PERMANENT MAGNET ENGINE DIGITAL CONTROL - PERFORMANCE IMPROVEMENT FOR THE INVERTER

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Abstract – **An engine of permanent magnets is projected and implemented together with its drive. The objective is to construct an adequate electric engine to be inlaid in the wheel for electric vehicle. The project has dimensional restrictions due to its application. These restrictions concur for a time electric constant that reduces the current rise inclination, reducing the performance of the engine. A solution is presented modifying the inverter switch triggering programation. This article presents a methodology to improve the reply in the permanent magnet CC-engine performance for the adjustment in the instant of the feedback inverter key discharge.**

KEYWORDS

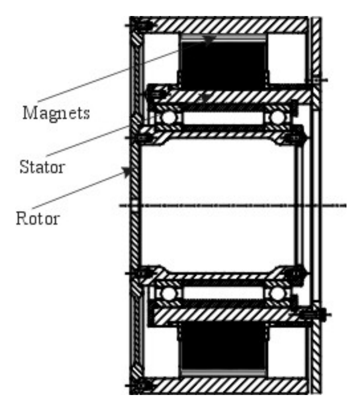
Electric machines, electric vehicle, permanent magnet machine, electric drives.

I. INTRODUCTION

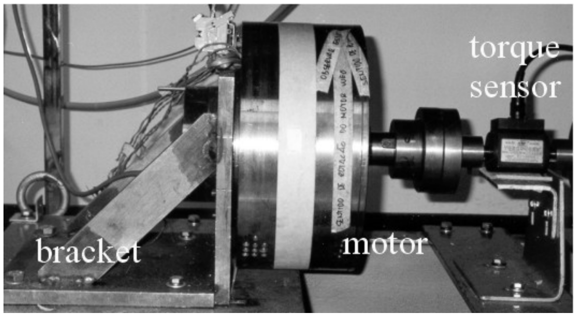
Pollutant emission to the environment is, largely, due to the internal combustion engines. These engines do exist almost that in the totality in automotive vehicles concentrated in the great cities reducing the quality of life with raised costs to the public health. A zero emission technological option to the internal combustion vehicles is the electric one. One of the mechanical transmission arrangement possibilities is to inlay the engine in the wheel. This possibility reduces the mechanical losses and the weight of the vehicle for the busy space elimination for the engine. This article initiates with the presentation of the characteristics of an engine projected and implemented to be inlaid in the wheels. After that, its mathematical model with results of simulation for torque control is described. The experimental results and the engine low income for high speed are presented. A solution for the engine feedback inverter discharge and analyzed the experimental results for this solution is proposal.

II. CHARACTERISTICS OF THE ENGINE

To reduce the engine size and weight the permanent magnet using was chosen. It was looked to maximize the number of polar regions and phases for reduction of the torque undulation and to increase the trustworthiness. Thus the chosen engine was the one of CC permanent magnets, with twelve polar regions, five phases and rolling up imbricate in double layer. The dimensional characteristics are of 275mm of diameter and 130mm of length with constructive characteristics that can be observed in the figure 1(a). Figure 1(b) shows the engine constructed in workbench. Considering a 500kg vehicle reaching the maximum speed of 90km/h, it is necessary to the engine a torque of 30Nm and a speed of 750rpm, for the dimensions above presented. For in such a way the necessary power it is of 3,2Hp.



(a) Motor-wheel construction parts



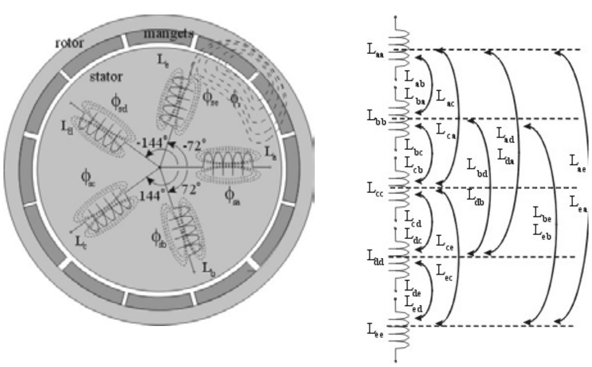
(b) Motor in workbench

Figure 1. Constructive features of multiphase permanent magnet engine

The five-phase inverter that feeds the engine receives energy from batteries that supply a voltage of 144V, the engine nominal current and voltage is of 133V and 7,45A, respectively. By the project data inductance in the value of 1,08H/fase and armature resistance of 0,941 Ohm had been calculated determining a 6,5ms time constant. The engine theoretical efficiency was calculated in the value of 93,3%. With a 15kHz inverter keying frequency and the engine with nominal speed, inverter switch commutation is carried through in intervals of time in the order of 177μs and each switch will lead until 2,306ms. For the 6,5ms time constant this interval of current commutation per phase is very short. Thus it can be foreseen that the current will have a rising tax that may not allow to establish its maximum value before the next commutation.

III. MATHEMATICAL MODEL

The Figure 2 shows the windings and the involved magnetic flux in the electromagnetic conversion of energy.



(a) Involved magnetic flux (b) Mutual flux

Figure 2. Mathematical model

These flux can mathematically be represented through an inductance matrix. On the other hand, the currents that pass for the winding and produce the magnetic flux are controlled by the five-phase inverter. Therefore the mathematical model is constituted by the engine and inverter equivalent circuit, as shown in figure 3. Inverter's control must be such that provokes a resultant rotating flux in air-gap. For in such a way four phases simultaneously covered by currents. Thus each phase is established a ten-stage sequence for operation allowing each phase to lead for 72 electric degrees.

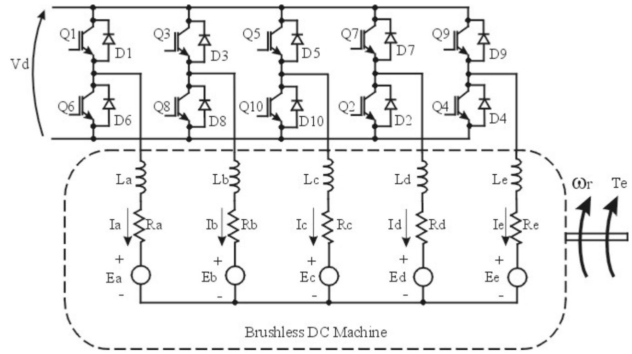


Figure 3. Five-phases IGBT power circuit

Each functioning stage is described for a system of equations, (1) by (7) for first step, for example, whose generalized form is given by (8). The electromechanical torque can be obtained from currents in each phase and engine speed using (9). In this equation the armature reaction is considered producing the distortion in the Electric Motive Force back (EMF-back).

$$\frac{d\ i_a}{d\ t}=\frac{1}{4\ L}\left(-4\ R\ i_a-3\ e_a^{'}+e_b^{'}+e_d^{'}+e_e^{'}+2\ V_S-4\ V_Q\right) \quad (1)$$

$$\frac{d\ i_b}{d\ t}=\frac{1}{4\ L}\left(-4\ R\ i_b+e_a^{'}-3\ e_b^{'}+e_d^{'}+e_e^{'}+2\ V_S-4\ V_Q\right) \quad (2)$$

$$\frac{d\ i_d}{d\ t}=\frac{1}{4\ L}\left(-4\ R\ i_d+e_a^{'}+e_b^{'}-3\ e_d^{'}+e_e^{'}-2\ V_S+4\ V_Q\right) \quad (3)$$

$$\frac{d\ i_e}{d\ t}=\frac{1}{4\ L}\left(-4\ R\ i_e+e_a^{'}+e_b^{'}+e_d^{'}-3\ e_e^{'}-2\ V_S+4\ V_Q\right) \quad (4)$$

$$\frac{d\ i_a}{d\ t}=\frac{1}{L}\left(-\frac{2}{3}e_a-R\ i_a\right) \quad (5)$$

$$\frac{d\ i_d}{d\ t}=\frac{1}{L}\left(\frac{1}{3}e_a-R\ i_d\right) \quad (6)$$

$$\frac{d\ i_e}{d\ t}=\frac{1}{L}\left(\frac{1}{3}e_a-R\ i_e\right) \quad (7)$$

$$\frac{d}{dt}\left[I_{adcde}\right]=\left\{\left[I\right]-\frac{M}{4\ L}\cdot\left[M_{abcde}\right]\right\}^{-1}\cdot\frac{1}{4\ L}\left\{-4\left[R\right]\cdot\left[I_{abcde}\right]+\begin{bmatrix}-3 & 1 & 1 & 1\\ 1 & -3 & 1 & 1\\ 1 & 1 & -3 & 1\\ 1 & 1 & 1 & -3\end{bmatrix}\cdot\left[E_{abcde}\right]+\left[VsVq\right]\right\} \tag{8}$$

Where:

$\left[I_{abde}\right]$ - armature current matrix

$\left[E_{abde}\right]$ - back-emf matrix

$\left[M_{abde}\right]$ - mutual matrix

$[VsVq]$ - transistor and diode drop matrix

$$T_e=\frac{1}{\omega(t)}\sum_{n=0}^{4}\left\{\left(K_V\left|\omega(t)\right|\Gamma_\omega\left(t-\frac{n}{5}2\pi\right)+K_a\left|i_n(t)\right|\Lambda_c\left(t-\frac{n}{5}2\pi\right)\right)i_n(t)\right\} \tag{9}$$

Where:

$T_e$electric torque

K_V speed constant

K_a torque constant

ω motor speed

Γ_ω EMF

Λ_c back - EMF

i_n phase n current

IV. TORQUE CONTROL

A control adjusted for drive of electric engine for automotive vehicles is the torque control. The diagram of blocks shown in figure 4 describes the closed loop. It is observed that the model considers non linearity produced by the mutual flux and the armature reaction, this last one through a table for the distorted EMF attainment.

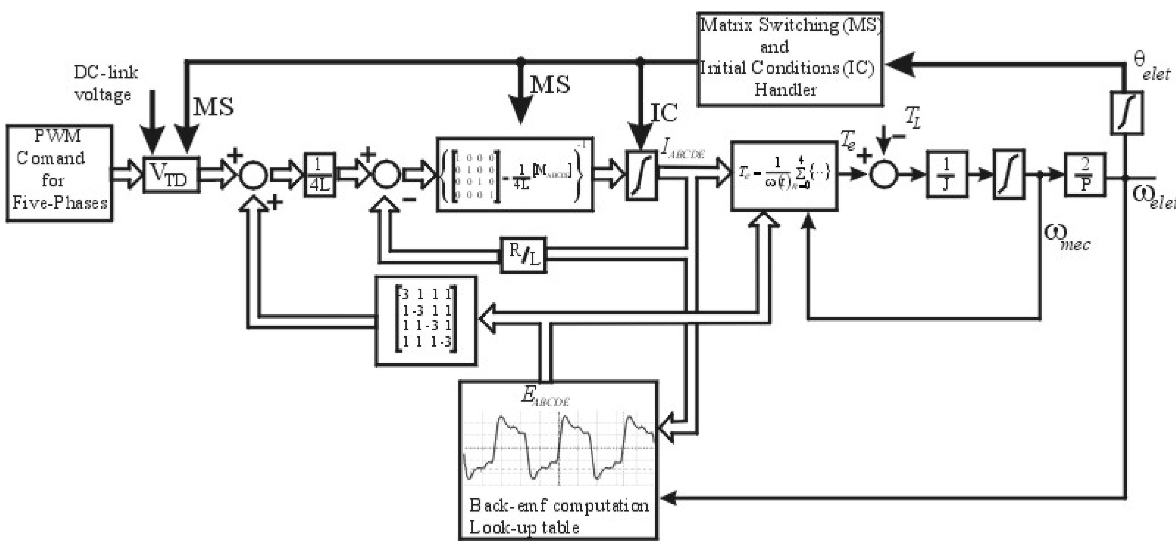
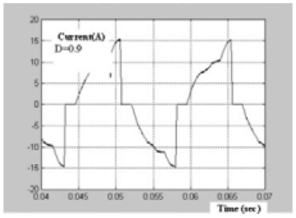


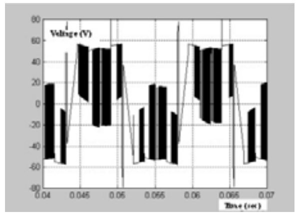
Figure 4. Block diagram for dynamic simulation in closed loop

V. SIMULATION RESULTS

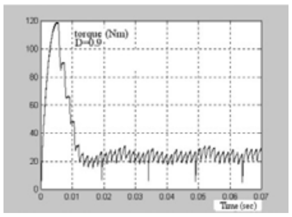
Using equations 1 and 2, SIMULINK/MATLAB simulation had been carried through and considering non linearity of the model in such a way for the mutual inductance as for the armature reaction. The results can be observed in figures 5 and 6 for open and torque control. In the first one a machine is operating with 70% of the nominal power. When in torque control the reference changes 10% to 70% of the nominal torque. The used controller is PI and the reply is satisfactory. As it was foreseen in the item II, from engine's characteristics, is also verified in the simulation that the current does not reach a maximum value, or either, the slope itself keeps constant for high speeds.



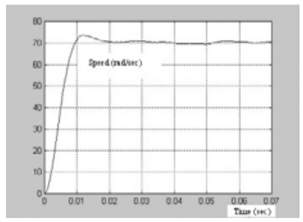
(a) Phase currents after steady-state



(b) Phase voltage after steady-state

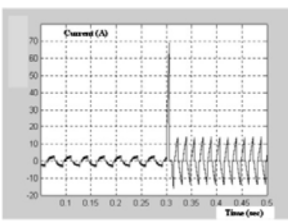


(c)Machine torque

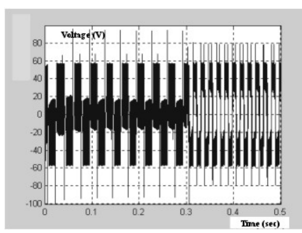


(d) Machine speed

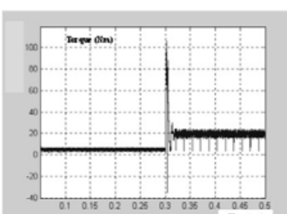
Figure 5. Wave forms for machine simulation



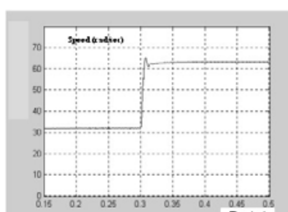
(a) Phase currents transient



(b) Phase voltage transiente



(c)Machine torque



(d) Machine speed

Figure 6. Closed loop behavior. An outer torque loop commands the machine operation

VI. IMPLEMENTATION

1) The Engine and its drive: To allow assay in workbench the five-phase engine was mounted in a support and connected to a DC engine through a continuous torque measurer, as it shows the figure 1(b). A speed measurer was connected to the axle for the DC-engine tip as it shows figure 7. A five-phase inverter with PWM of two levels operating in 15kHz was implemented and attached to a 140Vcc. To keep voltage bus in regeneration a *dynamic break* was implemented.

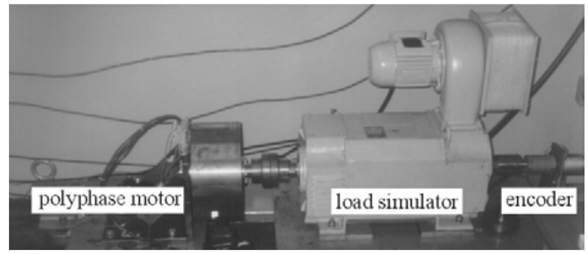


Figure 7. Encoder connected to the axle for the DC-engine (poly-phase motor)

2) Controlled Digital - The digital control plate implementation was developed through the insertion of a DSP development plate, from family 56800 of Motorola manufacture, in a plate with AD and DA converters and signal conditioners, this plate is shown in figure 8.

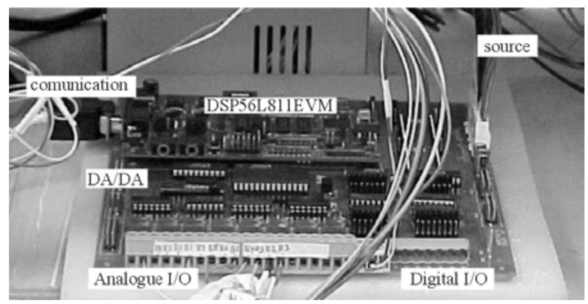


Figure 8. PCI EVM/ADDA evaluation

Basic programs as for example of reading and writing of data ones between the external devices and the DSP had been also developed. Control program structure is presented in figure 9.

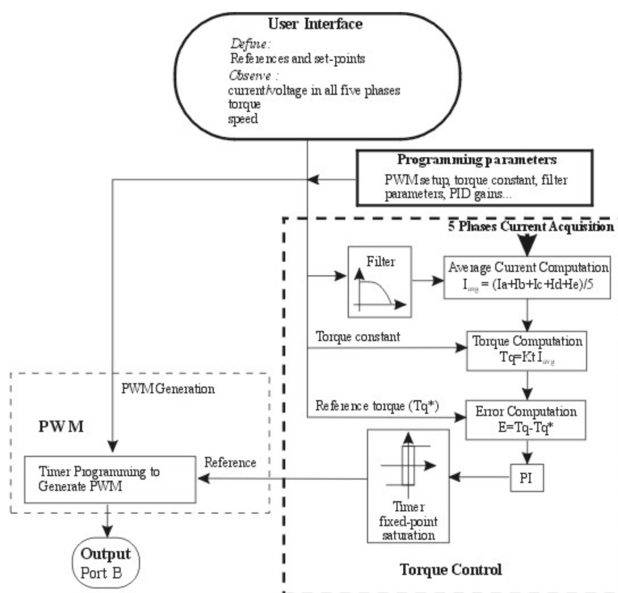


Figure 9. Torque control implementation structure

The used DSP56L811 processor operates in a 40MHz maximum frequency. Operating in this maximum frequency, the machine cycle is of 25ns; its internal architecture needs two cycles of machine to carry through an instruction, or either, in this operation frequency, its instruction cycle is of 50ns. Given the electric engines characteristics, where mechanical inertia is the predominant element in its dynamics, the necessary time for execution of the control mesh was considered the interval of 1ns.

VII. EXPERIMENTAL RESULTS

Through workbench for dynamic assays, shown in figure 7, dynamic tests in the five-phase engine had been carried out operating in open loop whose results they are presented in figure 10. In this figure the current versus the inverter cyclical reason for a constant speed is verified.

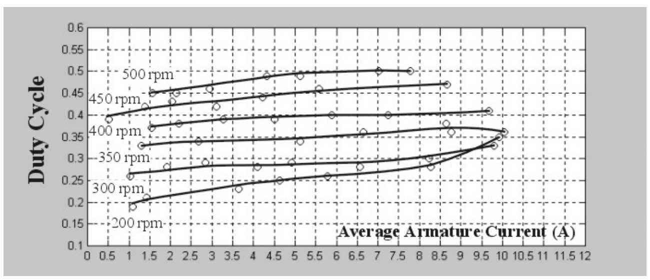


Figure 10. Open loop experimental evaluation of duty cycle relation with current

Constant speed in the five-phase engine axle is obtained by imposing DC-engine speed control. The five-phase engine torque loop is carried out through PI digital control. These torque loop results are satisfactory, as it can be observed in figure 11.

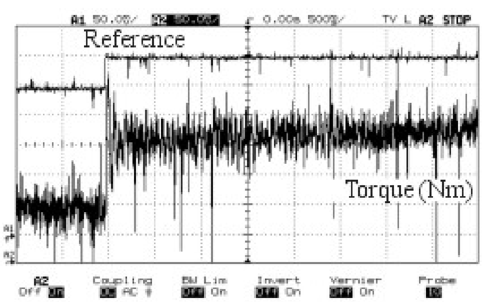


Figure 11. Step response for torque control

The five-phase engine phase-current waveform in low speed and torque is square, as it shows figure 12, and as foreseen in the theoretical study, it does not reach its maximum value for raised speeds and torque, as it shows figure 13.

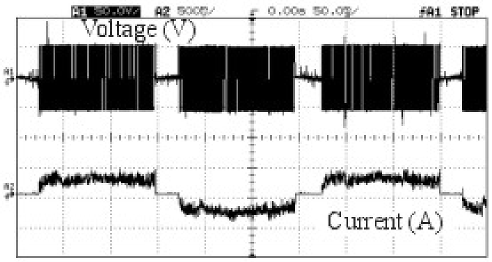


Figure 12. Terminal voltage and current for low torque level

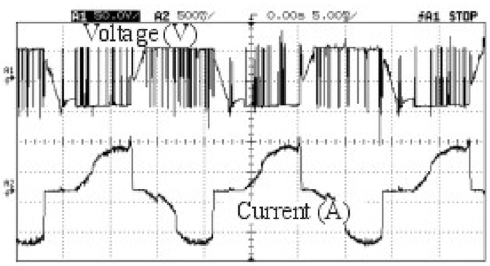
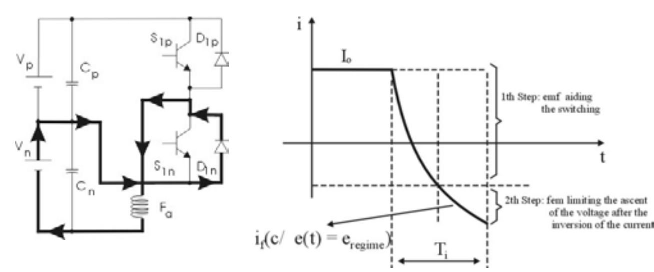


Figure 13. Terminal voltage and current for high torque level

VIII. ENGINE PERFORMANCE IMPROVEMENT AND EFFICIENCY

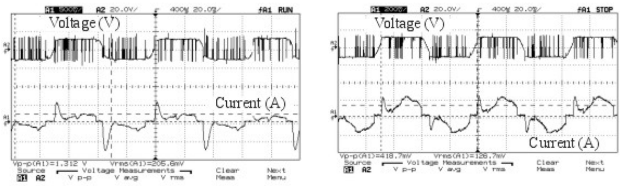
The rising current is related to the available instantaneous torque in the five-phase engine axle. Square phase-current waveform offer torque minor undulation and therefore it improves engine performance. Moreover the current rising limits the available power to the axle reducing the efficiency. To assist in the current rising and improve engine performance,, the digital program can anticipate the inverter's switch triggering in periods of time where the EMF values still are negative, as it shows figure 14.



(a) Freewheeling current (b) EMF effects in current

Figure 14. The current transient in switching

This offers to the circuit a short-lived additional voltage to the DC bus increasing current inclination. This triggering anticipation effect was implemented and its results can be verified in figures 15(a) e (b).



(a) Low torque (b) High torque

Figure 15. Improvement current wave form

III. CONCLUSION

A permanent magnet five-phase engine is presented to inlay in the wheel of electric vehicles. A dynamic mathematical model of the engine for open and closed mesh is developed. The simulation results of the voltage of phase, current, torque and speed of the engine are presented. The implementation validates simulation results. Digital torque control is implemented and reveals satisfactory. The current little efficient behavior theoretical forecast is confirmed. The solution to anticipate the switch triggering, through the digital control programming, to improve the current waveform, for raised speeds and torques, is proven.

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