Software-in-the-loop Simulation of a Test System for Automotive Electric Drives

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***Abstract*—The Automotive market is rapidly changing, as the increasing attention to the engine emissions pushes car makers to use vehicles less dependent on gasoline and diesel fuel, resulting in lower operating costs and emissions. Today, electric vehicles seem to be the best answer to the market demand. In this scenario, electric drives for traction play a key role, thus the necessity to develop effective and flexible test systems, able to ensure performance, quality and safety. In this paper a new automotive electric drives test system is proposed. The test system for electric drives is based on an inverter controlled through a real-time platform in which the Electric Vehicle model is implemented. The inverter emulates the behaviour of the motor and load at the load drive terminals. This paper describes the architecture of the system and shows the real-time simulation results. Three control methods are used for the load drive and compared in the paper.**

Keywords*—*Real-Time, Simulation, Electric vehicles, drivetrain, Hardware-In-the-Loop, Modelling, Electric Drives.

I. Introduction

Almost 25% of CO_2 emission is due to cars and trucks, other major transportation methods accounting for another 12% [1]. Over 50% of global population lives in urban areas and rely on transportation to contribute to society. In the opinion of many, cars are a large contributor to urban pollution levels and, in the bigger picture, global warming [2]. The majority of pollution problems derives from internal combustion engines (ICE). For this reason the European Union (like other global organizations), implement mandatory 2020 CO_2 limit emission targets for new passengers cars. The 2020 CO_2 limit as reported in Fig. 1 is set to 95 g/km of CO_2. One potential alternative to the world's dependence on standard combustion engine vehicles are hybrid cars. Hybrids are vehicles that use multiple forms of power to supply their engines. Modern hybrid cars are powered by a combination of traditional ICE with the addition of an electric motor. With this combination the combustion engine is used at high speeds (i.e. long distances) while the electric engine works at low speeds (i.e. short distances), typically in urban areas. Therefore hybrids are not completely clean because they have also an oil-consuming engine but they are surely cleaner than oil only cars.

At their present state of development, full-function hybrids reduce fuel consumption by about 30%, at a manufacturing cost increment of roughly $2,500 to $3,500. While mild-hybrid systems, such as belt alternator or 48-volt (48v) systems, are not as efficient, their cost-benefit ratio can be better because

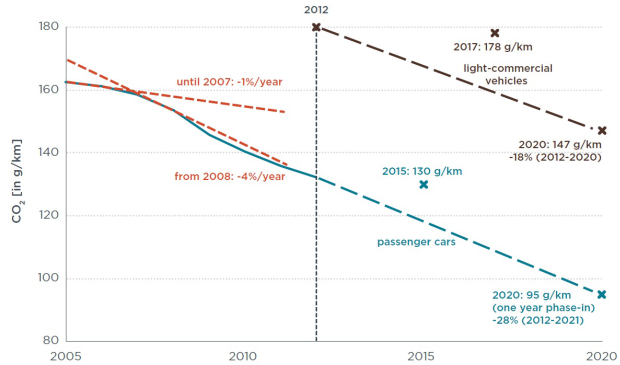

Fig. 1. Historical development and future targets for CO_2 emission levels [3].

they are less than half the cost of full-function hybrids [4]. It is expected that the proportion of the total market accounted for electric vehicles (EVs) and hybrid electric vehicles (HEVs) will grow significantly by 2020 [5]. The main hardware components of the electric powertrain systems are electric motors, inverters and batteries. Inverters are being asked to fulfill increasingly different roles and there is a growing need to decrease their size and their cost while increasing their power output. To guarantee high standard quality, inverter makers need reliable End of Line testing (EOL) systems to evaluate the inverter functionalities at the end of the assembly process. Many test systems can be used, one of them is a dyno test bench. Dyno test benches are closer to the target system, because the entire drive including power electronics and target e-machine is present. The mechanical load is generated by a load machine. The dyno test bench system begins as a simple mechanical interface between two electric powertrain drive systems, the source and the load. The most basic test requires a steady shaft speed regulated by a load reference motor. The system under test applies the desired torque on the shaft and power is measured at all input/output points of all components of the drive system. This configuration is very close to reality; however it is very expensive, dissipative, maintenance-intensive and has only limited speed dynamics, that make it difficult to use this test architecture where driving dynamics profiles are to be investigated. Furthermore, a cost intensive target machine especially designed for integrated transmission is necessary [6]. The aim of the present paper is to describe a new test system for traction electric drives. The main idea behind this work is to use an electric drive as load for the driver under test.

The paper describes the architecture of the test system and

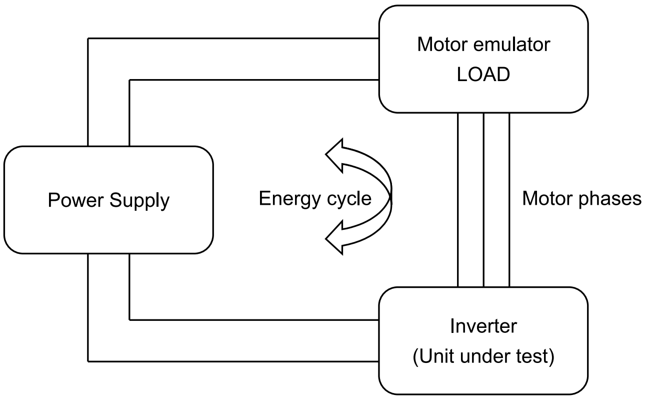

Fig. 2. Software in the loop architecture.

shows the procedure used for adjustment. The test inverter can be controlled using three main techniques, which are compared through simulation. A real-time Software-in-the-loop Simulation (SiLS) of the entire test system has been set up. The model used in this simulation are Matlab Simulink blocks integrated in the VeriStand Hardware-in-the-Loop (HIL) system even if for this stage of the work the real control signals aren't used to command the real drives. The architecture of the test system is described in section II, while the real-time simulation is in section III, taking in account three different load hypothesis. All the simulation results are finally reported and investigated in section IV.

II. Automotive Electric Drives Test System Architecture

The proposed system is able to test one or more electrical drives for EVs simultaneously. During normal operation, the terminals of the inverter phases are connected to the electric motor. Instead, in the electric drive test system shown in Fig. 2, a load drive is substituted to the electric motor. Although one load drive can be connected to one or more drives under test, the focus is on a test system containing one tested inverter and one load drive. The type and the power of the load drive may even be different from the tested drives. The load drive must operate in two quadrants, in order to emulate both motoring and regenerative operations. In order to operate, each drive must be provided of suitable inputs, namely analog or digital speed or torque commands and encoder or resolver inputs. The encoder/resolver inputs of both drives emulate the inputs from the rotor position transducer attached to the motor installed in the EV, and operating in the same conditions. It is therefore necessary to simulate in real-time (RT) the operation of the complete EV in one or more driving cycle. This simulation is very complex and can only be carried out in RT platforms with large computational capabilities.

The task of the real time system is therefore manifold [7]: it provides the speed or torque reference signals to the two drives and also the rotor angle translated into resolver or encoder compatible signals. In order to compute the rotor angle, the RT system integrates the vehicle equations on the basis of the measured currents of the drives. This is the heaviest computational task of the RT system. At present, only the drivetrain has been implemented in the RT simulator. In order to size the test system, a RT simulation of the complete system

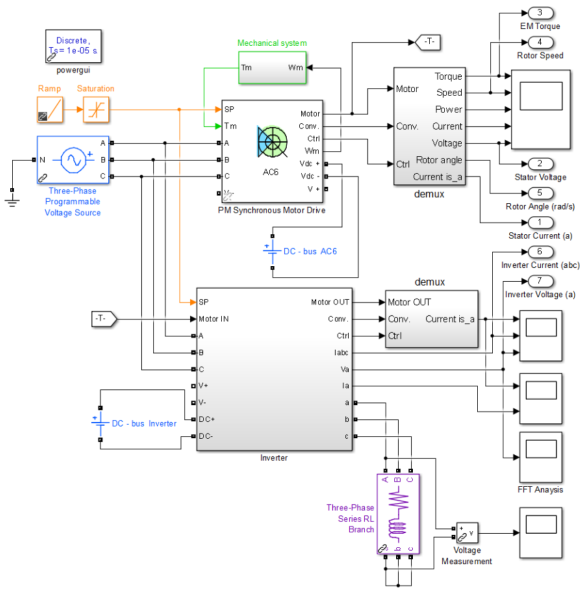

Fig. 3. Test bench for inverter - R-L load.

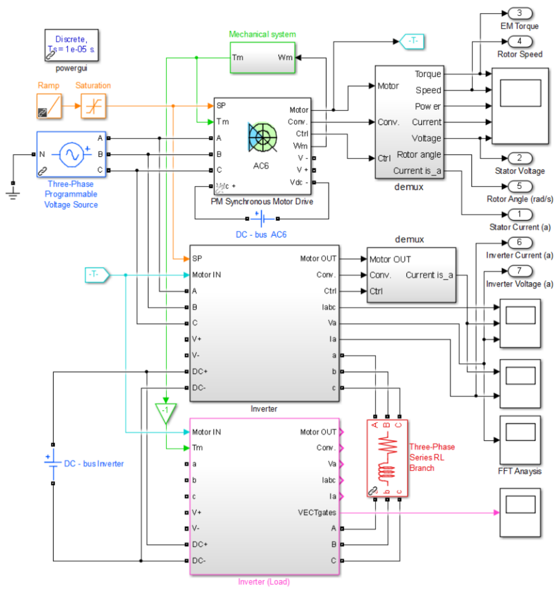

Fig. 4. Test bench for inverter - Inverter torque-controlled.

has been performed, including the two inverters besides the drivetrain. The Simulink scheme of the complete system that was simulated in real-time is shown in Fig. 4. The simplest way to load the tested inverter is to connect a passive load to its terminals. This solution, which is not viable in practice, as it is very expensive due to the large loss figures involved in the test, is shown in Fig. 3 and was also simulated to provide a proof of principle.

III. Real-Time Simulation

The purpose of the SiLS is to represent all the elements of the test bench by means of a virtual circuit, so that each of them may be replaced by its real counterpart and tested with the rest of the system. The advantage of this approach is given by the possibility of having virtual environments in which devices can be tested by using standard hardware (such as a PC); in addition, this allows to limit the presence of the physical components adopted within the test benches or, even, the expensive development of the entire system prototyping.

In this paper, the SiLS is adopted to represent the test bench of a driver, in which the real unit under test is an inverter and a modelled electric drive is adopted as its load. In order to check the correct reply of the control algorithm of the inverter, the power supply of the electric motor is analyzed: the basic operating logic is shown in (Fig. 2). To ensure a correct interaction between the simulated elements and the real ones under test, a real-time simulation is required [8], [9]. For this reason all the models were developed as Matlab Simulink block [10] and integrated in a NI VeriStand environment. NI VeriStand is a ready-to-use tool that provides a configuration-based software environment to create real-time testing applications, including HIL test systems.

According to this approach, the Matlab/Simulink blocks were compiled in a dynamic-link library and executed on a NI PXI platform, that is a dedicated multi-processor device which ensures the computation times needed to accomplish all tasks in real-time. The common functionality necessary for most of them, including host interface communication, data logging and I/O configuration, were managed by the NI VeriStand. To give access to the Matlab Simulink variables and permit a direct access to the models, the NI VeriStand environment allows the construction of synoptic interfaces. Some of them are reported in Figs. 5 - 7 both for motor and inverter, and used to interact with the respective component. A short description is reported in the following.

A. PM Sychronous Motor Drive (AC6) interface

The parameters of the virtual load can be modified by the interface, as illustrated in Fig. 5; the interface allows controlling some of the main parameters characterizing the PM Synchronous motor (PMSM) model, such as the d and q axis inductances, L_d and L_q, the stator phase resistance, r, the resistant torque of the the mechanical system T_r and the DC-power bus of the virtual drive AC6 (500 V). Furthermore, by the interface's diagrams, it is possible to control the evolution of the magnitudes of different quantities such as the stator current components, i_d and i_q, of the PMSM, the d-q axis components of the stator voltage vector, v_d and v_q and the electromagnetic torque T_m. The motor equations can be written as:

$$v_d = ri_d - p\omega_r\Psi_q + \frac{d\Psi_d}{dt} \tag{1}$$

$$v_q = ri_q + p\omega_r\Psi_d + \frac{d\Psi_q}{dt} \tag{2}$$

$$\Psi_d = L_d i_d + \Psi_{PM} \tag{3}$$

$$\Psi_q = L_q i_q \tag{4}$$

$$T_m = \frac{3}{2}p\big(\Psi_{PM} i_q + (L_d - L_q) i_d\, i_q\big) \tag{5}$$

$$T_m - T_r = J\frac{d\omega_r}{dt} + D\omega_r \tag{6}$$

where, Ψ_d and Ψ_q are the d-q components of the stator flux, Ψ_{PM} is the rotor flux, J is the inertia and D is the damping coefficient.

Fig. 5. PM Synchronous Motor Drive (AC6) interface.

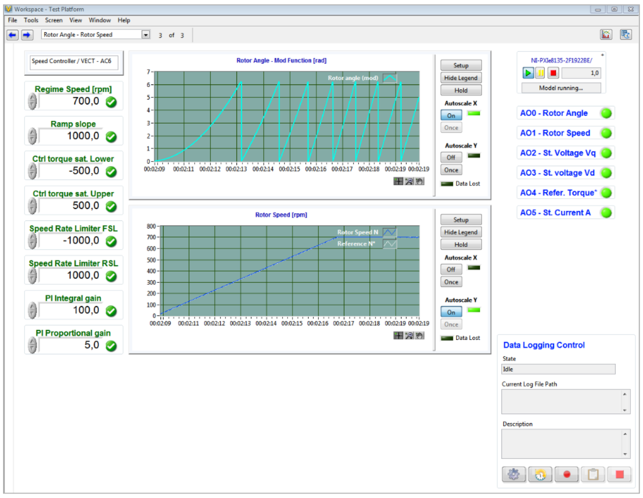

Fig. 6. Motor rotor angle (above) - Motor rotor speed (below) interface.

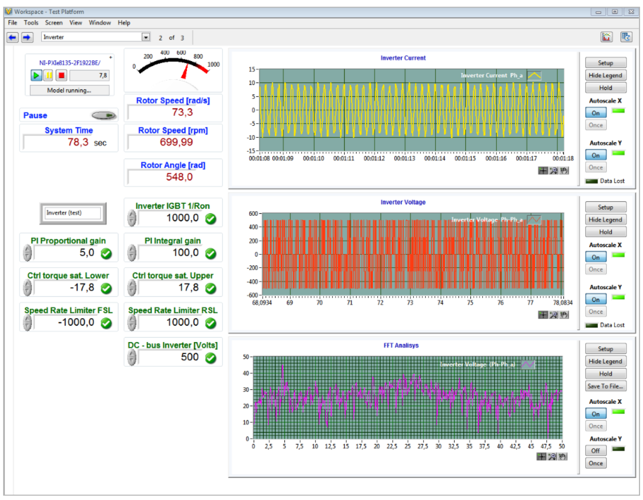

Fig. 7. Inverter interface.

TABLE I. MOTOR PARAMETERS

PM Synchronous Machine	
Equivalent circuit parameters	
Back electromotive force	sinusoidal
Resistance [ohm]	0.2
d-axis inductance [H]	8.50E-03
q-axis inductance [H]	1.20E-02
Initial currents [A]	0
Mechanical parameters	
Inertia [kg m^2]	0.089
Friction [N m s]	0.005
Pole pairs [.]	4
Initial speed [rad/s]	0
Initial angle [deg]	0

B. Motor Rotor Angle - Motor Rotor Speed interface

From this interface, illustrated in Fig. 6, it is possible to access the Simulink parameters related to the speed control of the motor, as well as changing the proportional and integral gains, the lower and upper saturation torques and the speed rate limiter.

C. Inverter interface

The last interface, illustrated in Fig. 7, allows operating on the speed controller of the inverter, as well as to monitor the current of the inverter and distortion introduced in the line-to-line voltage.

IV. RESULTS

The different parts of the simulator were calibrated and tested in three case studies. Their dynamic behaviours are illustrated for the different models in the following. The motor parameters are summarized in Table. I.

The possibility of a HIL replacement of the components is briefly discussed at the end.

A. Simulation of the PM Synchrounous Motor Drive

The dynamic behaviour of the virtual drive was analyzed. In Fig. 8 some of the main variables are illustrated for a standard case, assuming a DC-bus voltage of 500 V and a reference speed of 700 rpm. They show a good response of the system for the different variables of the drive.

In particular, it can be observed that the electromagnetic torque properly follows its reference value during the transient, maintaining at the end a slight oscillation around its stationary value. A similar behaviour is shown for the speed control.

B. Simulation of the electric motor, seen as a R-L load

In this case, which is only useful in principle, the PMSM motor is substituted by a R-L load (Fig. 3) that dissipates the power generated by the inverter. This choice allows to obtain a good level of fidelity with reality, but it is not applicable for high loads, where R-L values tends to became not feasible, and especially the power loss is too high.

The parameters of the R-L load are set so as to obtain an output current of the inverter as similar as possible to the one offered by the PMSM. The DC power supply (DC-bus) was chosen such as to maintain a load power less than 1 kW, considering a voltage level of 500 V for both the AC6 and the inverter.

For the chosen values of R and L, $R = 2\ \Omega$, $L = 8\ mH$, the trends of the inverter and PMSM currents are depicted in Fig 9. In this situation the simulation of the test bench gives for the inverter the currents and voltages of Fig. 10.

C. Simulation of load, seen as a torque-controlled inverter.

For high loads the previous approach is not applicable; a possible solution consists in the adoption of a second inverter powered by the same DC-bus considered as load (Fig. 4). The load inverter is torque-controlled differently from the one under test, which is speed-controlled; the torque is negative since the load inverter has to represent a motor.

The two inverters are connected together through a choke. The parameters were chosen to obtain an output current of the inverter under test as similar as possible to the one offered by the PMSM. Different values of inductance were tested. The value of the inductance must be chosen to minimize the current ripple while not slowing the current dynamics. The trends of the inverter and PMSM currents for a choke with $R = 1\ \Omega$, $L = 20\ mH$, are depicted in Fig 11. In this case, the simulation of the test bench gives for the inverter the currents and voltages shown in Fig. 12.

As it is apparent, the adoption of one inverter as a load, aimed at extending the physical feasibility of the test bench to the high loads, has the consequence of a worse approximation in the representation of the current of the simulated motor. This is not a limit, since this paper is mainly focused to examine the implementation issues associated to the representation of the test bench, rather than the accuracy of the parameters to be adopted in the simulation.

D. Simulation of load, seen as an inverter voltage-controlled

The last situation examined still considers the presence of an inverter as load; however this time it is voltage-controlled. This configuration is needed in practice to avoid over currents during transients. First, the output currents are measured, then

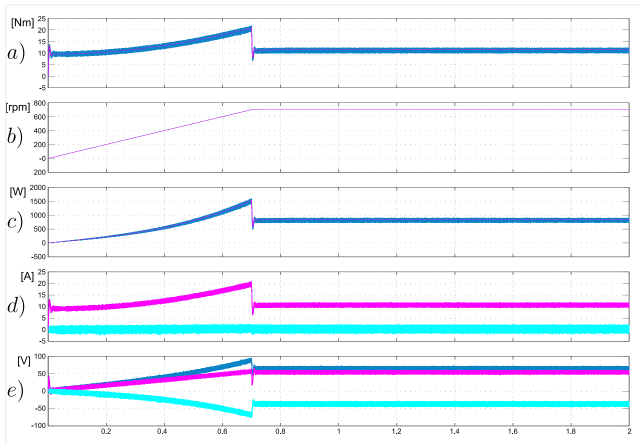

Fig. 8. Simulation of PM Synchronous Motor Drive, from above: a) the electromagnetic torque and its reference [Nm] - b) Rotor speed and its reference [rpm] - c) Mechanical power [W]- d) Statoric current (module and d-q components) [A] - e) Statoric voltage (module and d-q components) [V].

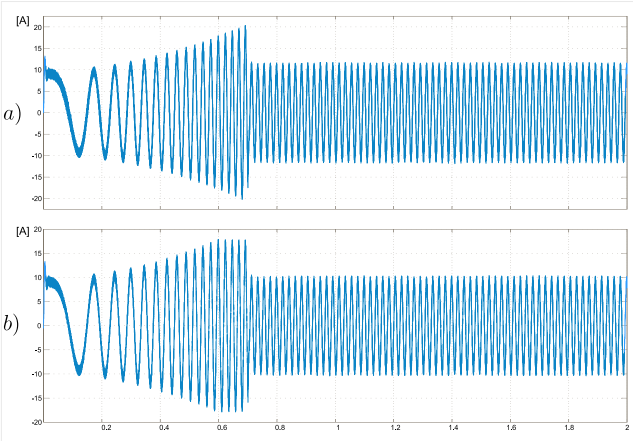

Fig. 9. Adjustment of R-L load - a) Current of IPMSM, phase A (above) [A] - b) Output current of the inverter (below) [A].

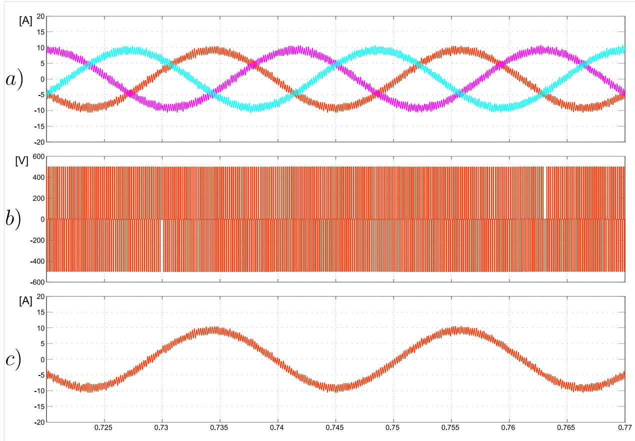

Fig. 10. Simulation of the tested inverter connected to the R-L load - from above - a) Output currents from the three branches of the inverter [A] - b) Concatenate voltage between the branches A and B of the inverter [V] - c) Output current from branch A of the inverter [A].

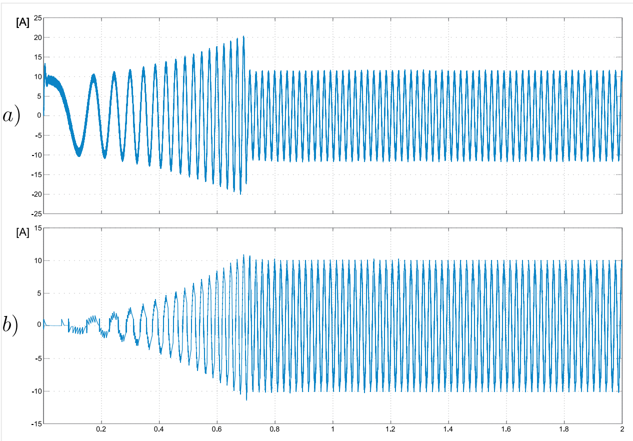

Fig. 11. Adjustment of R-L load - a) Current of IPMSM, phase A (above) [A] - b) Output current of the inverter (below) [A].

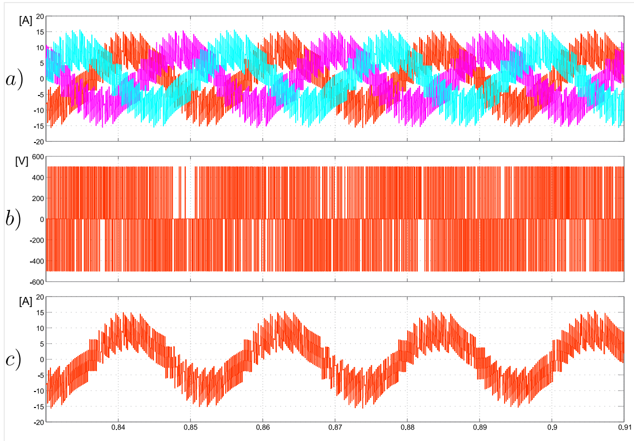

Fig. 12. Simulation of the tested inverter connected to the loaded inverter controlled with torque - from above - a) Output currents from the three branches of the inverter - b) Concatenate voltage between the branches A and B of the inverter - c) Output current from branch A of the inverter.

they are input in eq. (5). Afterwards, the speed is computed through eq. (6). The reference voltage for the load inverter is computed through eq. (1) and (2).

As in the previous case, the parameters R-L are set to obtain an output current of the inverter under test as similar as possible to the one offered by the PMSM. With the chosen values of R and L, $R = 1\ \Omega$, $L = 20\ mH$, the trends of the inverter and PMSM currents are depicted in Fig 13.

As it is apparent, this solution allows a significant better behaviour of the simulated current that is very similar to the one of the PMSM.

In Fig. 6 it is shown a possible implementation for both the control of the rotor angle and the speed of the motor.

V. Conclusion

This paper investigated a new automotive electric drive test system aimed at reducing the cost of the test bench for the inverter. The main idea behind this work is to use another electric drive as load for the driver under test. The test inverter can be controlled using three main techniques, which are compared through simulation.

A real-time Software-in-the-loop Simulation (SiLS) of the entire test system has been set up. The model used in this simulation is Matlab Simulink blocks integrated in the Veri-Stand Hardware-in-the-Loop (HIL) so as to allow a real time simulation.

The paper describes the architecture of the test system and shows the procedure used for adjustment of its setting. The simulation shows that the parameters of the virtual load require to be selected precisely to have a good substitution of the PMSM motor model which represents the electric vehicle (EV).

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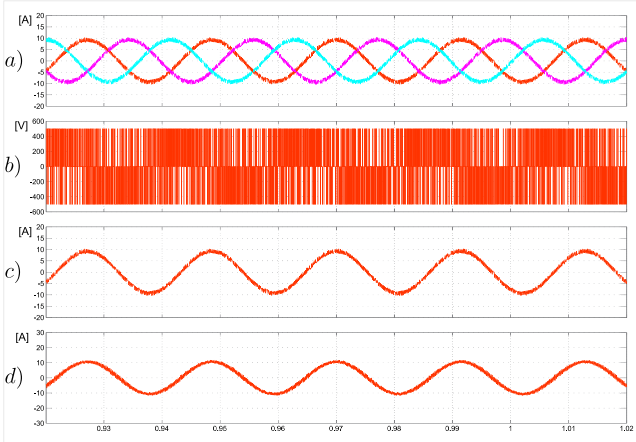

Fig. 13. Simulation of the tested inverter connected to the loaded inverter controlled with voltage - from above - a) Output currents from the three branches of the inverter [A] - b) Concatenate voltage between the branches A and B of the inverter [V] - c) Output current from branch A of the inverter [A] - d) Current of phase A of the IPMSM [A].