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Chapter 13

DYNAMIC RESPONSE OF ELECTRIC MACHINES FOR ELECTRIC VEHICLES/HYBRID ELECTRIC VEHICLES (EV/HEV)

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ABSTRACT

This chapter presents some of the most common traction solutions used machine for electric vehicle/hybrid electric vehicle (EV/HEV) adopted by different car manufacturers. It also covers the dynamic response of the most used electric machines applied in EV/HEV. We describe three types of electric machines: brushed direct current machine (DC), brushless machine (BLDC) and induction machine (IM). The brushed DC machine presents the important disadvantage related to its maintenance cost. The need for brushes change after a certain period of time makes it very costly. Brushless machines do not have this maintenance cost related problem. . For the induction machine the cost of production and maintenance is the smallest among the three analyzed machines. Consequently, this type of electric machine is more fitted to be used than brushed or brushless DC machines. .

This chapter describes the behavior of three types of electric machines used nowadays in EV/HEV commercial vehicles. To compare these types of machines we developed a testing regime based on the experience of a driver facing all functional situations met. Thus, we took into consideration the rapid and slow start-stop regime, speed change regime and the backward movement of the vehicle. We have studied the behavior of the three types of machines using these testing regimes. In spite of their advantages and disadvantages of one versus the others, these types of electric machines are all used nowadays in the prototypes and commercial EV/HEV.

Keywords: Electric Machine, Electric Drive, Electric Vehicle, Hybrid Electric Vehicle, DC Machine, Induction Machine, Brushless Machine, Dynamic Regime

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1. INTRODUCTION

Nowadays, there is a great interest in the field of EV/HEV. Many car companies develop solutions for EV/HEV both commercial as prototypes still under investigation. These solutions include different types of electric machines (DC, brushless, induction, synchronous, etc.). However, these machines present advantages and disadvantages and there has not been adopted a standardized unique solution adopted yet.

These solutions are available today on EV/HEV market [1,2]:

- DC machine: PSA Peugeot-Citroen/Berlingo
- Induction machine: GM Silverado ISG, Continental ISAD, Delphi-Automotive ISG, Valeo ISA, Renault Kangoo, Chevrolet Silverado, BMX X5
- Brushless permanent magnet machine: Honda Insight and Civic mild hybrids, FCX-V3 FCEV; Mannesman-Sachs
- Synchronous machine: Toyota Prius, Estima, Ford Hybrid Escape, Nissan Tino, Honda Insight

The electric drive is an essential part in the EV/HEV structure. In order to ensure the desired capabilities of a vehicle, the traction sub-ensemble has to fulfill certain characteristics given by the electric drive system which includes the electric machine.

It is known that electric machines are manufactured in a variety of configurations and that they are able to drive all kind of industrial applications. Theoretically, any kind of electric machine could be used to drive EV/HEV, yet the car companies focused on some specific electric machines that proved to provide advantages over the others.

The electric machine for EV/HEV needs to have various specific characteristics related to the different functional regimes: acceleration, braking, very fast change in the functional regime, capability of developing very low and also very high speeds, frequent starts and stops, good proportion between mass and volume, robustness, functionality and low maintenance cost, etc. [3]. The mechanical characteristics for electric machines used for EV/HEV are presented in Figure 1.

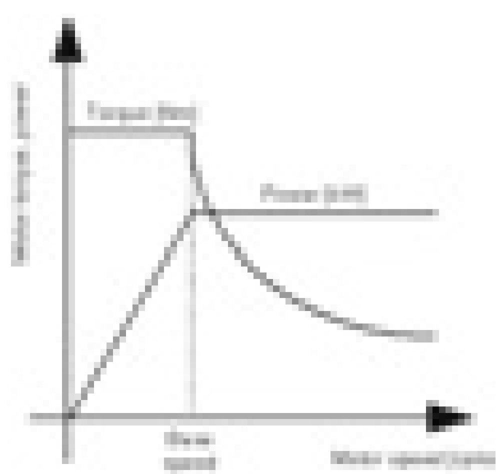


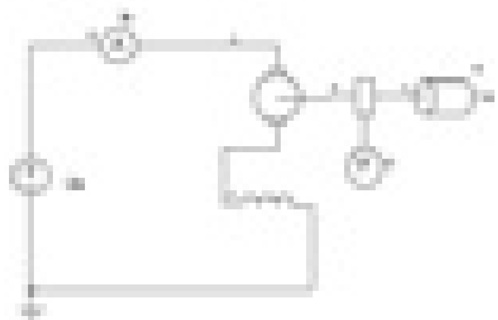
Figure 1. Typical Performance Characteristics of Electric Machine for Traction [4].

In this chapter we present some of the most common electric machines for EV/HEV adopted by different car manufacturers. We also describe the dynamic response of the best know electric machine used in EV/HEV, and we end by comparing the studied electric machines.

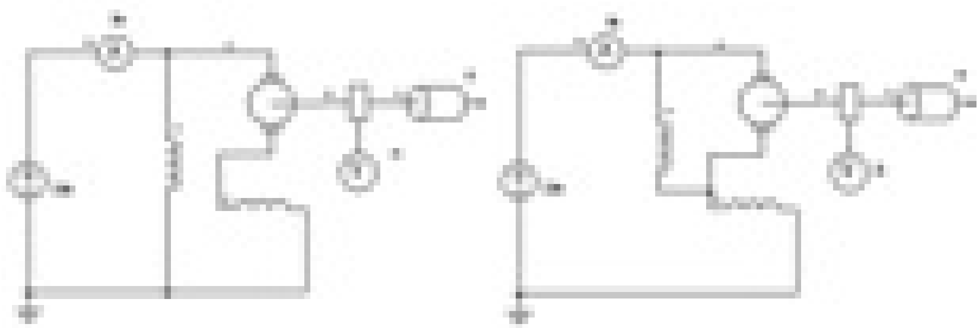
2. Electric Machines Used in EV/HEV

2.1. The DC Machine

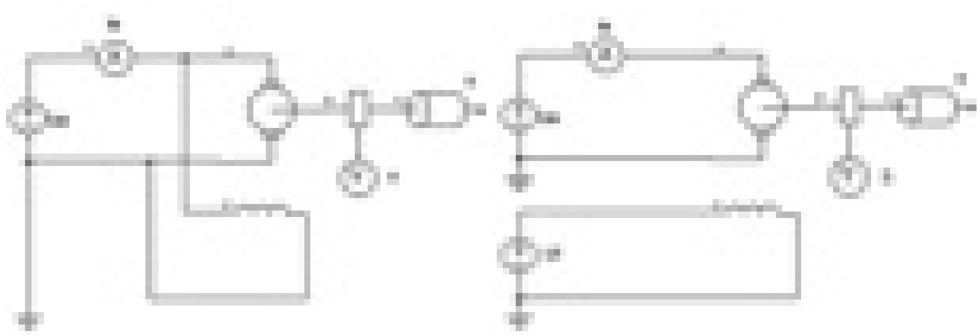
There are four constructive types of DC machines, depending on the excitation field: series, independent, shunt and compound. The DC permanent magnet machine falls in the category of independent field excitation machines. The constructive type depends on the way the winding field is connected to the winding armature shown in Figure 2.



(a) Series connection [6]



(b) Compound connection



(c) Shunt connection

Figure 2. DC machines configurations.

The use of DC machines in electric traction is not novel. The most used DC electrical machines in traction applications are the series excitation winding, due to their mechanical characteristics that allows a smooth start with a large resistive torque. Even though the behavior of the DC machine is well known and well covered in the literature, there is still interest in developing new functional regimes. The ideal traction machine should have both the characteristics of series field connection (for starting regime) and of the shunt connection (for regenerative braking and speed control). Such behavior should improve the EV/HEV functionality and the battery use [5].

2.1.1. Mechanical Characteristics

The steady state equivalent circuit of the DC machine is indicated in Figure 3, and it is widely covered in the technical literature.

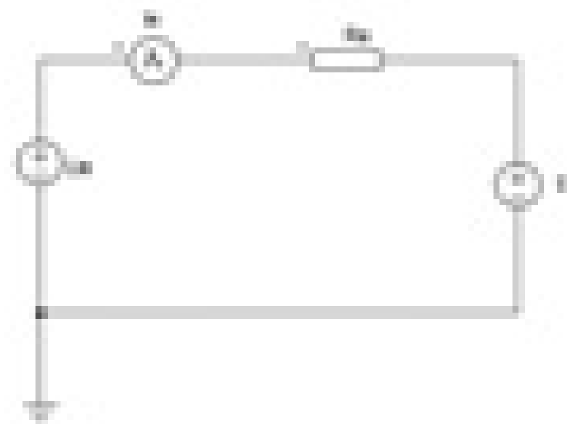


Figure 3. Equivalent circuit for DC machines.

The basic equations, using the standard notations that describe the steady state functional regime of a DC machine, are as follows:

$$\begin{cases} U_A = R_A \cdot I_A + E; \quad E = K \cdot \Phi \cdot \Omega \\ T = K \cdot \Phi \cdot I_A \end{cases} \tag{1}$$

where R_A - armature resistance, I_A - armature current, T - developed torque, Φ - field excitation, K - machine constant, Ω - rotor angular speed.

The relation between the rotor angular speed and the developed torque T is derived from the Equation(1), represents the mathematical form of the mechanical characteristic:

$$\Omega = \frac{U_A}{K \cdot \Phi} - \frac{R_A}{(K \cdot \Phi)^2} \cdot T \tag{2}$$

The Equation (2) refers to all types of DC machines, and the graphical representation is indicated in Figure 4.

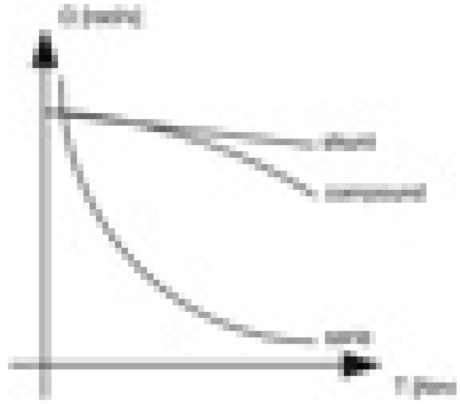


Figure 4. DC machines' mechanical characteristics.

Before development of power electronic devices, the DC series machine was the only fitted for electric traction applications, due to its mechanical characteristic, such as: development of high rated torque values for low values of speed. Even though this special characteristic is very important for electric traction vehicles, the use of DC series machines has its limitations, especially because the speed rises as the torques values decrease.

Nowadays, when power electronics and numerical control developed very much, manufacturers overcame the past limitation of using DC shunt machine for EV/HEV applications. Due to the modern drive systems, they combined the ease in controlling the DC independent/shunt connection machines and the advantages of DC series connection machines.

Analyzing the Equation (2) for DC shunt machines, there are several functional regions that could be defined as indicated in Figure 5:

- Nominal functionality
- Below nominal functionality
- Above nominal functionality

The "nominal mechanical characteristic" is obtained when the machine functions at the nominal parameters. The point in Figure 5 represents the Static Operating Point (SOP) when the voltage and torque are at nominal values.

The "below mechanical characteristic" is obtained by varying the armature voltage. The point in Figure 5 represents the SOP when applied voltage is below the nominal value. The "below mechanical characteristic" is characterized by lower speed comparing to the nominal value. The mechanical characteristics are parallel to the nominal. When the machine works at low and very low speed, the ventilation is lower and the temperature of the machine rises. Thus when working at this parameters, cooling of the machine should be taken into consideration.

The "above mechanical characteristic" is obtained by varying the field voltage. The point in Figure 5 represents the SOP when applied voltage is above the nominal value. The "above mechanical characteristic" is characterized by higher speed comparing to the nominal value. The mechanical characteristics are not parallel to the nominal. The load capacity of the machine is lower than the nominal and below nominal mechanical characteristics. Thus, when working at these parameters, the load capacity has to be taken into consideration.

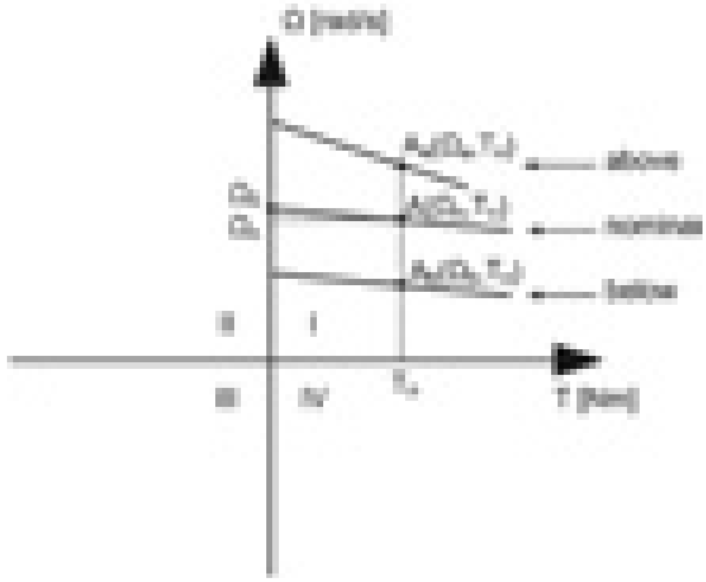


Figure 5. Mechanical characteristics for shunt DC machines.

2.1.2. Chopper Control of DC Machines

The chopper control is not the only controlling method by which the speed of a DC machine can be varied. A different method of speed control is by adding supplementary resistors. Because of energetic consideration, this method is not appropriate for EV/HEV, and therefore it is not covered in this chapter.

The variation of speed for the machine can be controlled by variation of the field voltage variation. This method is not covered in this chapter.

2.1.2.1. Chopper Control for Single-Quadrant DC Functionality

The control of the armature voltage applied to the DC machine can be obtained by the use of chopper control techniques.

The generic chopper schematic consists in a power electronic switch connected in series with the DC machine, like in Figure 6.

The power source has constant value V, which in case of an EV/HEV is provided by the main battery. The voltage is applied to the DC machine through the power electronic switch PES. The free regime diode (FRD) ensures power dissipation from the machine while PES is open.

In the duty period of time $0 < t < \delta T$, the PES is closed and the source voltage is applied to the machine. In this period of time, the current rises from the minimum value $I_{A\_\min}$ to the maximum value $I_{A\_\max}$. In the freewheeling period of time $\delta T < t < T$, the PES is open and no voltage is applied to the machine. In this time interval the current falls from the maximum value to the minimum value $I_{A\_\min}$. The FRD ensures the electric current while the PES is open, thus improving the current waveform.

2.1.2.2. Chopper Control for Multiple-Quadrant DC Functionality

The problem of the indicated schematic in Figure 6 is that the DC machine functions only in one functionality quadrant. For EV/HEV the DC machine has to be able to operate in all four functionality quadrants.

In order to obtain this, a generic schematic for the chopper is used in Figure 7. All PES are closed and opened alternatively PES1 + PES3 and PES2 +PES4 in order to ensure full functionality of the DC machine for all four quadrants. FRDs also work in groups of two depending of the working quadrant of the DC machine.

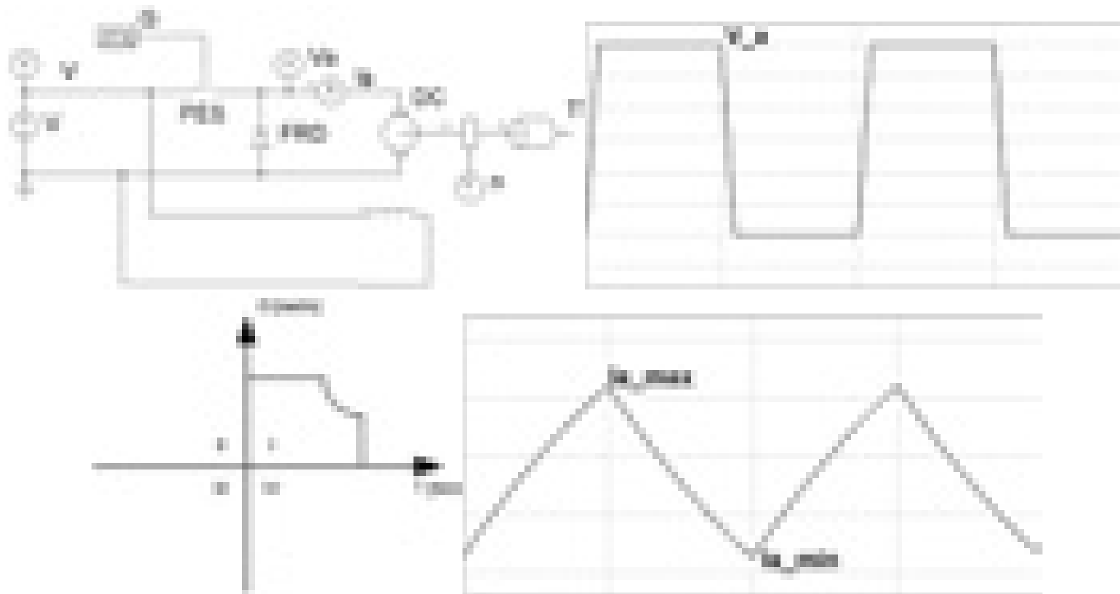


Figure 6. Single-quadrant DC machine chopper drive.

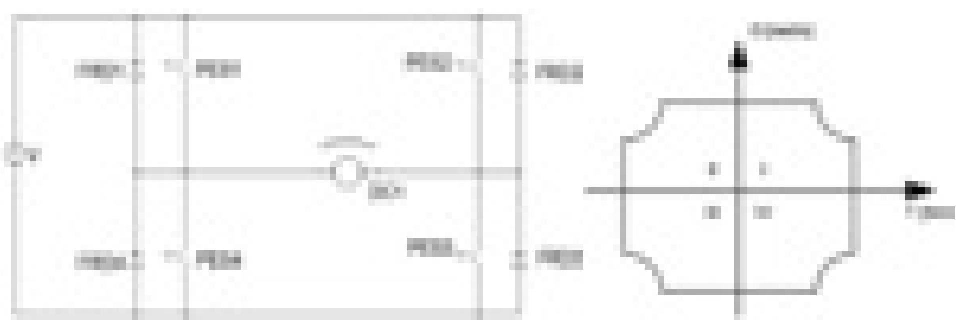


Figure 7. Four quadrant DC machine chopper drive.

2.1.2.3. Driving System of Chopper Controllers for DC Machines

Either for single-quadrant or multiple-quadrant functionality of DC machines, the driver is a closed loop system that controls both the current and speed.

The schematic of closed loop control of shunt DC machine is indicated in Figure 8.

In Figure 8, the is the current transducer and the is the speed transducer. The R_w and R_{Ia} are the speed and current regulators placed in the speed and respectively current closed control loops. The measured current and speed are compared with the prescribed values and the result is applied to the respective regulator. The output signal of the current regulator, is the G command signal for the PES. Thus the voltage level applied to the machine armature is obtained.

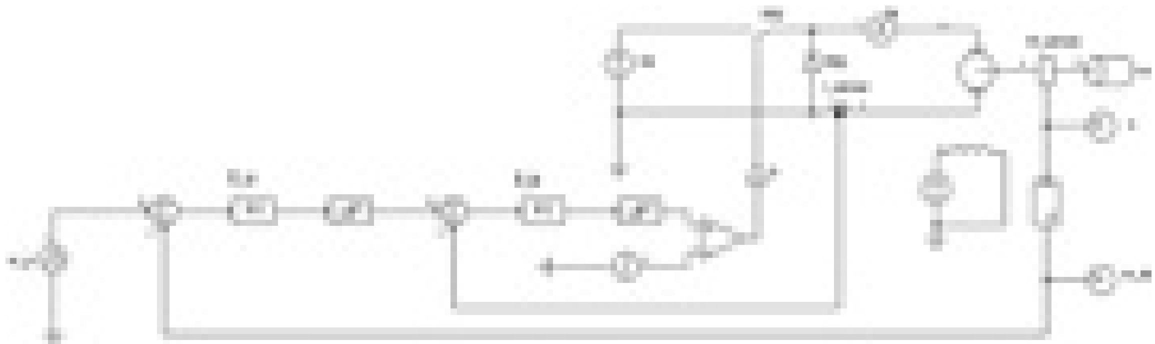


Figure 8. Schematic for a drive system for chopper controllers for DC machine.

2.2. Induction Machine

There are two types of induction machines: squirrel cage (short circuit rotor) and wounded rotor.

Because of their high maintenance cost due to brushes, the wound-rotor induction machines are not as convenient as the squirrel cage induction machines for EV/HEV applications.

The squirrel cage induction machines have a simple construction and thus their fabrication and maintenance cost is lower comparing with other types of electric machines.

One disadvantage of the induction machines is the difficulty of controlling in closed loop systems. Sometimes the controller is more expensive than the machine, making these machines difficult to integrate in variable speed applications. However, these difficulties were overcome by the evolution of power devices and industrial computing.

2.2.1. Mechanical Characteristics

In order to determine the functional characteristics of the induction machine, its equivalent schematic is used in the specialized literature. This is indicated in Figure 9.

In Figure 9, the U_s, I_s, R_s, and L_s are the stator quantities of voltage, current, resistance and inductance. The I_r', $\frac{R_r'}{s}$, and L_r' are the rotor quantities of current, resistance and inductance reported to the stator. The rotor slip is s, which indicates the delay between the angular speed of the stator field and the rotor angular speed defined as:

$$s = \frac{\omega_1 - \omega_2}{\omega_1} \tag{3}$$

where ω_1 is the synchronous speed (the speed of the inductor field), ω_2 is the rotational rotor speed and p the number of pole pairs.

Analyzing the equivalent schematic, the Kloss relation indicates the relation between the torque and slip speed, is approximated by:

$$\frac{T}{T_{cr}} = \frac{2}{\dfrac{s}{s_{cr}} + \dfrac{s_{cr}}{s}} \tag{4}$$

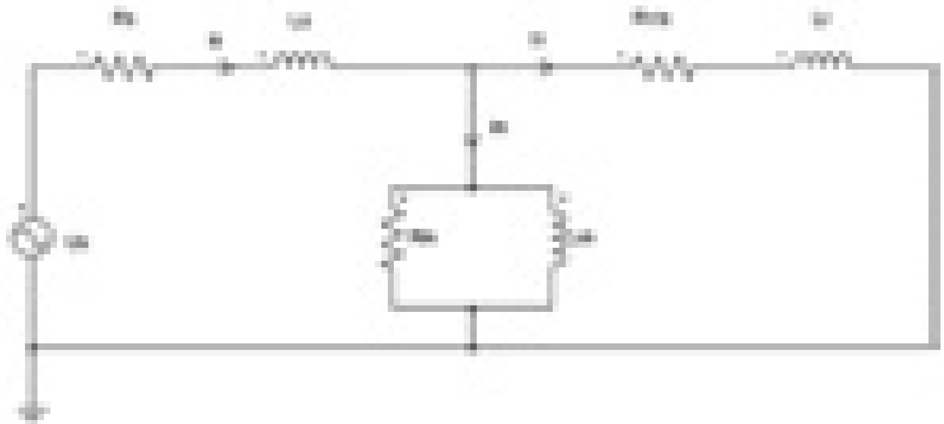
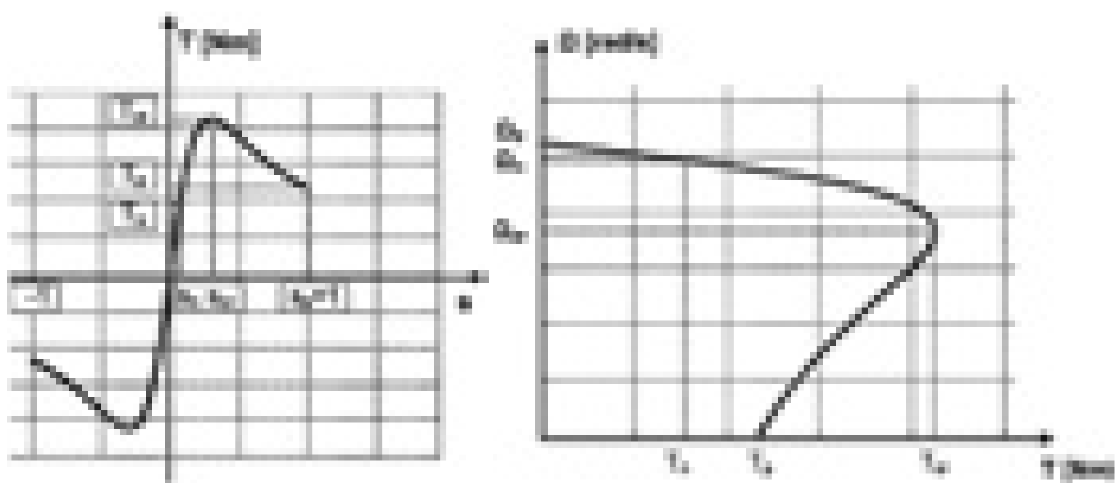


Figure 9. The equivalent schematic of induction machine.

In the Equation (4), T_{cr} and represents the critical torque and respectively the critical slip speed, while and s represents the torque and slip speed at certain functional conditions.

From Equation (4) we obtain the mechanical characteristic for the induction machine, displayed in Figure 10.



(a) (b)

Figure 10. Mechanical characteristic of induction machines for U, f constant control, (a) $T = f(s)$, (b) $\Omega = f(T)$.

As mentioned above, Figure 10 presents the mechanical characteristic of an induction machine when the supply voltage and frequency are constant. It can be observed that the starting torque of the induction machine has low values and the speed variation is very small with the load variation. When the induction machine is operated, the stable functional domain is when $s < s_{cr}$. This domain is very narrow and therefore the speed can vary in a very limited domain. For the EV/HEV applications, this behavior is not acceptable.

2.2.2. Control of Induction Machines for Constant U/f

In the domain of constant *U/f* the induction machine behaves similar with DC machines. The mechanical characteristics of its control are indicated in Figure 11.

The "nominal mechanical characteristic" is obtained when the machine functions at nominal parameters. The point in Figure 11 represents the Static Operating Point (SOP) when all physical quantities applied to the machine are at nominal values.

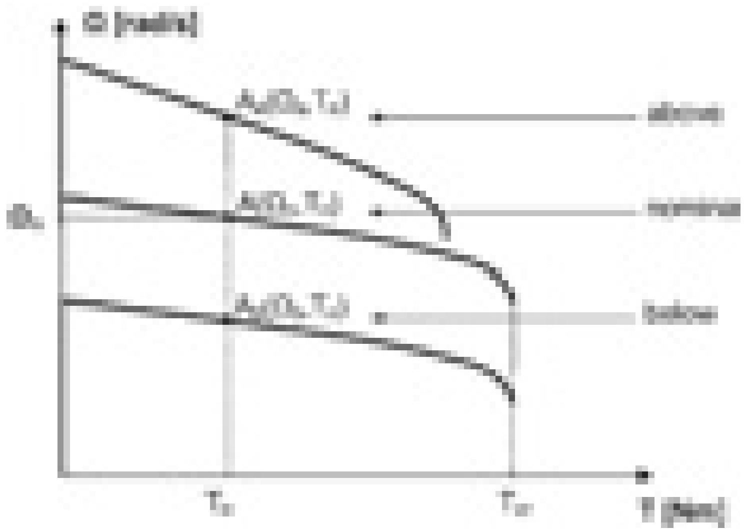


Figure 11. Mechanical characteristics for *U/f* constant control.

The "below mechanical characteristic" is obtained by varying the supply voltage and frequency so that *U/f* is maintained constant. The point in Figure 11 represents the static operating point (SOP) when the applied voltage and frequency are below the nominal values. The "below mechanical characteristic" is characterized by lower speed compared to nominal value. The below mechanical characteristics are parallel to the nominal. When the machine is working at low and very low speed, the ventilation decreases and consequently its temperature rises. Therefore when working at these parameters, machine cooling has to be taken into consideration.

The "above mechanical characteristic" is obtained by varying the frequency of the supply voltage. The value of the voltage is maintained constant at the nominal value. The point in Figure 11 represents the static operating point (SOP) when the applied frequency is above the nominal value. The "above mechanical characteristic" is characterized by higher speed than the nominal. The mechanical characteristics are not parallel to the nominal. The load capacity of the machine is lower than the nominal and below nominal mechanical characteristics. Therefore, when working at these parameters, capacity load has to be taken into consideration.

2.2.3. Driving System of U/f Controllers for Induction Machines

The *U/f* controller consists of 6 PESs, displayed in Figure 12. These PESs ensure that the source voltage is applied to the stator windings of the induction machine IM. The PESs are commanded with signals provided by three comparators. The command signal is obtained by comparing the 3ph sinus voltage provided by $U_{\sin}$ with the triangular signal provided by U_{tri} .

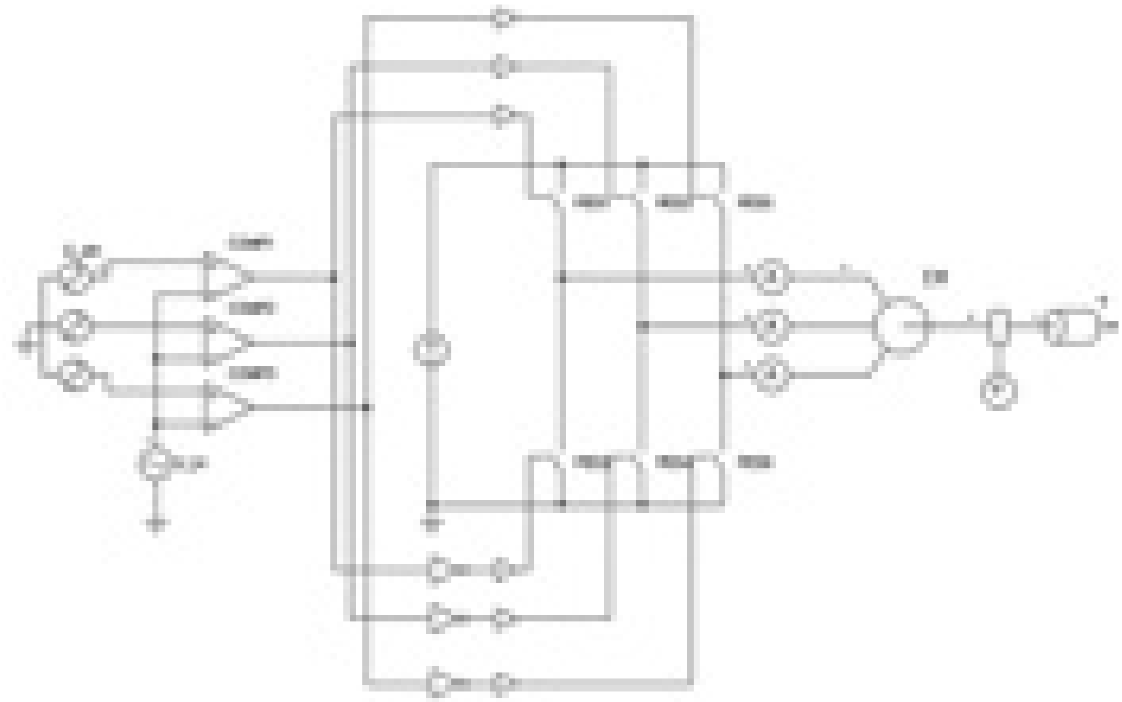


Figure 12. Schematic for a *U/f* constant controller drive system of s for induction machines.

The PES1…6 are power electronic switches that could be of different types, depending on the power of the machine, and consequently on the absorbed current. The groups of PES1,3,5 and PES2,4,6 are closed alternatively depending on the output signal of COMP1-3. When the sinusoidal voltage the output signal $COMP_1 > 0$. When the output signal $COMP_1<0$ (Figure 13).

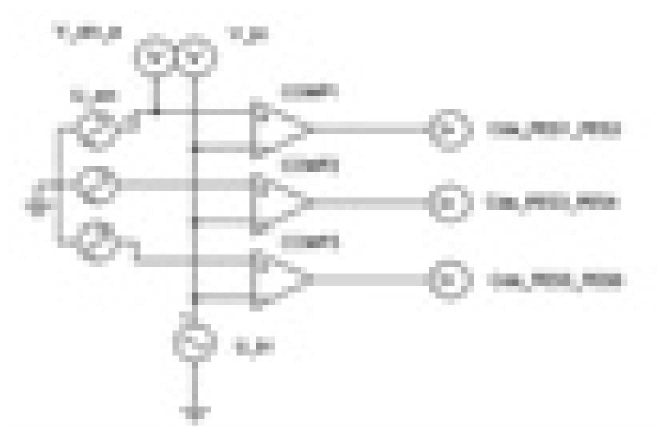


Figure 13. (Continued)

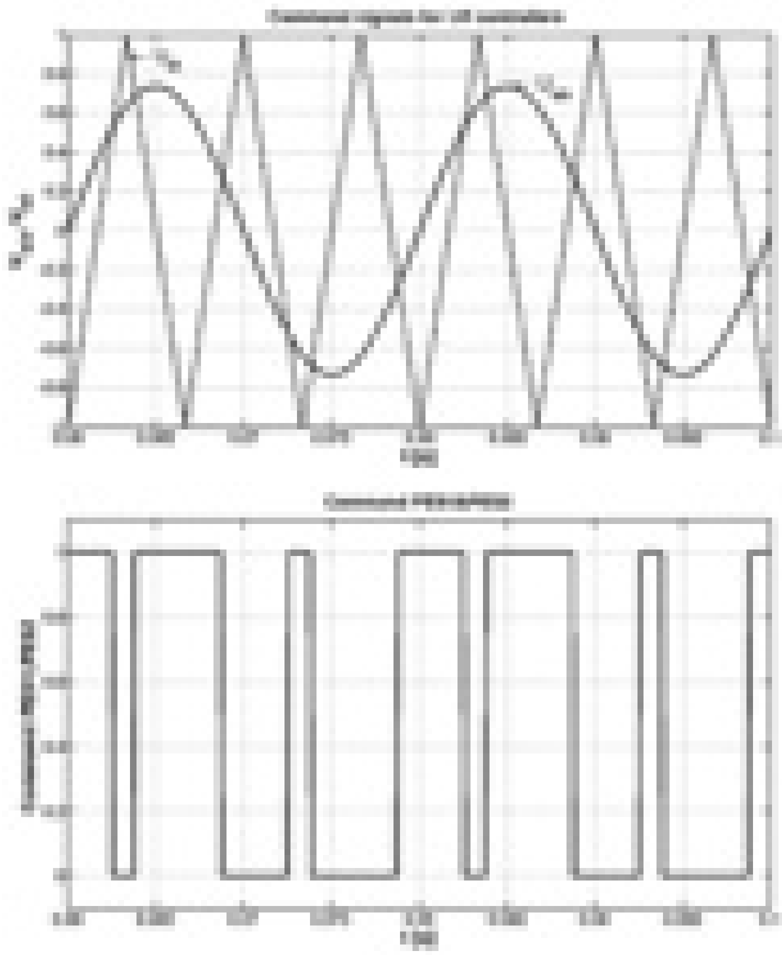


Figure 13. The schematic of command circuit of *U/f* constant controllers for induction machines

Depending on the polarity of signal either PES1 or PES2 conducts providing maximum or minimum values of the voltage supply applied at machine's phases, obtaining the alternating current values in its windings.

2.3. Brushless Machine

Regarding construction principles, brushless (BLDC) machines are similar to the permanent magnet synchronous machines. The similarity between brushless machines and synchronous machine lies in the fact that both magnetic fields produced by the stator and the rotor rotate at the same frequency.

In a brushless machine, the stator windings' configuration is similar to that of poly-phase AC machines, especially to the induction machines. However, the winding configuration is distributed differently.

The structure of the rotor of a brushless machine contains one or more permanent magnets, and can vary from 2 to 8 pole pairs.

The brushless machines are manufactured in 2-phase or 3-phase configuration, although the 3-phase is wider spread in industrial applications.

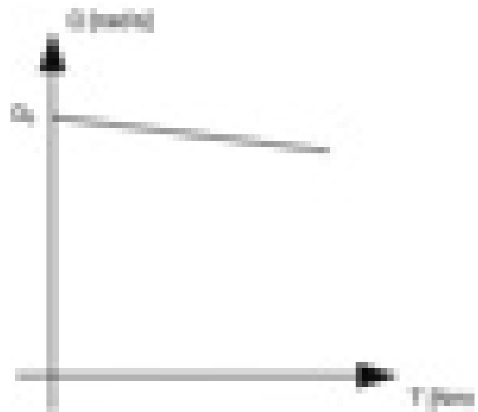


Figure 14. Mechanical characteristic of BLDC machines.

Compared to the brushed DC machines, the BLDC present some important advantages, such as:

- Easier cooling due to windings placement in the stator
- Lower maintenance cost due to the lack of brushes
- Higher efficiency, as the Joule loses are lower than the corresponding DC brushed permanent magnet machine due to the windings placement in the stator

2.3.1. Mechanical Characteristics

In the technical [7] and scientific [8] literature, it is considered that the mechanical characteristic of BLDC is very similar with the brushed DC machines.

Analyzing the mechanical characteristic of BLDC machine, it can be stated that its behavior is similar with the brushed DC machine. At starting the machine develops a high peak torque, which leads to a high peak current.

2.3.2. Control of Brushless Machines

The brushless driving system contains six PES controlled by a Gate Command System (GCS). The GCS block receives signals from the machine and the imposed speed ω*. Based on the input signals, the GCS forms the command signals for the PES1-6 that drives the machine. Both the electronic system GCS and PES1-6 function as an electronic commuter which drives the machine. In traction applications, the speed control for brushless machine raises a special interest [7].

Figure 16 displays some waveforms that appear in a driving schematic of brushless machines. Figure 16(a) indicates the currents waveforms. Depending on the inertia of the machine and the resistant torque at the shaft, the current of the machine at starting has a high peak value.

The CGS block forms the command signals for the PES1÷6 indicated in Figure 16(c). The inputs of CGS are the machine currents, feedback signals and the output of a PI speed regulator.

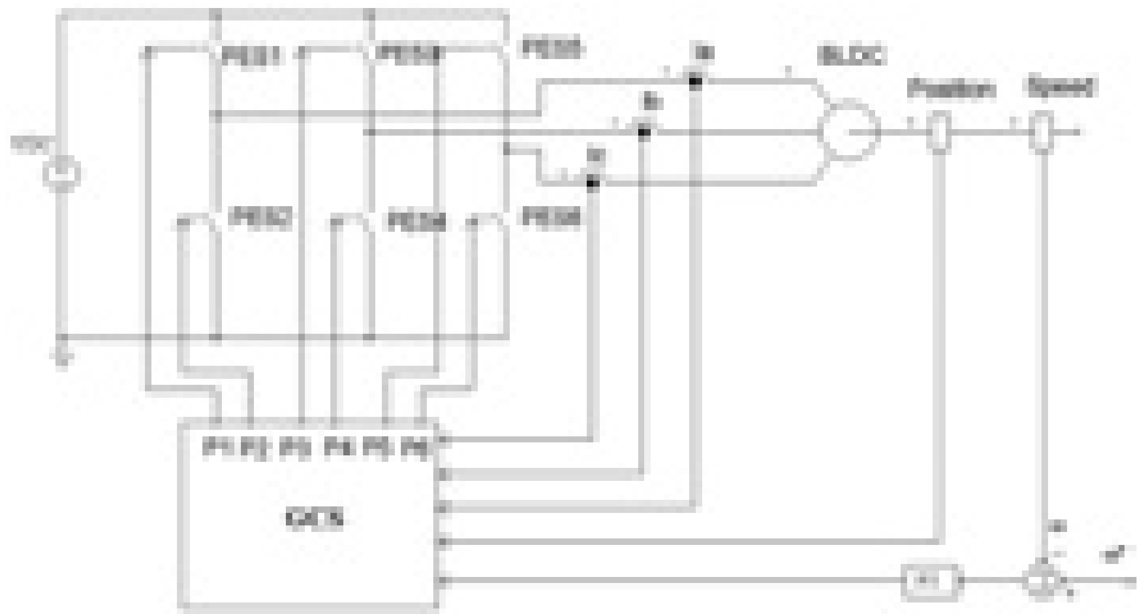
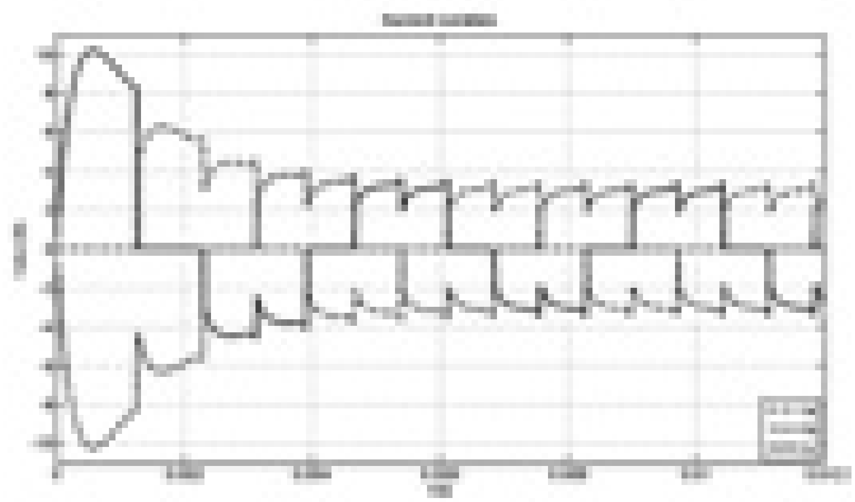
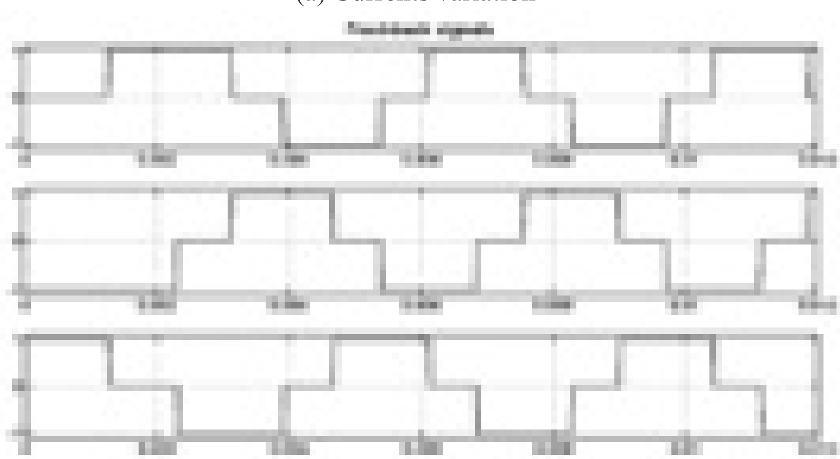


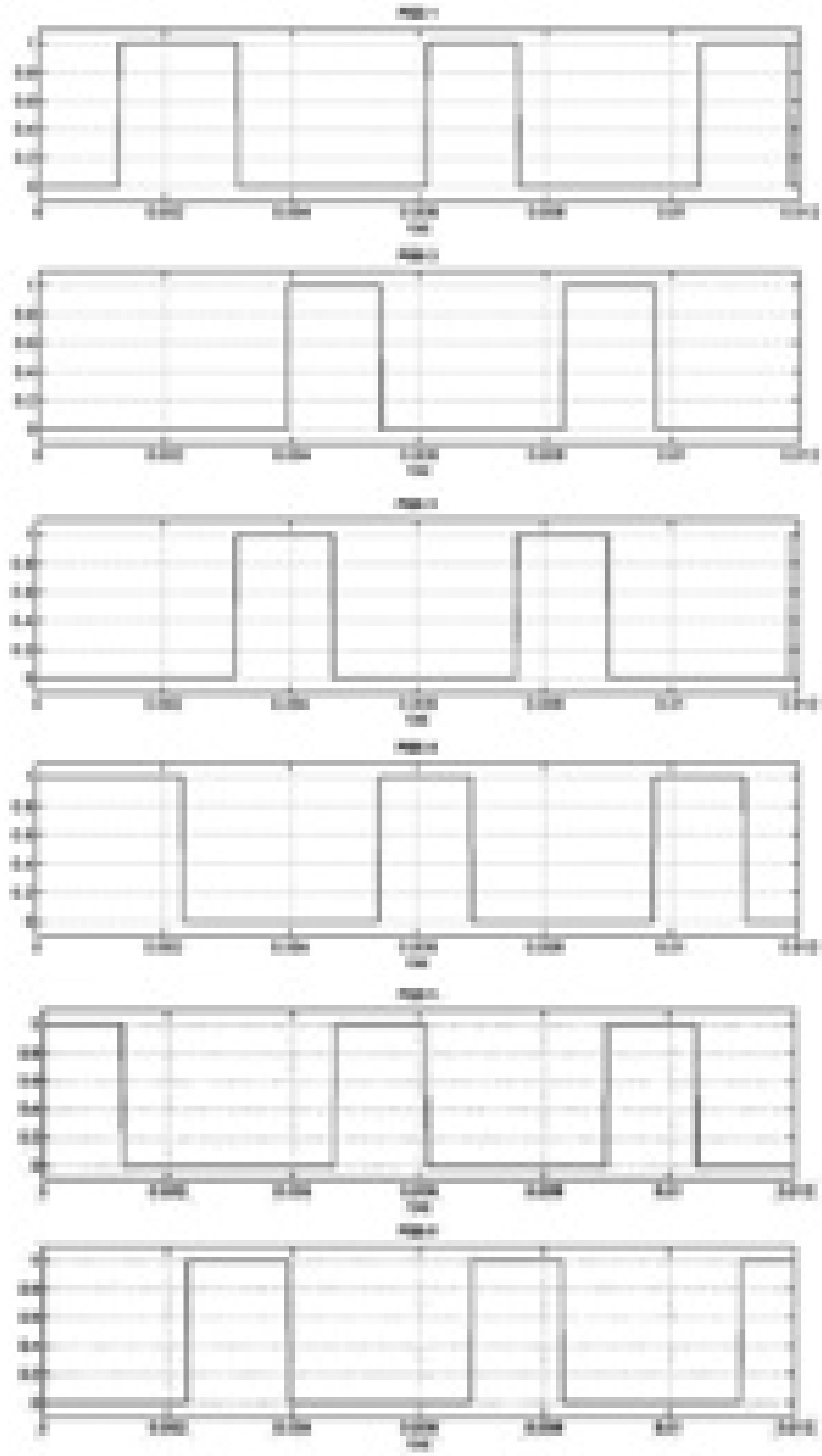
Figure 15. Driving system schematic for a brushless machine.



(a) Currents variation



(b) Feed-back signals



(c) PES command

Figure 16. Waveforms in the driving circuit of brushless machine.

3. Dynamic Regime of Electrical Machines Used in EV/HEV

In EV/HEV the functional regime of the electric traction machine could be of two types:

- transient or dynamic
- stable

The dynamic regime for EV/HEV has some particularities compared to the industrial applications. In the normal use of a vehicle, various situations can occur consisting in: acceleration, braking, very fast change in the functional regime, capability of developing very low and also very high speeds, frequent starts and stops etc [9].

For the purpose of comparison between different types of electric machines used nowadays for EV/HEV, a speed profile was created to be applied to each type of machine (Figure 17).

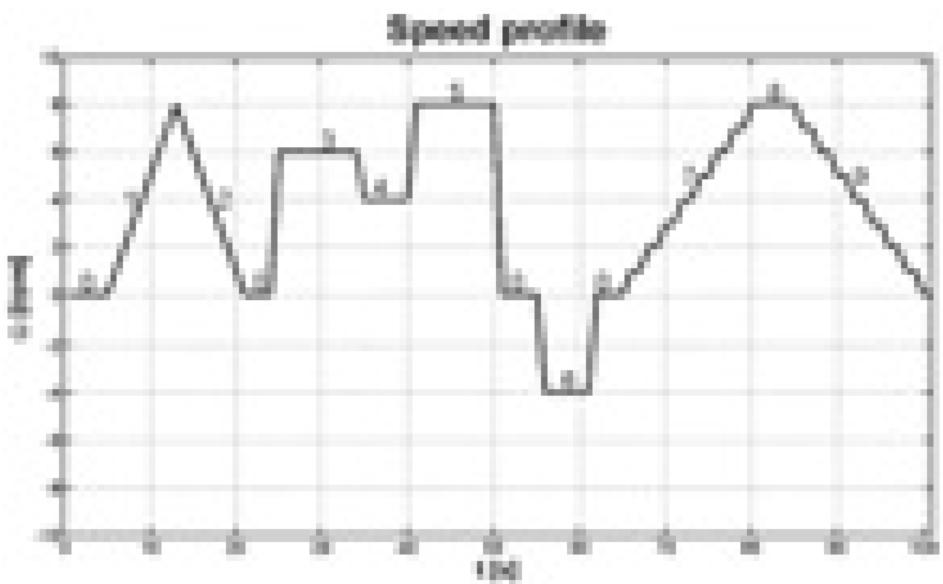


Figure 17. Testing speed profile.

The following notations are used in Figure 17:

- 0 periods of time when the vehicle is stopped
- 1, 2 rapid variation of speed
- 3, 4, 5, 8 stable speed regime when the vehicle is moving forward
- 6 stable speed regime when the vehicle is moving backward
- 7, 9 slow speed variation

The speed variation situations presented above are intended to simulate several functional regimes most likely to appear during the use of a real vehicle. The 1 and 2 could be speed regimes likely to appear at the traffic light crossroads. Situations 3, 4, 5, 8 could be various levels of speed cruise, while 6 is moving backward. Situations 7, 9 are likely occur while starting/stopping the vehicle. The transition 0-3 simulates very rapid starting, while 3-4-5 simulates rapid braking and accelerating situations. The 5-0 simulates a dangerous situation when a very rapid stopping of the vehicle is needed. The situation simulated by 3-4-5 could very easy be a cruise situation, when a rapid increase of speed is needed for overtaking other vehicle. All these transitory regimes are very common in daily driving, especially when using vehicles in crowded urban areas. For the experimental data, we applied the same resistant torque at the shaft to the analyzed machines: DC, induction and brushless.

Nominal data of the machines are indicated in Table 1.

Table 1. Nominal data of tested machines

DC machine	Induction machine	BLDC machine
U_{An} = 220 V c.c.	U_n = 230/400 V	M_0 = 2.6 Nm
I_A = 2 A,	I_n = 3,5/2,1 A	M_{max} = 13 Nm
I_{field} = 0,2 A	f_n = 50 Hz	I_0 = 4.2 A
n_n = 1.500 rpm	P_n = 1 CV = 0.735 kW	I_{max} = 21 A
P_n = 0.373 kW	n_n = 1500 rpm	n_n = 4000 rpm

3.1. DC Machine

The DC machine functions in a closed loop control speed schematic. The schematic contains also a subordinate current control loop. In order to accurately function, the driver should be set before use and the most appropriate configuration for current and speed regulators should be chosen. The procedure of setting up the DC machine's driver is presented in previous works of the authors [10,11]. Briefly, this procedure consists in adjusting the values for the current and speed regulators' parameters to obtain the most appropriate behavior in the transient regime.

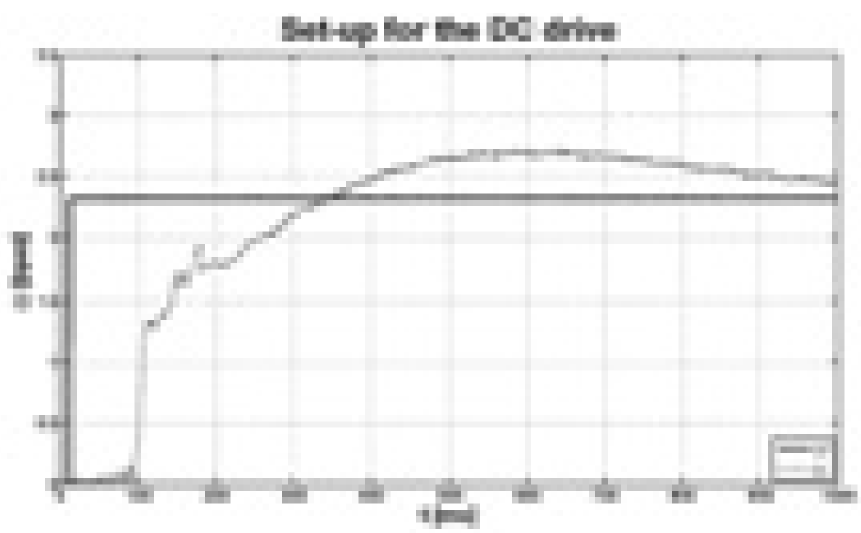


Figure 18. (Continued)

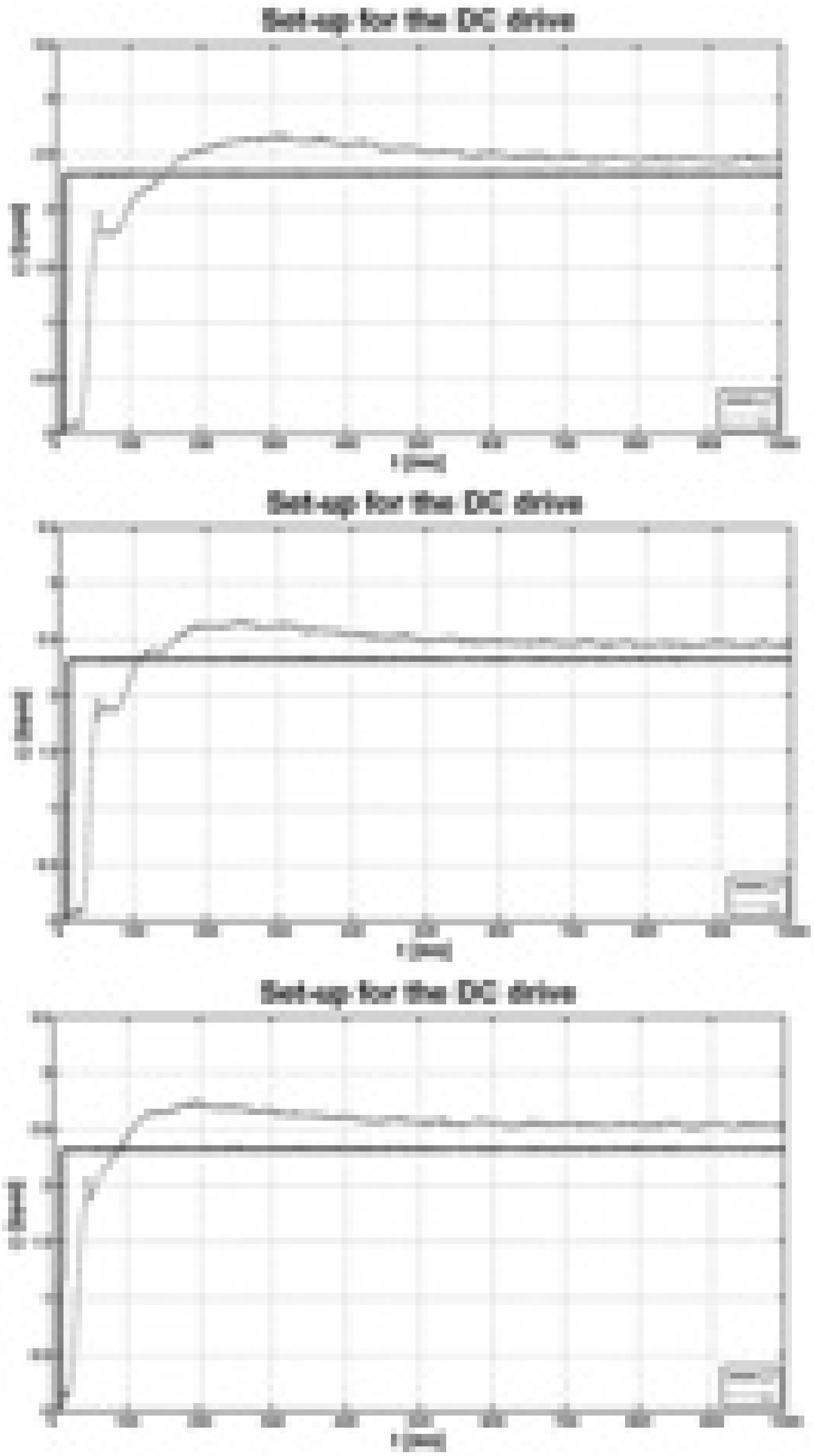


Figure 18. Set-up of DC machine driver control loops.

Figure 18 represents the excitation speed signal and the acquired output speed signal for various configurations of the driving schematic. During the parameter adjustment, different improved output signals are obtained. The best configuration of the driver is the one that provides the quickest answer from the machine. The best response is a compilation of the time delay, the override output signal and the delay of the steady state.

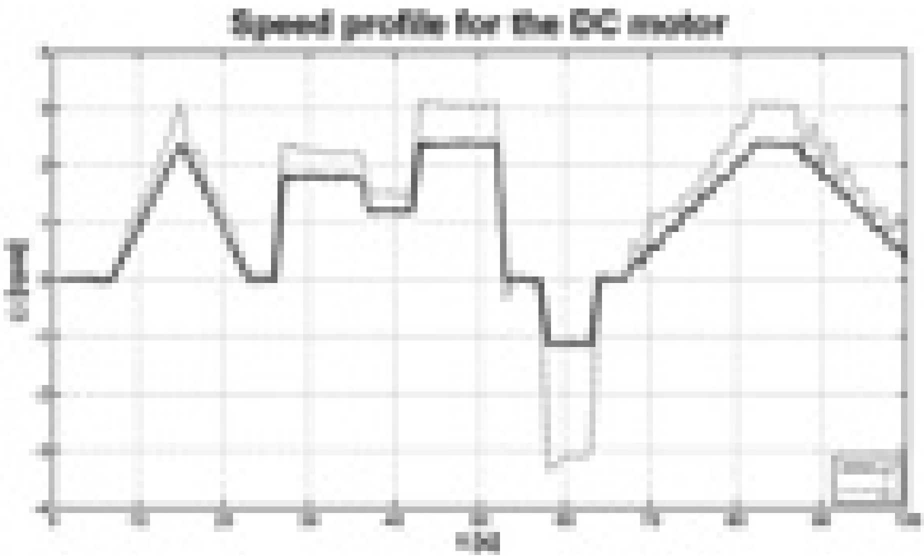


Figure 19. Dynamic behavior of DC machine.

Once the best considered configuration is chosen, the system is tested using the user-defined speed testing profile as indicated in Figure 19. It is noteworthy that the output speed of the machine follows the testing speed profile.

3.2. Induction Machine

The induction machines function in an open loop *U/f* converter. This means that there is no speed feedback to the controller. For this reason, there is no need for adjustment of internal regulators dynamic parameters.

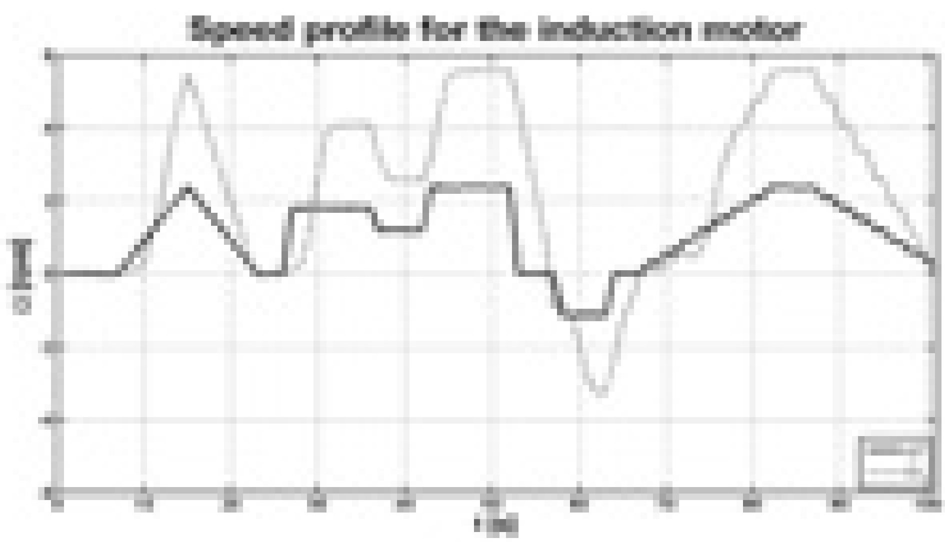


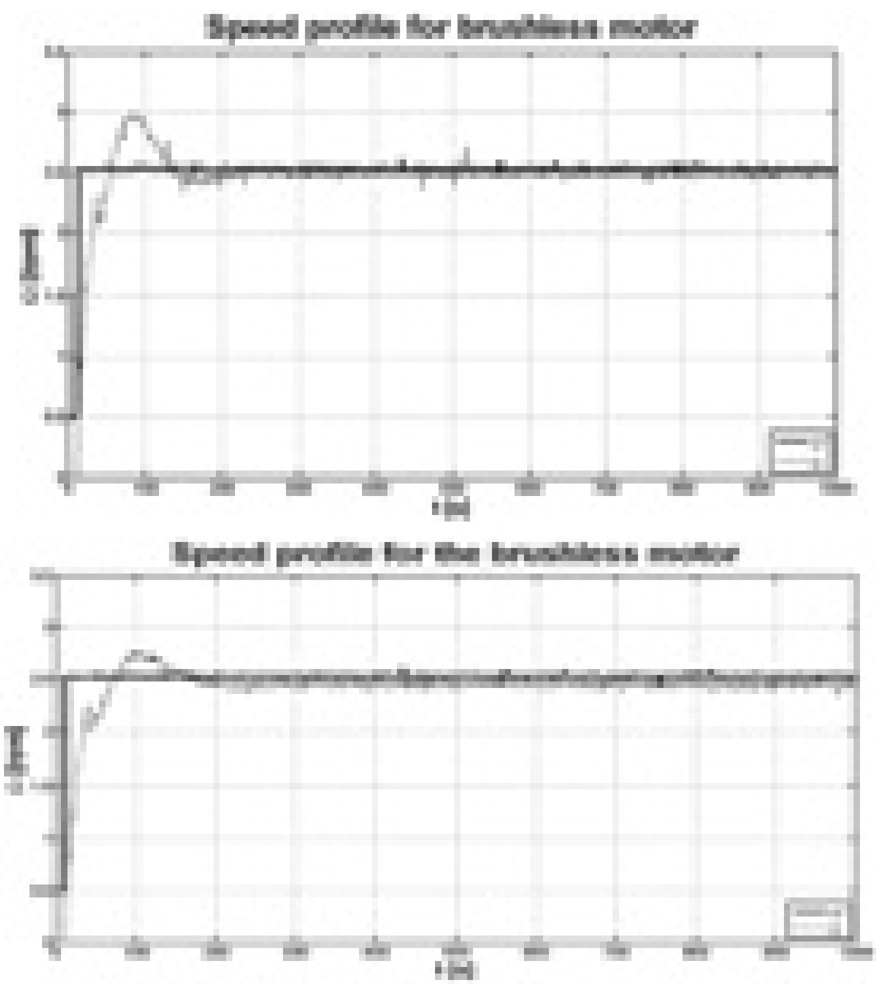
Figure 20. Dynamic behavior of induction machine.

The dynamic behavior of the system containing the induction machine is indicated in Figure 20. The output speed signal follows the testing speed input signal. The shape of the input and output speed signals is similar, but there are substantial errors between the two signals. The main reason for these errors is that the system functions in open loop configuration. Thus the speed error is not corrected in any way through a feedback.

3.3. Brushless Machine

The brushless machine, likewise the DC machine, functions in a closed speed control loop. The brushless machine's driver parameters should be set-up before any experiment is conducted. The procedure of setting up the brushless machine's driver is covered in previous works of the authors [12]. Just as for the DC machine, the procedure consists in establishing the parameters for the current and speed regulators' parameters.

Figure 21 presents the set-up procedure for the brushless system. Equally as the DC brushed machine, the BLDC machine drive includes a regulator parameter configuration in order to achieve the best behavior. As in any closed loop systems, monitored parameters are: the delay of the dynamic response, the override signal and the delay to reach the steady state.



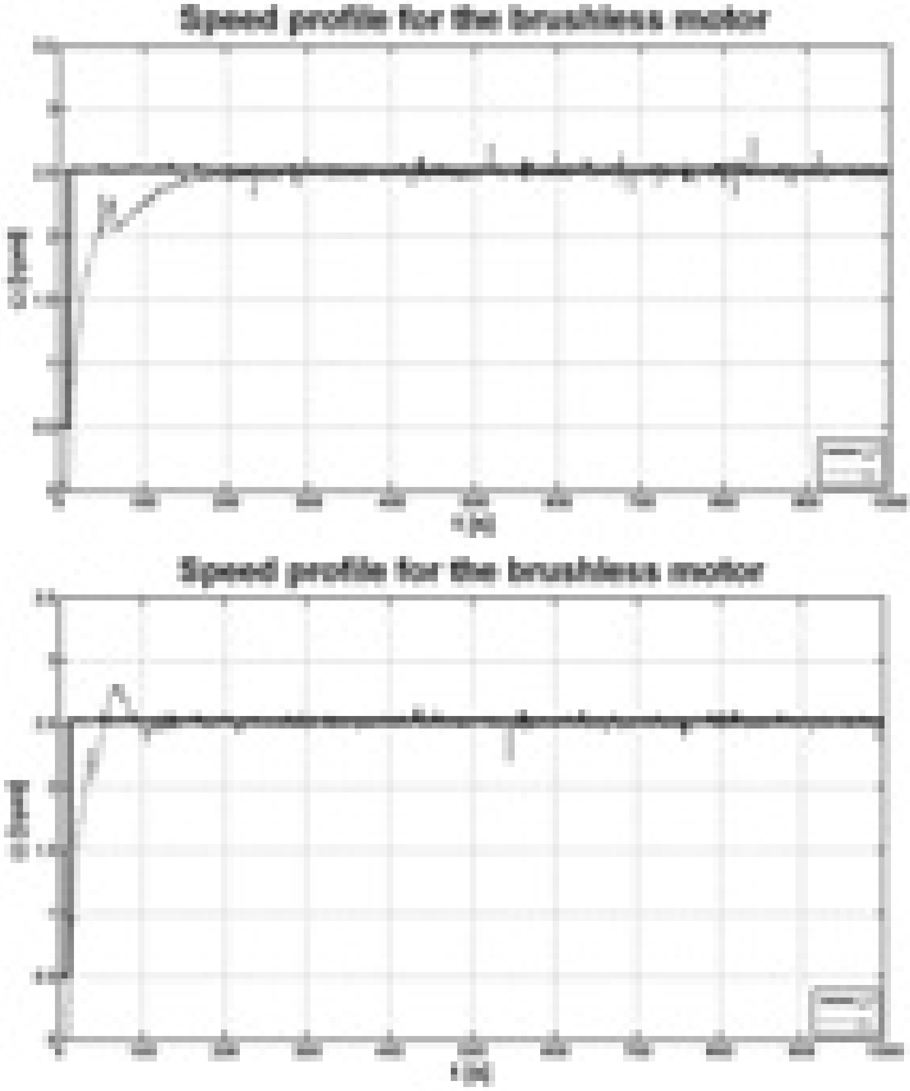


Figure 21. Set-up of brushless machine driver control loops.

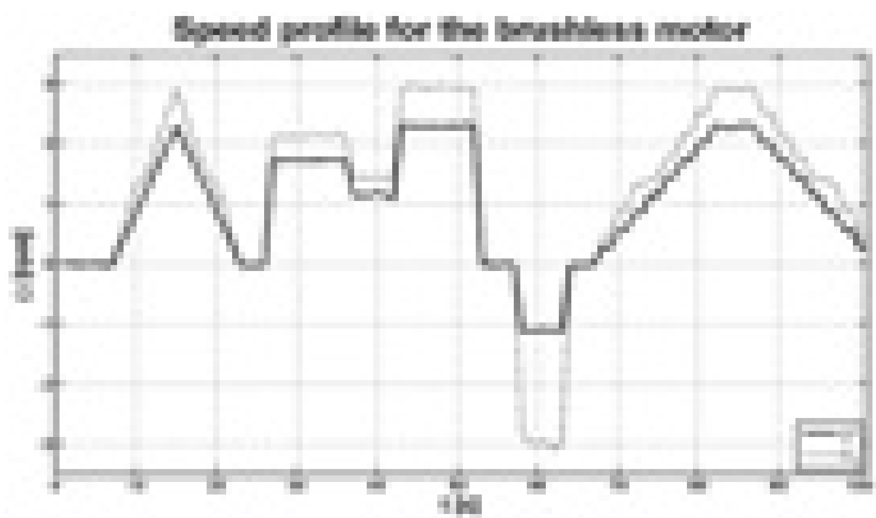


Figure 22. Dynamic behavior of BLDC machine.

The effect of the feedback loop of the driver for BLDC machine is displayed in Figure 22. The shape of the output speed signal is similar to the input speed excitation signal. There are slight errors between the input and the output speed signals.

4. Comparative Behavior of Electric Machines for EV/HEV

For the comparison of the dynamic regime for the three electric machines, an excitation speed signal was applied to its' drivers (Figure 23). The dynamic response of these machines was recorded (Figure 24)

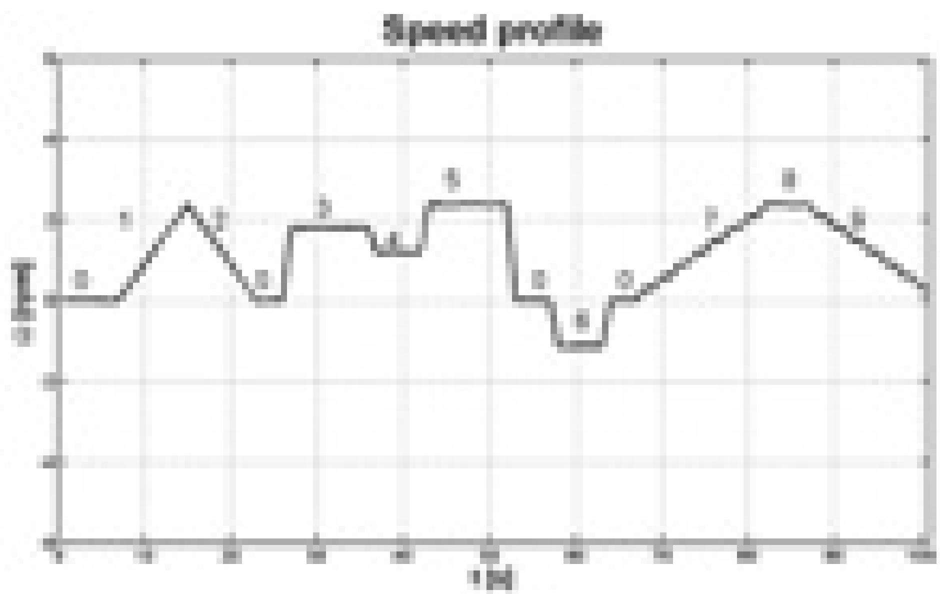


Figure 23. Testing speed profile.

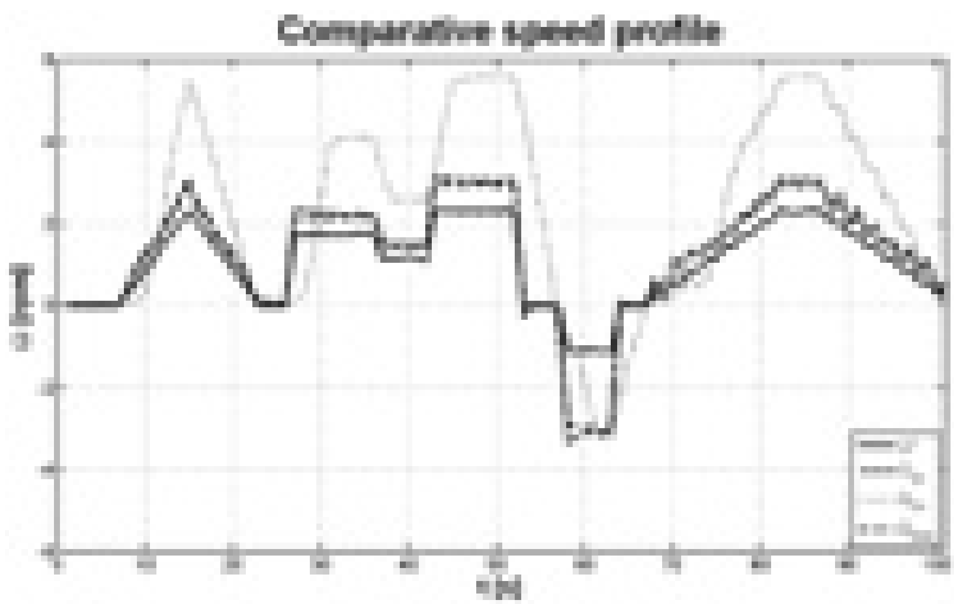


Figure 24. Comparative dynamic behavior of DC, induction and BLDC machines.

Firstly the speed responses of DC and BLDC machines are very similar, which is consistent to other results from technical [8] and scientific literature [13] . Secondly, for the forward move of the EV/HEV equipped with these kinds of machines, the error between the input and the output speed signals is small. Therefore in all imposed functional regimes, the output signal follows the input signal with an acceptable error.

Third, in the slow deceleration regime (9 in Figure 24) a smoother behavior for the BLDC machine compared to the brushed DC machine can be noticed. In addition, at a sudden change of functional regimes, the DC machine has bigger override value of measured speed than the BLDC machine. When the slow acceleration is applied (7 Figure 24) the override of the DC machine is again bigger than the one for the BLDC machine. Nevertheless, the response is attenuated rapidly and the brushed DC machine has a very similar behavior with the BLDC machine.

Forth, a different situation can be observed for the induction machine. The experiments revealed a very large error of the induction machine's output speed compared to the input speed-testing signal. At every regime change there is a notable delay, in both senses of rotation. The profile of output speed for the induction machine follows the profile of the testing signal, but there is an important difference in amplitudes.

One of the reasons for such behavior is the fact that in this circumstance, the induction machine's controller is an open loop *U/f* driver. Therefore the output speed is never compared with the input signal and speed regulators never process the error.

Conclusion

From the above mentioned analysis the following conclusions could be drawn:

- The most accurate dynamic behavior for regime changes is offered by the BLDC machine as indicated by our tests
- The dynamic behavior of brushed DC machine is similar with the BLDC machine
- The dynamic behavior of the induction machine controlled by a *U/f* driver in an open loop configuration presents very large errors

Each analyzed solution for traction for EV/HEV in this chapter has its advantages and disadvantages.

The brushed DC machine fabrication technology and control systems arrived at their maturity, it is envisaged its costs will decrease [14]. Nevertheless the brushed DC machine presents the important disadvantage of high maintenance cost.

The brushless machines do not present the same problem as the brushed DC machines related to maintenance cost, as the brushes are eliminated. Since the fabrication process of magnets improves and the price for control and power electronics decreases, the BLDC machines become a very suitable solution for replacing the brushed DC machines.

Comparing the brushless machines with induction machines, it is outlined in the literature that the stators for a three-phase induction machine and for a BLDC machine are practically identical [14]. However, these machines differ in the rotor construction and the electronic controller.

The cost of production and maintenance for induction machines is the smallest among the three types analyzed. For this reason they are more fitted to be used than the brushed or the brushless DC machines in EV/HEV, but they are more difficult to control.

In spite of presented advantages and disadvantages, all three categories of machines are used in prototypes and already commercial EV/HEV. There is still more room for further studies to develop the best electric machine configuration to be implemented in EV/HEV.

Nomenclatures

BLDC	Brushless DC
COMP	Comparator
DC	Direct Current
FRD	Free Regime Diode
GCS	Gate Command System
PES	Power Electronic Switch
SOP	Static Operating Point

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