CONTROL METHODS OF AN SINGLE STATOR DUAL ROTOR PMSM

Associate Prof. Eng. **Lucian TUTELEA** PhD., Assoc. Prof. Eng. **Sorin-Ioan DEACONU** PhD,
Lecturer Eng. **Gabriel-Nicolae POPA** PhD

Politehnica University of Timisoara

REZUMAT. Sistemele actuale pentru vehiculele electrice hibride paralel necesita două maşini electrice şi două invertoare. Pentru vehiculele electrice hibride de tip serie se utilizează un generator şi un motor distincte împreună cu convertoarele statice aferente , toate dimensionate la puterea nominală. Într-o încercare de simplificare se propune o soluţie de înlocuire a celor două maşini şi a celor două convertoare cu o singură maşină electrică cu întrefier axial cu un stator bobinat pe ambele părţi , două rotoare cu magneţi permanenţi având număr de poli diferiţi şi un invertor PWM.

Cuvinte cheie: maşină cu întrefier axial cu magneţi permanenţi, un convertor de tip PWM, metode de control

ABSTRACT. The actual solution for the parallel Hybrid Electric Vehicle (HEV) requires two electric machines, two inverters. A distinct electric generator and a propulsion electric motor, both with full power converters, are typical for a series HEV. In an effort to simplify we hereby propose to replace the basically two electric machines and their two power converters by a single, axial-air-gap, electric machine central stator, fed from a single PWM converter with dual frequency voltage output and two independent PM rotors.

Keywords: axial air-gap machine, dual PM rotors, single stator, single PWM converter, control methods of drive.

1. INTRODUCTION

The change from classic vehicles (ICEVs) to electric vehicles (EVs) cannot be suddenly made, due to the non-existence of the necessary infrastructure for reloading the accumulator batteries on one side, and the high duration of this process on the other side. The intermediary solution is represented by the hybrid electric vehicles (HEVs). Currently, almost all the automotive producing companies have developped at least one hybrid model.

There are four main types of HEVs (micro, mild, power assist (full) and plug-in). The micro HEV is only featured by: electric cranking, engine off at idle and mild regeneration during vehicle's braking. For mild HEV more regeneration and some torque assist are added. The power levels are less than 6-10kW in general [1]-[3].

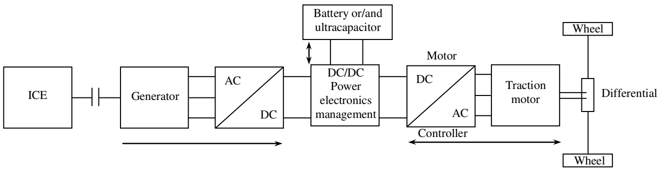

Fig. 1 Series HEV powertrain

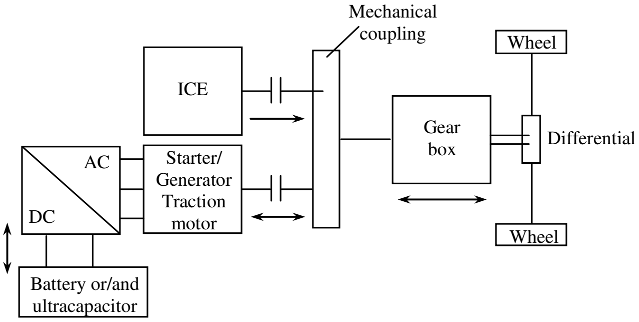

Fig. 2 Parallel HEV hybrid powertrain (with one electric machine)

For basic full HEVs there are quite a few HEVs topologies. Historically, there are series HEVs (fig.1), parallel HEVs (fig.2) [3], and series-parallel configurations.

The drawbacks of the series HEVs over parallel types are the requirements for two electric machines and larger dimensions for the traction motor, in addition to the losses incurred during the conversion of mechanical to electric energy and back to mechanical energy again. On the other hand, the mechanically decoupled structure of the engine from the wheels in HEVs also presents some advantages: very low operating noise, higher efficiency levels for the engine and low-level dynamic control [4], [5].

In parallel hybrid vehicles the engine directly delivers its mechanical power to the driven wheels. The major disadvantage is that the engine cannot always operate in a narrow speed region, because of its mechanical coupling to the driven wheels. Thus, the average engine efficiency is lower than that in the series hybrid drive train [3].

One of the most important components as regards the design of HEVs drive trains is the electric traction motor-controller unit. Traction motors employed in HEV drive trains usually use efficiency maps to describe total efficiency with respect to particular speed/torque combinations [6]. Basically, a hybrid propulsion system includes two electric machines: one is used to while drive; while the other is mainly used for battery charge. Although these machines play different roles, their operating cycles are more or less linked. Moreover, their locations within the power train represent a drawback from the point of view of volume optimization. Therefore, the integration of both machines into an electromechanical set, in an attempt to improve the compactness and the cost-effectiveness, is currently considered a challenging technology.

Chapter 2 approaches the constructive problems and the designing and chapter 3, the problems related to the control of this machine, being approached the control version with a single inverter of the two serial windings.

2. CONSTRUCTION AND DESIGN

Hybrid electric vehicles (HEV) are considered the way of the future for automobiles, to reduce energy consumption and air pollution. A key problem with HEV is the electric propulsion corroboration with the thermal engine (ICE) such that the latter is allowed to operate close to the sweet point (torque and speed for maximum efficiency or minimum emission) indifferent to the vehicle speed.

In an effort to simplify the planetary-geared e-CVT for the parallel HEV (Fig. 2) or the series HEV (Fig. 1) we hereby propose to replace the basically two electric machines and their two power converters by a single axial-air-gap electric machine central stator, fed from a single PWM converter with dual frequency voltage output ($V_1(f_1)$, $V_1(f_2)$) and two independent PM rotors with $2p_1$ and $2p_2$ poles placed on the sides of the central stator with N_{st} slots and a tooth-wound (or Gramme) winding, one placed on one side and another side of the slotted magnetic core, the two groups can be connected in parallel or in series. An important advantage of using the synchronous axial air-gap single stator dual-rotor permanent magnet machine is representing the smaller length, this being able to be introduced in the clutch's place between the motor and the gearbox. A few 3D drawings of the machine are shown in Fig. 3.

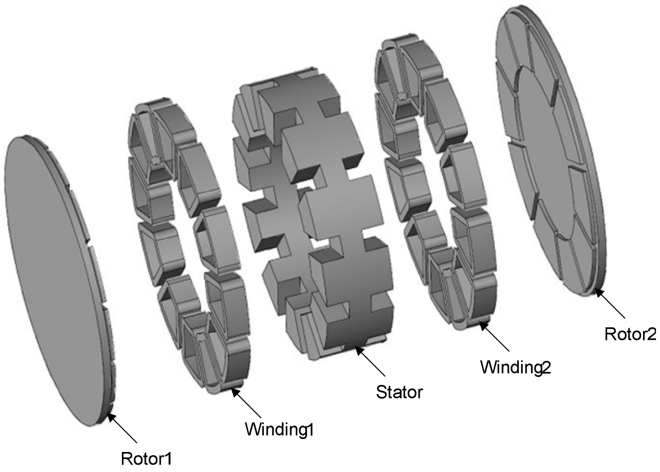

Fig. 3 Three-dimensional exploded view of the proposed machine

The axial flux permanent magnet machines with double rotor and single stator has smaller axial length than the corresponding solution with radial flux, for given larger than 6 number of poles and diameter. The different number of poles may impose a rather different amount of permanent material but if we select the arc pole ratio adequately it is possible to use the same amount of permanent magnet material on both rotors. The key to this machine construction is the way the laminations are assembled. It has presented a formidable problem over the years but manufacturing solutions have been around to mitigate the complexities of manufacturing the laminations and their assembly.

3. VECTOR CONTROL STRATEGY AND DYNAMIC SIMULATION

The mixture of 2 frequencies in the inverter output voltage (with corresponding phase angles) leads to two different speeds ω_{r1} and ω_{r2} in the two rotors and different positive (or negative) torques as required. Both frequencies voltages and their currents travel the whole single stator winding coils sides, though only the left side produces torque at ω_{r1} speed and only the right side interacts to produce torque at ω_{r2} speed. This implies additional copper losses in the stator but if the end connections are kept small, part of this inconveniency is removed. On the other hand, the single inverter has to handle the entire apparent power related to the interaction of stator magnetic fields with both rotors at different speeds. Only when the two frequency are equal (and electric rotor speeds related by $\omega_{r1} = \omega_{r2}$ ($n_1p_1 = n_2p_2$), a direct transfer of power directly through the winding, for say, one motoring and one generating operation modes, seems to be possible. Apart from the evident simplification and compactness of the proposed solution, attempts to reduce somewhat the inverter power rating based on motor/generator simultaneity are worth trying. Though there will be ω_2 - ω_1 torque pulsations from one frequency (rotor) to the other, the torque stress on the stator will be reduced when one rotor is motoring and one is generating [6]-[10].

A. Speed control strategy

The first proposed dual vector control strategy is illustrated in Fig. 4 via a dedicate Matlab Simulink Code, for the speed control mode and windings in series. The objective of the dynamic simulation is to evaluate the dynamic and steady state operation of the dual vector control algorithm using two frequency modulation operations. In Fig. 5 was presented the control block, Fig. 6 shows the Simulink diagram of the single stator dual PM rotors axial synchronous machine, and in Fig. 7 is the inverter model.

The simulation results for this control mode are shown in Fig. 8, 9 and 10. There is noticed that the mechanical velocities both at reduced and increased reference have pulsations and the velocity of rotor number 2 hardly increases ,not succeeding into reaching the predicted value. The tension is limited and the current has high peak values. Also, the torques of the two rotors have great pulsations.

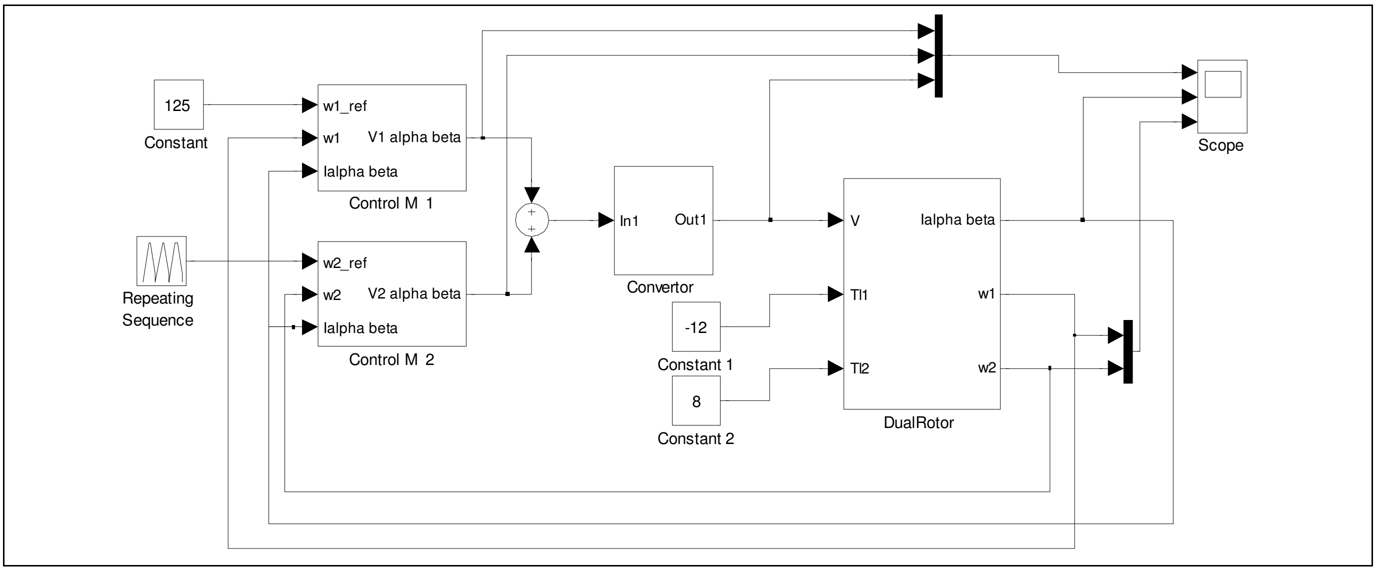

Fig.4 Simulink diagram of the drive system with double speed control

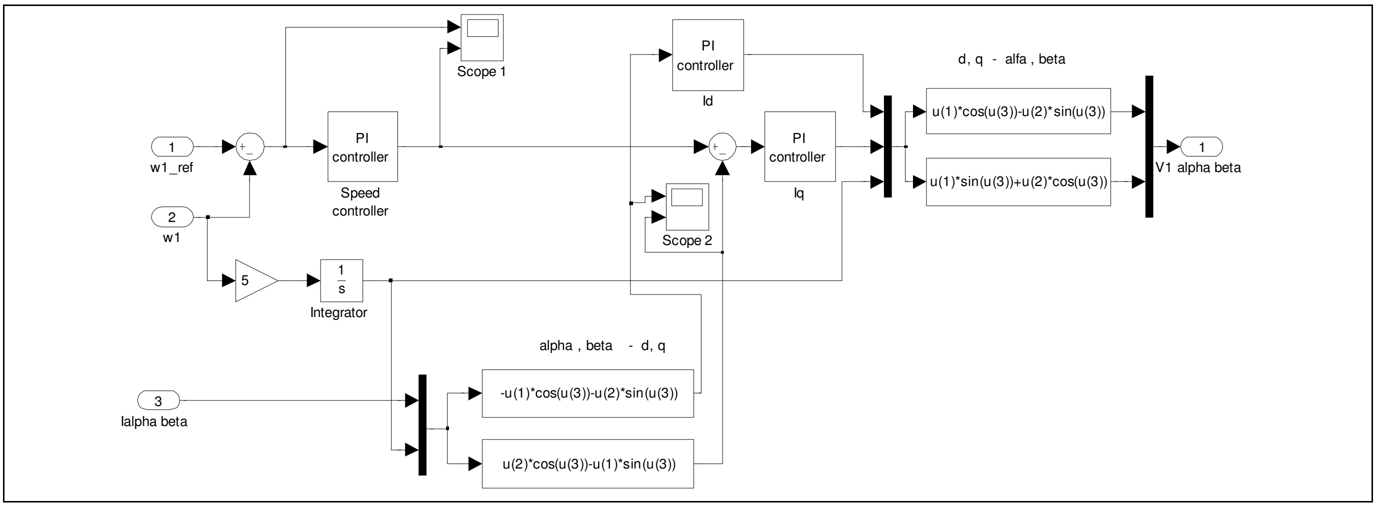

Fig. 5 Control of rotor 1 strategy with double speed control

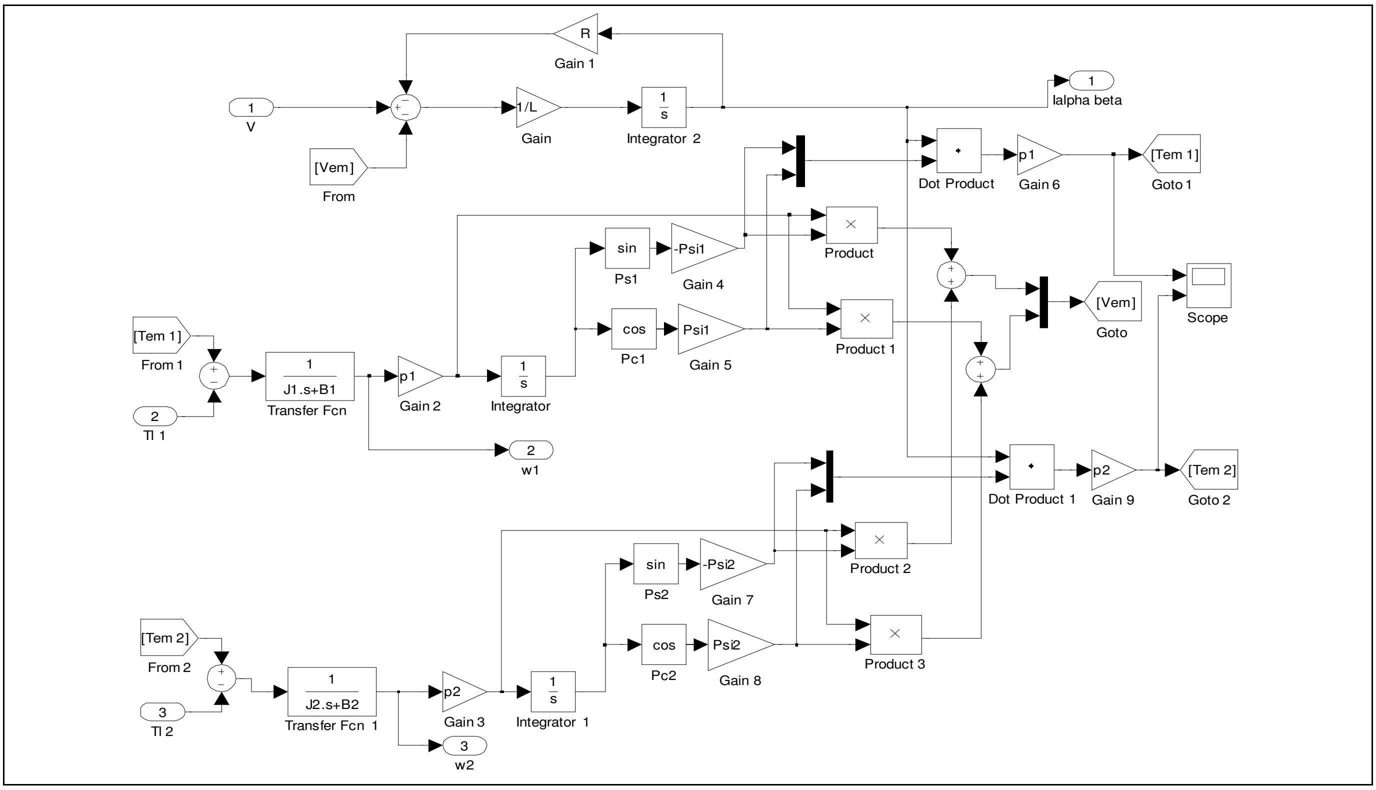

Fig. 6 Dual rotor single stator machine model

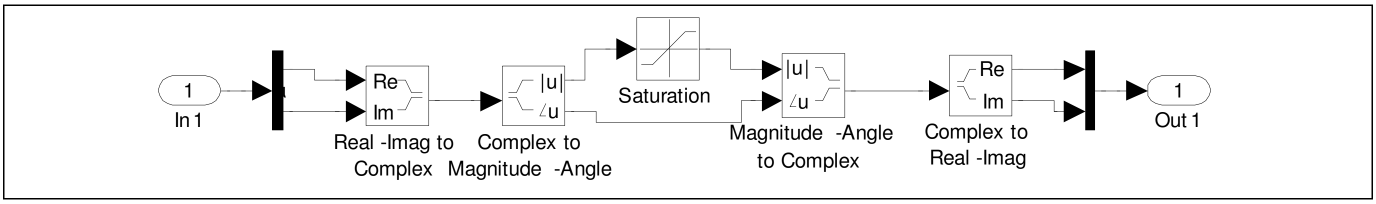

Fig. 7 Inverter model

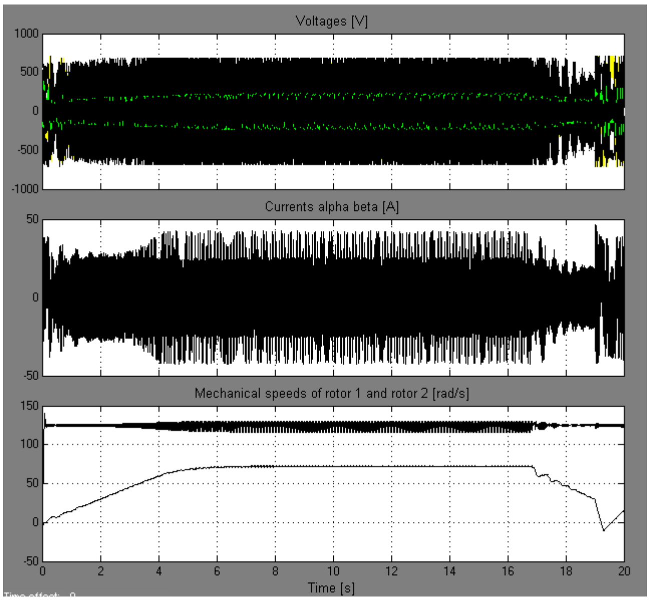

Fig. 8 Voltages, currents and speeds of dual rotor single stator machine with double speed control

In Fig. 11 are presented a dedicate Matlab Simulink Code, for the torque and speed control mode and in Fig. 12 the mechanical speeds in this case.

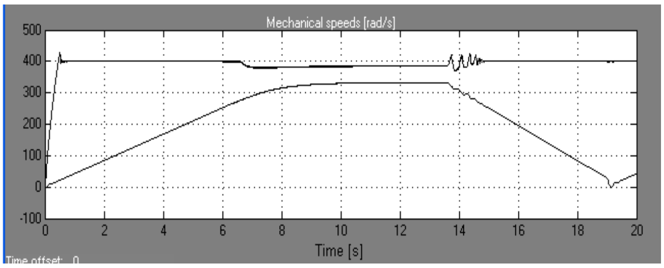

Fig. 9 Speeds variation at high reference value

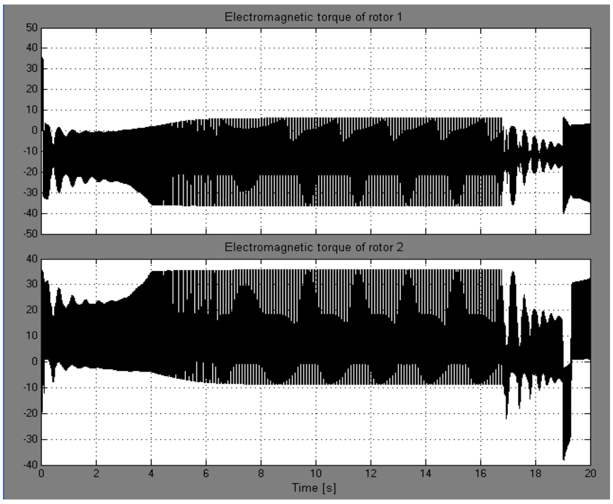

Fig. 10 Torque of rotor1 and rotor 2 for dual rotor single stator machine with double speed control

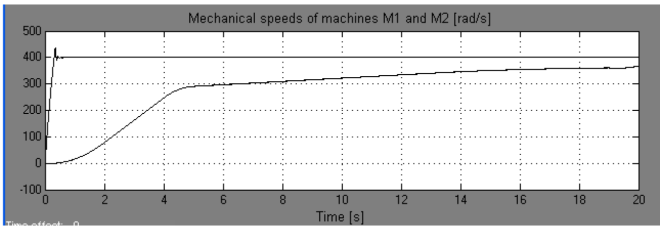

Fig. 12 Mechanical speeds of rotors with torque and speed control

B. Torque control strategy

We assume that the stator windings are connected in series and the objective of the dynamic simulation is to evaluate the dynamic and steady state operation of the dual vector control algorithm using two frequencies modulation operation. Fig. 13 illustrates this vector control strategy.

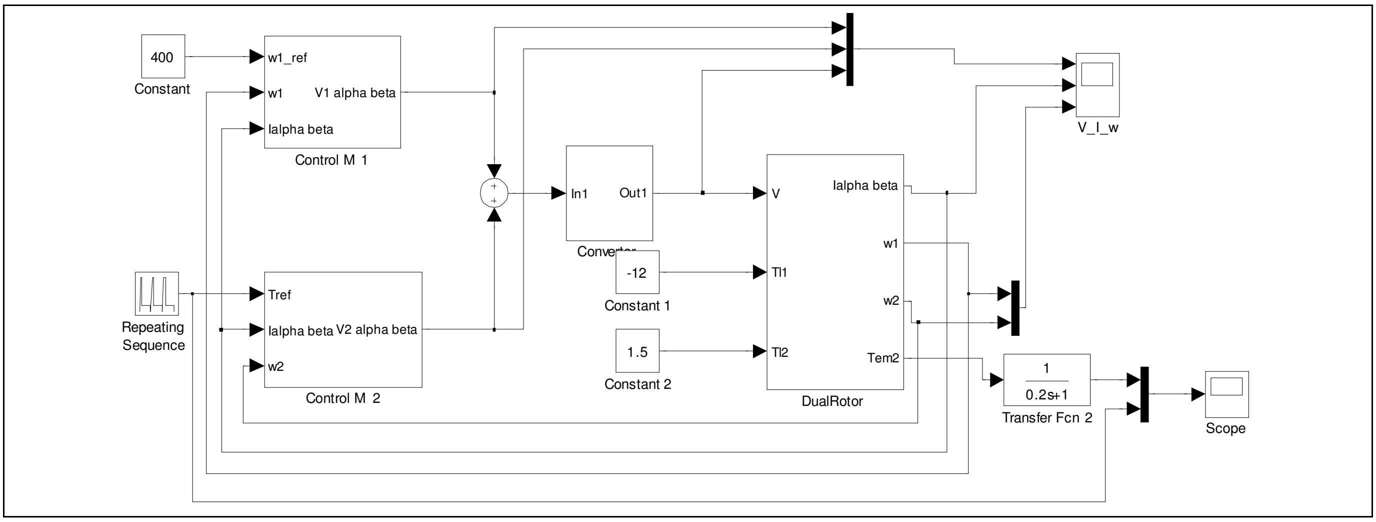

Fig.11 Simulink diagram of the drive system with torque and speed control

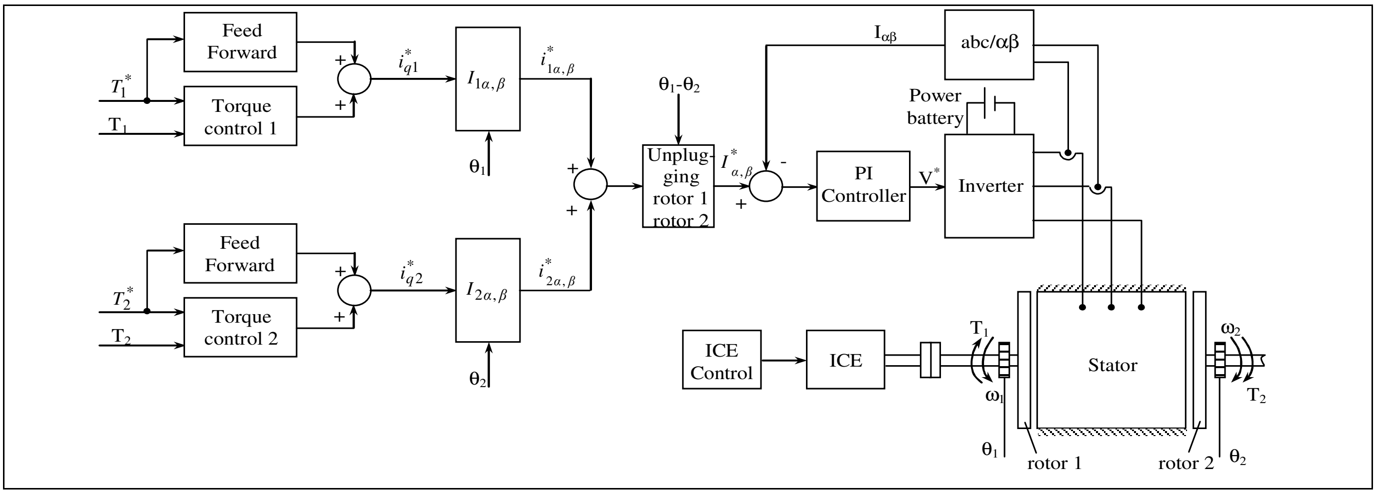

Fig. 13 The proposed dual vector torque control strategy

The dual vector control strategy is illustrated in fig. 14 via a dedicate Matlab Simulink Code, for the dual torque control mode. Figure 15 show the Simulink diagram of the advanced dual torque controllers of the AFPM drive, respectively. The drive torque of the thermal motor in stationary regime is equal with the electromagnetic torque of rotor 1 (Fig. 17). In Fig. 17 is presented the torque reference for the rotor 2 and the torque achieved by this, observing that is monitored the reference with quite high accuracy. The strongest oscillations that appear both in the torque of rotor 2 and the rotor 1 have place in the moment when the electric speeds of the two rotors become equal (Fig. 16). The delay between the reference and the achieved value is due to the rank 1 filter with a time constant of 0.2 s. The speed of rotor 1 reaches rapidly to the reference value imposed to the thermal motor and the speed of rotor 2 results depending on the torque reference (Fig. 16). Equalizing the electric speeds, it appears an oscillation but passing is made quite easily.

In the electric speeds' equalizing area the current shows an increase. To be noticed also the current and voltage modulation, specific to the components that contain two frequencies.

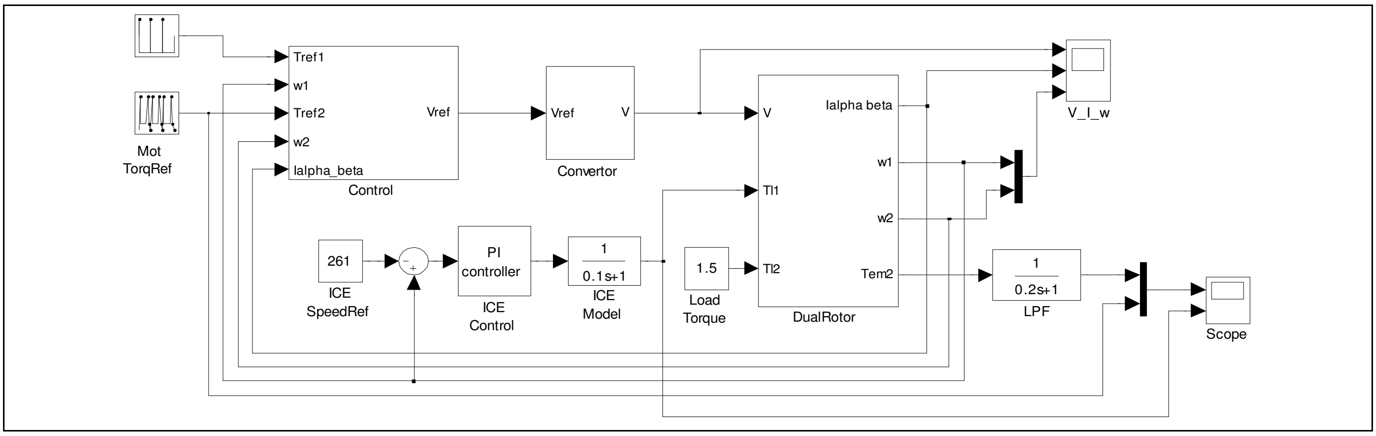

Fig.14 Simulink diagram of the drive system with double torque control

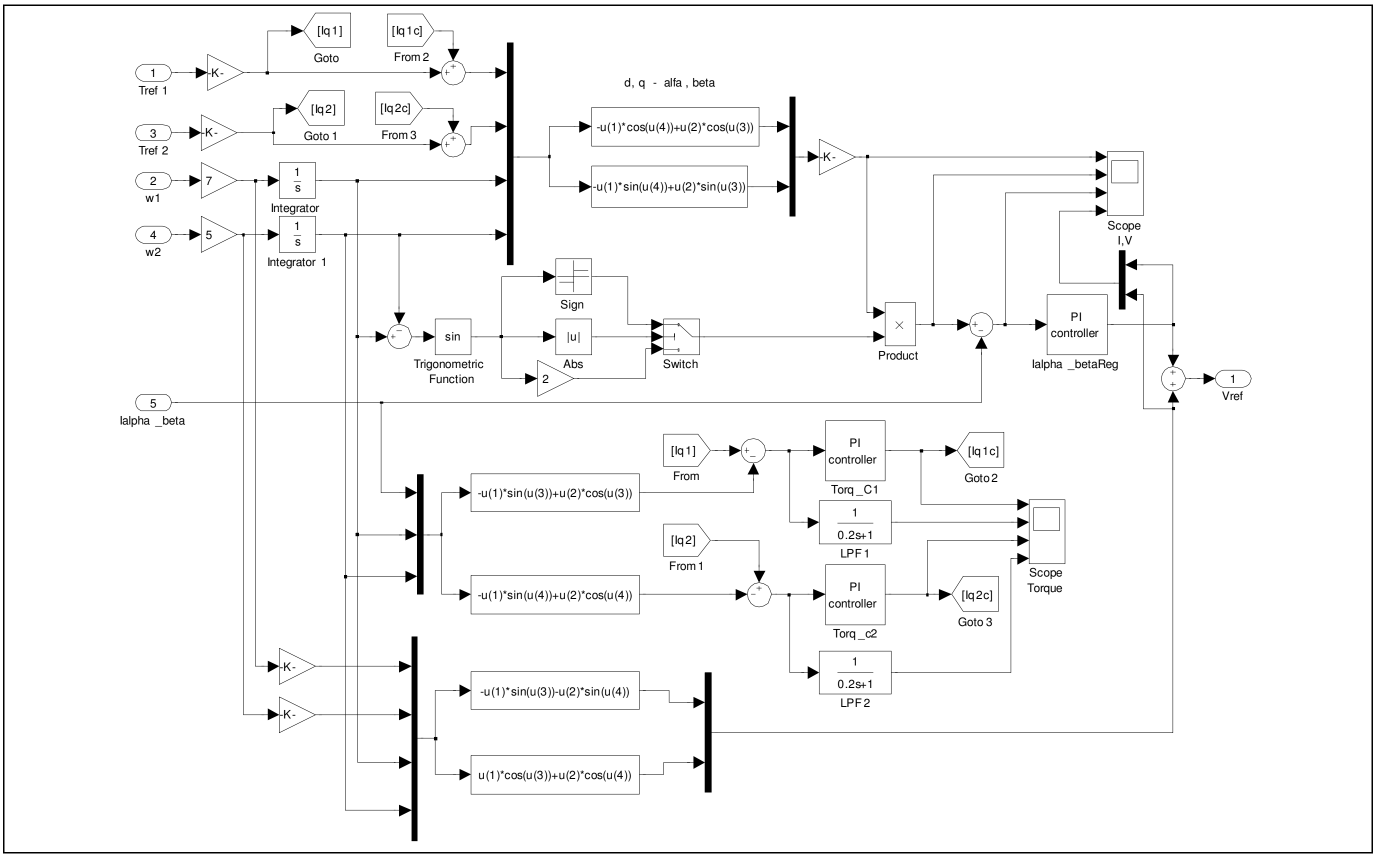

Fig. 15 Single block control strategy of two rotors with double torque control

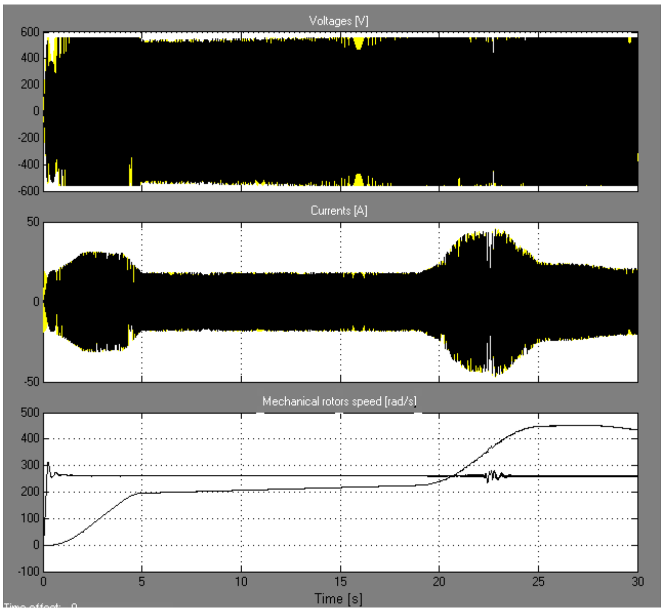

Fig. 16 Voltages , currents and speeds of dual rotor single stator machine with double torque control

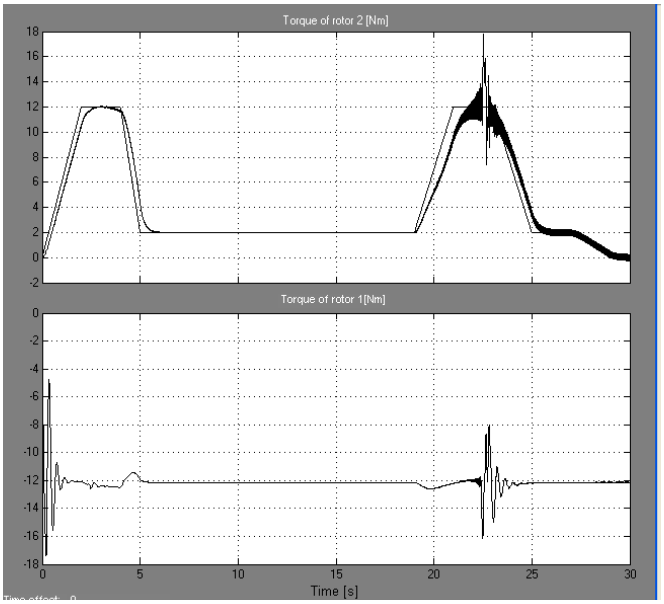

Fig. 17 Torque of rotor2 and rotor 1 for dual rotor single stator machine with double torque control

4. CONCLUSIONS

A rather extended simulation for two cases was considered (steady state and dynamic). The dual vector speed control for the independent rotors with one common stator is presented and proven to be effective. The next steep was the dual vector torque control simulations. The single stator dual-rotors permanent magnet axial synchronous machine can be controlled by a single inverter and two frequencies, the two rotors being able to operate both as motor and as generator in a wide speed range, in the same sense or in different senses. By simulation is shown that the rotors reach at a certain moment in the situation of equality of the electric speeds, the power transfer between generator and motor being made directly without the inverter, and the transitory regime due to this equality is exceeded without important torque oscillations and speed. It is found also that passing from one operation regime into another (motor-generator or reverse) is made rapidly and easier.

These preliminary results prove the concept quantitatively but further studies in relation to prototyping are needed to fully prove the practicality of the proposed system.

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About the authors

Associate Prof. Eng. **Lucian TUTELEA** PhD.
Politehnica University of Timisoara
email:luci@lselinux.upt.ro

Lucian Tutelea was born in Alba, Romania. He received the B.E. and Ph.D. degrees in electrical engineering from the University Politehnica of Timisoara, Romania, in 1989 and 1997, respectively. He is currently an Assistant Professor at the University Politehnica of Timisoara in the Department of Electric Drives and Power Electronics. His research interests include design and control of electrical machines and drives.

Assoc. Prof. Eng. **Sorin-Ioan DEACONU** PhD.
Politehnica University of Timisoara
email:sorin.deaconu@fih.upt.ro

Sorin I. Deaconu (M'07) was born in Orastie, Romania, in 1965. He received the B. S. degree in electrical engineering in 1989 and Ph.D. degree in electrical machines in 1998 from "Politechnica" University of Timisoara, Romania. He is currently Associate Professor at the Department of Electrical Engineering and Industrial Informatics, Engineering Faculty of Hunedoara, "Politechnica" University of Timisoara. He has authored almost 160 international papers in the field of electrical machines, electrostatics, electric arc furnaces and renewable energy. Since 1994, he has collaborated with Bee Speed Automation Ltd, Timisoara, where he is involved in several industry projects regarding industrial automation, machines and drives.

Lecturer Eng. **Gabriel-Nicolae POPA** PhD.
Politehnica University of Timisoara
email:gabriel.popa@fih.upt.ro

Gabriel N. Popa (M '09) was born in Hunedoara, Romania, 1973. He received the B.Sc. in electromechanical engineering from the Politechnica University Timisoara, Romania in 1996, M.Sc. and Ph.D. degrees from the Politechnica University Timisoara in 1997 and 2004, respectively, both in electrical engineering.
He is currently lecturer of electrical engineering at Faculty of Engineering Hunedoara, Politechnica University Timisoara, Romania. His current research interests are electrical equipments used in electrotechnology, power compensations systems, and power electronics for motor drives.