figure 7 Output Current
From figure 4 it is seen that the motor reaches the reference speed at 0.17 msec. The torque obtained is shown in Figure 10 which gives the designed value.

5.1 Magnet results after co-simulation

The waveforms for speed, position, flux linkage, phase voltage, phase current and torque obtained in MAGNET Software after simulation are shown below in the figures 11-16.
Figure 11 Speed

Figure 12 Position
Figure 13 Flux Linkage

Figure 14 Input Voltage
The waveform in figures 11-16 clearly shows that they are in par with the one which is obtained in MATLAB simulation as shown in figures 4-10. It is verified from the figures that in this pre design stage the integration of FEA and MATLAB environment is working good for low speed application.
6. Conclusion

PMSM for the application of automotive field which can be implemented for EV is modeled and the analysis is done using magnet software. Also, the performance is verified from the design. The FEA results confirmed that the design is meeting the expected performance. The performance of the machine is predicted with the help of 2D-transient analysis by applying necessary velocity (speed) and load.

The final design 10 pole 12 slot PMSM with 12 turns/phase is meeting the requirement at both lower and higher rated speeds by delivering corresponding rated torques. The difference in the conventional method and this method is to introduce a new step in the pre design stage to overcome the problems that occur in the performance analysis. However, to identify the possible problems in classical design approach, a new step is added into the prototype stage where the behavior of the machine for the final application is analyzed by evaluating the interaction between different elements of the system.

In order to achieve this purpose, both FEA and matlab are integrated so called as co-simulation. Field oriented control of PMSM was executed in this co-simulation. The performance is verified for lower speed of 10 pole 12 slot interior PMSM motor. The future work is to verify the performance of final design at higher speed of motor by this co-simulation.

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