Suitability of Electric Motors and Conventional Control Techniques for Electric Vehicle Applications

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***Abstract*—This article proposes the control of the induction motor intended for the traction of an electric vehicle using direct torque control (DTC) technique. The main advantage of this technique is the simplicity of the hardware implementation in low cost platforms and precision in achieving any speed setpoint while the resistance torque variation. To expose the induction motor to the real challenges that arise in the electric vehicles, the speed control algorithm is tested under the New European Driving Cycle (NEDC) while imposing a resistive torque that emulates that of the real electric vehicle. The whole system is simulated under very challenging conditions in the PSIM platform , then the algorithm is implemented in the DSP TMS320F28335 platform to confirm its effectiveness in the real environment. The obtained simulation and processor-in-the-loop (PIL) results confirm that the direct torque control technique can be very useful in the speed control of electric vehicle induction motor.**

***Index Terms*—Electric vehicle, propulsion system, induction motor, drive cycle, DSP TMS320F28335**

I. Introduction

Testing the performances of induction motor speed control techniques in typical industrial applications will not expose this motor to the real challenges that arise in the electric vehicle, such as the rapid and continuous variation of the speed and of the resistive torque.

The technological advance in the efficiency and lifespan of the batteries , as well as in the microelectronic devices (microprocessors, microcontrollers and digital signal processors (DSP's)), whether in their high speed of execution or in their reduced prices, adding to that, the global fear of the ill effects of fossil fuel burning and its resultant carbon emissions, lead together to a rekindling of interest in electric vehicles (EVs). At the end of the year 2020, the number of EVs circulating on the world's roads was 10 million, marking an increase in EV registrations of 41% [1]. EVs are distinguished from those equipped with an internal combustion engine by the type of engine and the source of energy. the EVs engine is an alternative motor powered by the electric energy stored in the battery. Therefore, the battery and the electric motor are the core components by which the EV development is revolved around. Propulsion motors are developed to meet the main requirements of robustness, high torque, high power, high efficiency, wide speed range, ease of control, low cost, low maintenance-free, low noise, and reduced clutter [2], while the principal exigencies of the battery are large capacity, a good life cycle, fast charging, low cost, low weight and low degradation factor [3].

The electrical part of the EV is composed of the propulsion motor, the power converter and the electronic controller. However, unlike the last two components mentioned, the evolution of electric motors is slow and long, so that several common electric motors are found to be among the motors used in electric vehicles. These include permanent magnet (PM) brushless dc motors, induction motors (IM), PM synchronous motors, switched reluctance motors (SRM) and DC motors (series, shunt and separately excited) [4]. Being applied by big companies in EV industry, such as General Motor and Tesla (Roaster and Model S), IM secures its place as the best choice for EV propulsion motors [5], it is known by it's reliability, robustness, less maintenance, mature technology, and low price [2], while its only drawback is its low efficiency at low loads [6]. In industrial applications, this motor typically operates for long periods of time at constant speed and under varying loads, however, this latter requires frequent start-stop and acceleration-deceleration operation modes when applied in the EVs which is totally incomparable with industrial applications. Thus, the purpose of this article is to test this motor under challenging conditions that are comparable to those it would face in the real EV. For this reason, we propose in this work to apply the direct torque control (DTC) technique to impose the speed on the motor regardless the amount of the resistive torque. Therefore, the speed reference is set in line with the New European Driving Cycle (NEDC) while applying a resistive torque that emulates that of the actual EV to cover all the possible EV operating conditions.

II. Fully electric vehicle propulsion system

Fig. 1 illustrates the functional block diagram of a fully EV propulsion system where black arrows and colored lines represent power flow and control/sensor signals, respectively.

It converts electrical energy stored in the energy storage system (ESS), consisting solely of a battery pack or hybrid with another energy storage system, into mechanical energy that drives the vehicle wheels. If the ESS is of a high voltage, it can be connected directly to the DC bus, which must be maintained at constant voltage in the case of a hybrid energy storage system. However, if it is of a low voltage, a boost converter is required to step up the ESS voltage. The DC/AC converter has a dual role in this system, it acts as an inverter when controlling the propulsion motor speed and as a rectifier during braking period to store the kinetic energy transformed into electrical energy in ESS [7].

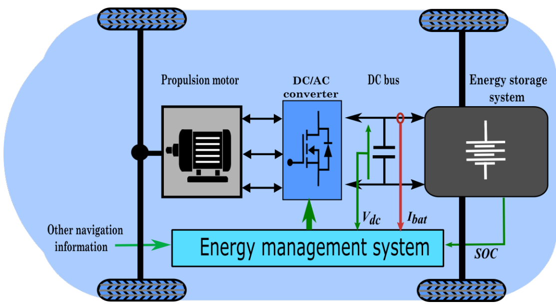

Fig. 1: Functional block diagram of the fully EV propulsion system

The propulsion motor interfaces with wheels via the transmission device. It also acts as a motor to drive the wheels and set the EV in motion, and as a generator in braking mode to store regenerative braking energy in the ESS [8][4]. The number and position of this traction motor depends on the type of the motor and the traction technique adopted in the vehicle. Some EVs have a single-motor configuration, while others have a two- or four-motor configuration. For the motor position, in the single and dual motor configuration, it is usually placed in the vehicle's chassis, while for the four-motor configuration, it is placed inside the wheel, the in-wheel technology has the advantages of being independently controllable four-wheel torque, high energy utilization rate and fast engine response speed [9]. Permanent magnet brushless DC motor (PMBLDC) is the most attractive motor type in the field of in-wheel technology due to its high-power density and high efficiency [2]. One of the most important part of fully electric vehicles is the energy management system (EMS), it helps to optimize the energy usage which will increase the EV range and improve the driving efficiency. The EMS collects all data pertaining to the energy stored using a variety of sensors and the power that needs to be supplied using prediction tools, then, using one of the intelligent techniques (fuzzy logic, predictive control, neural network, ..) decides how to act on the converter(s) to maximize energy usage and increase the ESS lifetime [10].

III. Electric motor for EV application

It is crucial to note that the performance characteristic of the electric motor in traction applications differs from those in industrial applications. It is only required, in industrial applications, to run for a long time at constant speed and under variable loads. However, for traction applications, it needs frequent start/stop operations as well as a high acceleration/deceleration rates , which means that it is required to guarantee a high torque throughout the all speed range. [11], especially at low speed in order to accelerate quickly, and climb the hill easily and successfully negotiate obstacle [12]. Therefore, in order to fulfill its function must meet certain requirements [13] :

1) High torque density and power at all speeds
2) Variable and a wide range of speed
3) High starting torque and high power at cruising speeds
4) High efficiency especially for regenerative braking

In general, the performance of any type of vehicle is measured by the profile of its torque versus the speed of the vehicle. In fact, as the engine has a rated power, the torque profile versus the speed should be accompanied by a fixed power profile through all the speed range. In the combustion engine vehicle, the issue of maintaining constant power over the entire speed range is solved by the use of the multi-gear transmission. While in electric motor, the torque-speed profile is naturally accompanied by a constant power-speed profile as shown in Fig. 2, therefore, only a single-gear transmission is needed for the electric motor, except in some extreme conditions for off-road vehicles, the power demanded can be higher than the rated power, in this particular case it was necessary to use the multi-speed transmission to meet the higher tractive effort [12].

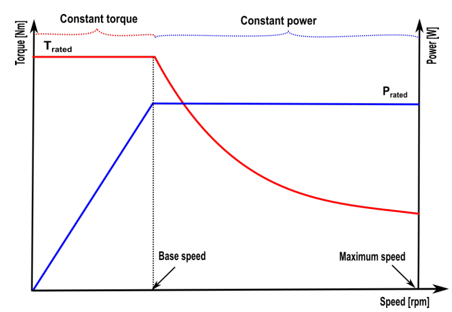

Fig. 2: Typical characteristics of electric motor

A. Candidates for EV application

As mentioned earlier, both DC and AC motors are used for electric propulsion application, in fact, although DC motors have the best characteristics to be the prominent candidate for this application, their bulky construction based on commutators and brushes requiring periodic maintenance has ousted it from this position. Nevertheless, the tremendous advances achieved in power electronics, microelectronic devices and digital control have have paved the way for other advanced motors including permanent magnet brushless dc (BLDC) motors, induction motors (IM), PM synchronous motors and switched reluctance motors (SRM). For this application, the torque density is considered as the main criterion for evaluating the most suitable motor when it makes it possible to consider the weight and the volume of motor in relation to the torque [14].

TABLE I: Torque density for EV candidates motors [14]

Motor type	T/V $[Nm/m^3]$	T/Cu mass $[Nm/kg]$
Permanent magnet brushless dc motor	28860	28,7-84
Induction Motor	4170	6.6
Switched Reluctance Motor	6780	6.1

As presented in Table II, the PMBLDC motor has the highest torque density among the three types of motors owing to its permanent magnet rotor which has no windings or copper losses, in other words, the same torque can be obtained from this less weight and volume motor. Unfortunately, its main drawback is that inherently has a small constant power range and a limited extended speed range, caused by its field weakening capability limitation that can only be produced by stator field that opposes that of the PM field. New development have been introduced on this motor to solve this problem, which are the introduction of additional field windings that allow the speed range to be extended.

The great advancements in digital control technologies have pushed AC motors to make great strides over DC motors. This for the various advantages they offer: more efficiency, more reliability, higher power density, lower price, negligible maintenance costs. While considering high reliability and zero maintenance as primary requirement for traction motors, the AC motors became very attractive in EV industry [4].

For the IM, Field Orientation Control (FOC) allows this motor to behave like a separately excited DC motor, as it allows flux control to be decoupled from torque control. Using flux weakening technique, the IM has the ability to extend its speed range below and above 2 to 4 times its base speed, under constant power operation. Regarding its construction, it has two types of rotor, wound-rotor and squirrel-cage rotor. In most application, including the EV field, squirrel-cage induction motor is the most widely used type because it requires less maintenance and is inexpensive [15].

The forth candidate is permanent magnet synchronous motor (PMSM), it is widely used the EV application and has become a good competitor to IM . It has simple structure with high efficiency and a high power density. According to interior or surface mounted PM, two types are distinguished, interior (IPMSM) and surface mounted (SM-PMSM) [16] . Due to the more advantages of the SM-PMSM, simple construction, easy control and low rotor inertia, has become used in many EV applications. Regarding the control aspect, different techniques are used, Field-Oriented Control (FOC), Flux-Weakening Control (FWC) and Position Sensorless Control (PSC) technique [13].

The last candidate is the switched reluctance motor (SRM), it is gaining more and more importance in electric propulsion systems due to its simple and robust construction, easy control and ability to operate at high speed, more than that, it doesn't need rare earth materials in its construction. The obvious disadvantage of this motor is its acoustic noise and torque ripple In fact, through the use of advanced control strategies and field reconstruction technology, acoustic noise and torque ripple have been reduced to an acceptable level in EV application field [2][14].

For concluding this section, it important to note that all cited types of motors are being used in many EVs models. In this way, it difficult to prefer one over the other. However, they can be evaluated based on their various characteristics as was done in [13]. Table 2 gives a comparison between five type of motors based on eight characteristics, each of them is rated by five levels, starting with level one up to level five which is the best level.

TABLE II: Comparison of characteristics of EV motors [13]

Parameter	DC	IM	PMSM	PMBLDC	SRM
Power density	2	3	4.5	5	3.5
Efficiency	2	3	4.5	5	3.5
Controllability	5	4	4	4	3
Reliability	3	5	4	4	5
Maturity	5	5	5	4	4
Cost level	4	5	3	3	4
Noise level	3	5	5	5	2
Maintenance	1	5	5	5	5
Total	25	35	35	35	30

IV. Drive cycle tests for EV motor

As discussed in the last section, the operation of the EV motor differs from that of industrial applications, thus,to prove the effectiveness of conventional or newer control techniques on the EV motor, appropriate tests that mimic the driving conditions encountered by an actual vehicle must be performed. The suitable method for this is to use drive cycle simulation. The drive cycle is a speed profile that gives the speed as a function of time. so the motor speed must therefore be controlled to track the drive cycle speed reference. the commonly used driving cycle are: urban dynamometer driving cycle (UDDC), highway fuel economy test (HWFET) and new European drive cycle (NEDC). These driving tests are initially used to assess the carbon dioxide emissions and fuel consumption of vehicles. However, as they mimic urban and highway scenarios, they can be used to as speed profiles to assess speed control techniques. Fig. 3 shows the NEDC drive cycle, it is composed of 4 urban driving cycles (UDC) to reflect driving in towns and 1 extra-urban for open road driving.

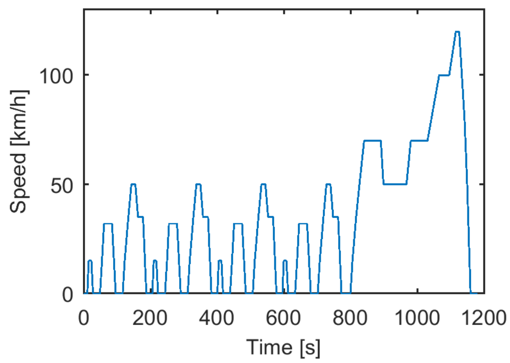

Fig. 3: The New European Driving Cycle (NEDC)

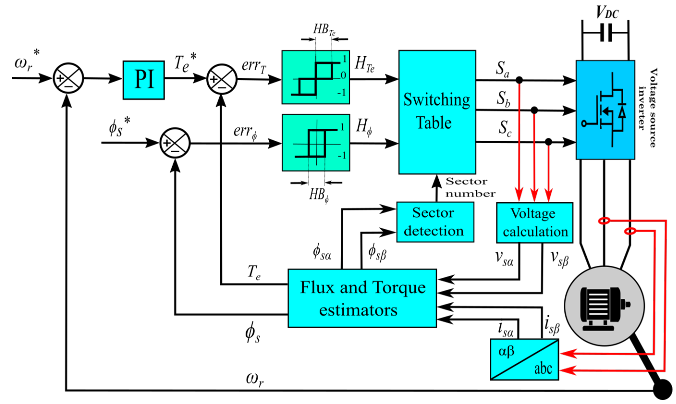

Fig. 4: DTC block diagram the rotor speed regulation loop

V. Case study

Among the five EV motors presented earlier, we chose to use the induction motor in this section, it has been used by General Motor and Tesla in their EVs, it is a reasonable choice among other commutator-less motors. In this part of this study, a classical and popular control technique will be used to control the speed of the IM dedicated to the EV application, it is the direct torque control (DTC). Although it has simple control structure than the field oriented control (FOC) technique, it provides a fast instantaneous torque control whether under transient or steady-state operation, so it is considered to be optimal for EV applications [2][5].

The DTC was proposed by Takahashi [17] and Depenbrock [18] in the mid-1980s. It principle is to generate the voltage source inverter switching signals based on the errors between the actual and reference values of the torque and the flux. These errors are calculated using two-level and three-level hystrisis controllers for flux and torque successively.

Fig. 4 shows the block diagram of the DTC with the rotor speed regulation loop based on PI controller. After the torque reference is generated by the PI controller of the outer rotor speed loop, the errors between references and the actual values of the torque and stator flux linkage are entered to three-level and two-level hystrisis controllers receptively, then the switching table use the three information, the outputs of the hystrisis controller with that of the sector number, to generate the appropriate switching singles which turn on/off the voltage source inverter switches. This is a brief explanation of the principle of DTC and more details can be found in [5].

The NEDC driving cycle of Fig. 3 is intended for testing real vehicles, whether for the driving time (1200s) or for the speed range (120 km/s). So, it must be adapted to fit EV motor test. The test time was divided by eight to be reduced to 150 seconds, while the speed was multiplied by ratio of maximum vehicle speed to the IM rated speed. the new obtained NEDC that will be in the IM test is depicted in Fig. 5

VI. Simulation implementation and results

To check how IM reacts to the DTC technique under working conditions similar to those that will be imposed to

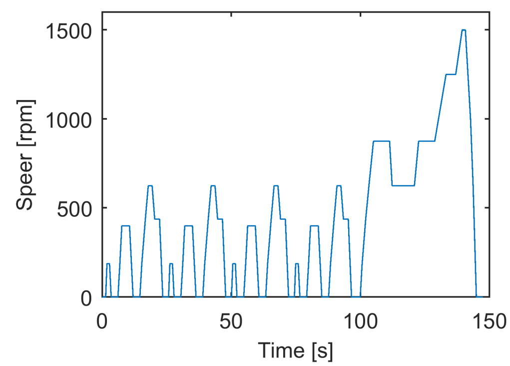

Fig. 5: NEDC modified for EV intended IM test

it in real EV, the block digram of Fig. 4 is simulated in the PSIM software platform using an IM of 4kW and a V_{dc} voltage of 600V.

In addition of using the NEDC drive cycle which covers different driving conditions regarding reference speed, this factor is usually related to the driver who set or chose the speed reference, the second factor is the toque which is related to the vehicle load and the shape or condition of the road, to solve this second problem, the resistive torque to be given to imitate real driving conditions as much as possible, when starting or stopping the vehicle or while it is on the road in acceleration or deceleration.

The simulation is done in two stage :

1) Simulation using the PSIM C block: In this first step, the simulation is performed by implementing the DTC algorithm in the PSIM C block. For the speed reference, we can clearly see that the modified NEDC (Fig. 5) is composed of four urban cycles and one extra-urban cycle. To assesse the fuel consumption or carbon dioxide emission, it is necessary to run all the cycles, but for the speed control, it is completely sufficient to test the IM how it repond to DTC for the very complicated cycle, which is our case is the UDC, because it contains a frequent start/stop, and a very rapid acceleration/deceleration.

After simulating the whole system for the entire period of one UDC, the obtained results are shown in Fig. 6-10

Fig. 6 depicts speed and speed reference with zoom. Fig.

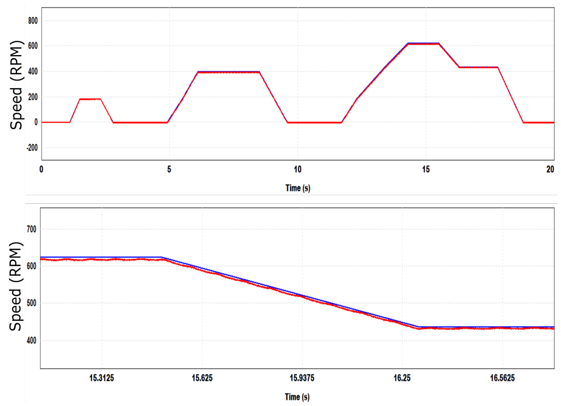

Fig. 6: Speed and speed reference with zoom [Rpm]

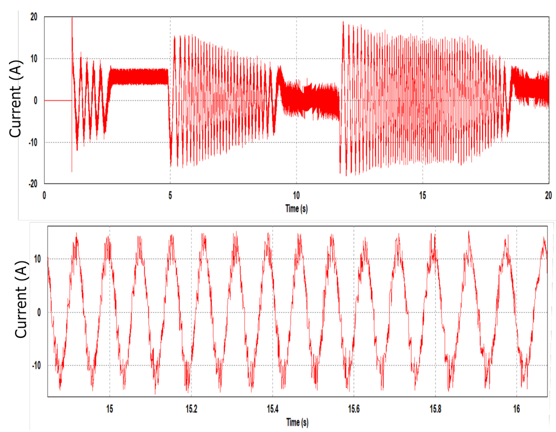

Fig. 7: Output current with zoom [A]

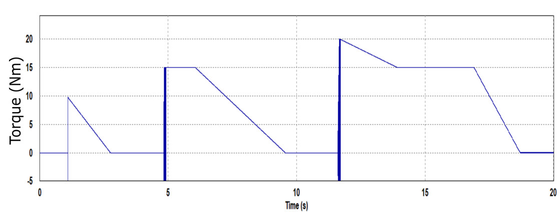

Fig. 8: Resistant torque [Nm]

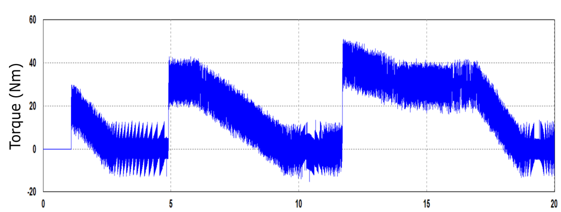

Fig. 9: Electromagnetique torque [Nm]

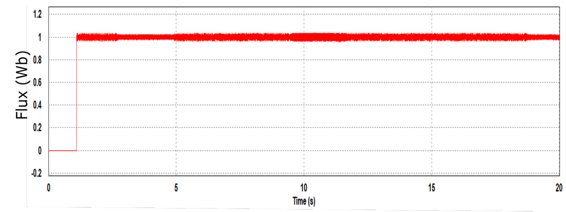

Fig. 10: Flux [wb]

7 shows the output current, it has sinusoidal shape and its amplitude follows the value of the resistant torque depicts in Fig. 8 because the current value is increased and decreased according to the applied torque. The obtained electromagnetic torque shown in Fig. 9 is also in accordance with the imposed resistant torque shown in Fig. 8. While the flux is imposed 1wb as shown in Fig. 10

2) Simulation using DSP TMS320F28335: In the second step, the simulation is carried out by implanting the DTC algorithm in the DSP TMS320F28335 as shown in Fig. 11. The speed reference is kept as in the first simulation step (Fig. 6), only the resistant torque is modified to expose regulation algorithm to another challenging resistant torque and see how it will react. the obtained results are shown in Fig. 12-14.

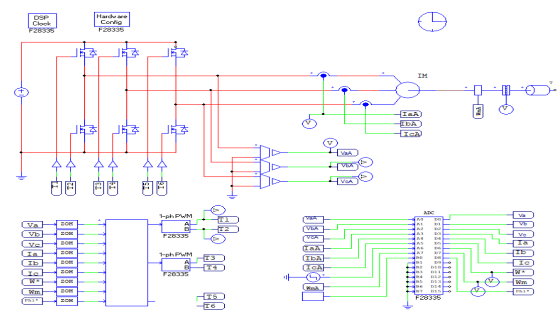

Fig. 11: Block diagram of simulation circuit using the DSP TMS320F28335

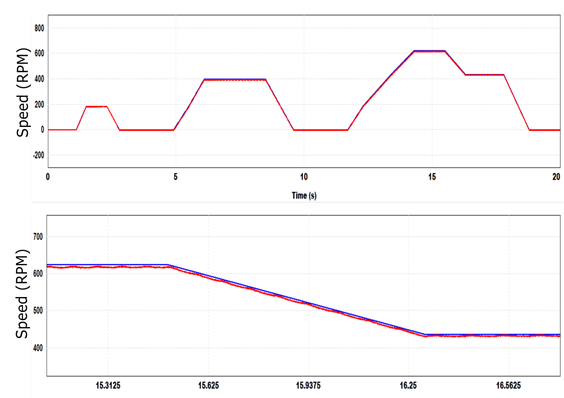

Fig. 12: Speed and speed reference with zoom [Rpm]

Fig. 12 shows how the speed and the speed reference waves are superposed on each other, which confirms once again the

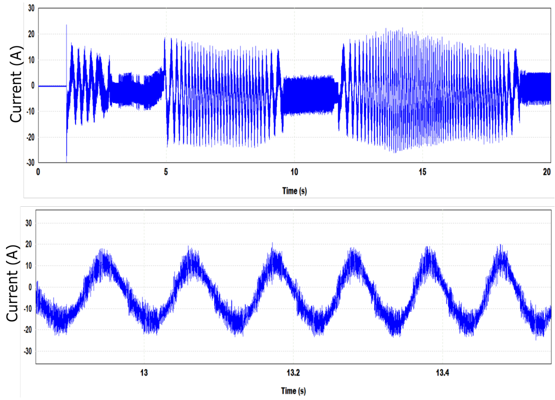

Fig. 13: Out put current with zoom [A]

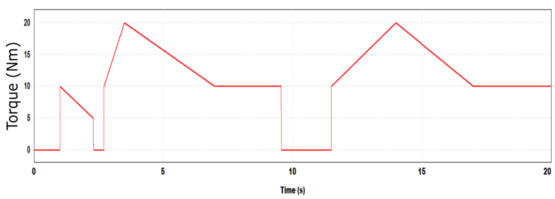

Fig. 14: Resistant torque[Nm]

effectiveness of the DTC algorithm in the speed control of the induction motor intended for the electric vehicle . For the torque, it can be seen in Fig. 13 that the amplitude of the output current also takes the shape of the resistant torque (Fig. 14) .

VII. Conclusion

The main objective of this study was to verify the effectiveness of the conventional DTC technique in controlling of the speed of an electrical motor intended for EVs. After explaining the main difference between the use of these motors in industrial applications and in EVs and giving the properties of the electric motor that can be used in EVs, the IM was chosen to apply the DTC technique in a simulation environment presenting a similar environment encountered by this motor in real EV, whether for the speed reference or for the resistive torque. The simuation was performed while implementing the DTC algorithm in DSP TMS320F28335. The obtained results confirmed how the conventional DTC was able to accurately follow the speed reference of UDC under a very challenging resistive troque.

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