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CURRENT AND TORQUE CONTROL OF MULTI-CONVERTER MULTI-MACHINE SYSTEMS

BY

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Abstract. This paper studies original and efficient power division methods for ac high power converters and machines. The rated power of the elementary converters and/or machines becomes lower when the number of converters and/or machines increases. Therefore, power switches with high switching frequency can be used. Then, the current and torque ripples would have theoretically lower amplitude. This paper aims to analyse the pseudo multi-converters and/or the pseudo multi-machines system. First of all, one presents the different structures of multi-converters multi-machines, as well as the specific vocabulary that has been defined for these structures. One is going also to define the elements forming a chain of conversion. Simulations of three examples of these systems are presented. Three current and torque control methods will be also discussed and compared.

Key words: multi-converter; five leg inverter; multi-machine; double stator machine; power division; control; simulation.

1. Introduction

Electrical propulsion in embarked applications like ships, aircraft, etc., requires high power machines with variable speed drives. In this field, ac machines are increasingly used. These machines can be supplied by GTO

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Voltage-Source Inverter (VSI). The disadvantage is the low commutation frequency of the GTO and, consequently, the important current and torque ripples. In order to reduce these ripples it is necessary to use high commutation frequency semi-conductor devices. Several solutions based on power division can be envisaged.

Actually, in high power applications, association of multi-converters with multi-machines is developed. For economic reasons, these electric systems may share some resources in the energizing chain which imply some couplings between the various components. Taking into account these couplings, the system passes by a global approach of the set of the electric components connected to a same supplying source. The global system is defined then by the denomination "Multi-Converter Multi-Machine System (MMS)". It is composed of coupled subsystems which are going to interact between them.

A MMS can be divided, for example, in subsystems of mono-converter and/or mono-machine. Switches with reduced power rating and higher switching frequency can therefore be used. The modularity of the used converters, as well as the possibility of functioning with one or more than one converter in service, make the MMS very attractive.

The paper is organized as follows. Section **2** is devoted to a review regarding the different structures of multi-converter multi-machine systems. Section **3** presents specific vocabulary for these structures and defines the elements forming a chain of conversion. In the fourth Section, simulations of some examples of multi-converter multi-machine systems are given. In Section **5**, three current control methods are applied to the studied examples. Simulation results of currents and torque waveforms are presented and analysed in Section **6**. Finally, conclusions are given in Section **7**.

2. Structures of Multi-Converter Multi-Machine Systems

During these last years, the evolution of the studies in the domain of the industrial systems permits to present more and more effective systems. A graphic formalism is proposed in order to present the various structures of Multi-Converter Multi-Machine Systems (MMS): a rectangle for a converter, a circle for a machine (Moubayed, 1999 ; Bouscayrol *et al*., 2000). Two elements sharing common resources are represented by two diagrams having a domain of intersection (Fig. 1).

The different systems are defined as follows:

a) *Mono-Machine System*. It is composed of only one machine. The number of the phases is superior or equal to two.

b) *Mono-Converter System*. It is composed of only one converter whose components possess the same power ratings. The number of the legs is superior or equal to two.

c) *Multi-Machine System*. It is composed of several machines not sharing any physical resources and being able to be therefore independent.

d) *Multi-Converter System*. It is composed of several converters not sharing any physical resources and being able to be therefore independent.

e) *Pseudo Multi-Machine System*. It is composed of several machines sharing physical resources (magnetic coupling). The number of phases is a multiple of three.

f) *Pseudo Multi-Converter System*. It is composed of several converters sharing physical resources (electric coupling). The components of the leg placed in common do not have the same power rating as those of the other legs.

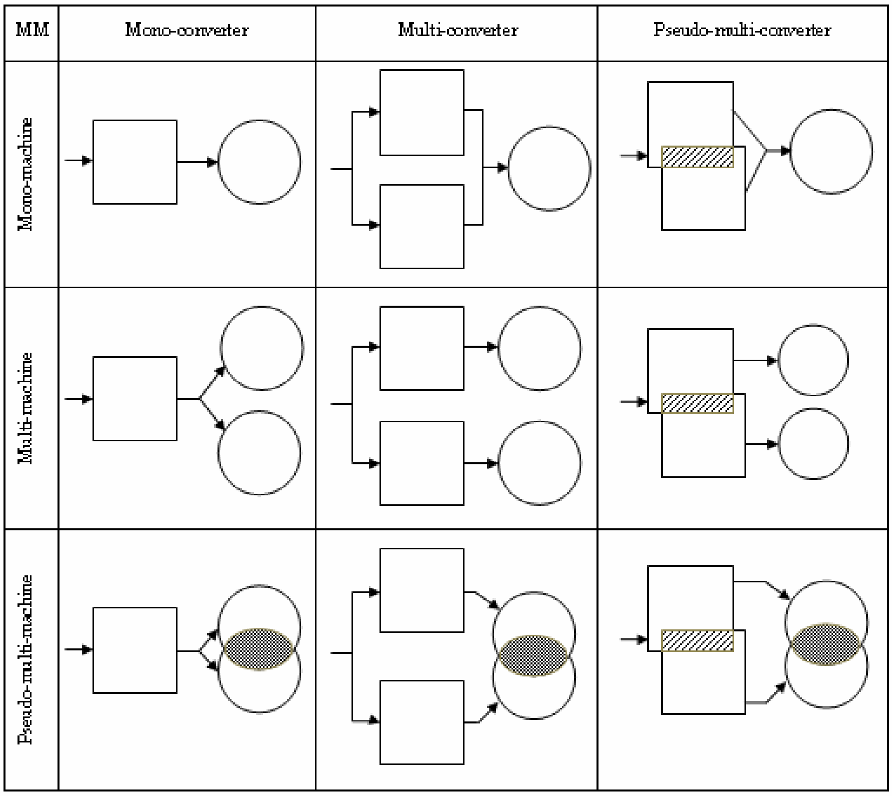


Fig. 1 – General classification.

3. Characterization of Electromechanical Chain of Conversion

The notions of energizing conversion are now restricted to the Electro-mechanical Conversion (EC): the used sources are or of electric nature either of mechanical one (Bouscayrol *et al*., 2000).

3.1. Elementary Chain of Electromechanical Conversion

An elementary chain of electromechanical conversion (Fig. 2) assures an energizing transfer between an electric source (SE) and a mechanical one (SM).

This chain is composed of three elements of conversion possessing each one a control input namely

1° The electric converter, (CE – square pictogram), assures a production of the electric energy (dc, ac, etc.). Its control input is indicated by *cereg*. An example of an electric converter is a static converter or a filter.

2° The electric machine, (ME – circular pictogram), assures an electromechanical conversion. Its control input is indicated by *mereg*. Example: a dc machine regulated by its field voltage.

3° The mechanical converter, (CM – triangular pictogram), assures an adaptation of the mechanical energy between the machine and the mechanical source. Its control input is indicated by *cmreg*. Example: a gear to adapt the speed of rotation.

Some element of the electromechanical conversion chain can function without control parameters. Examples: a mechanical reducer with fixed ratio, the squirrel cage asynchronous machine.

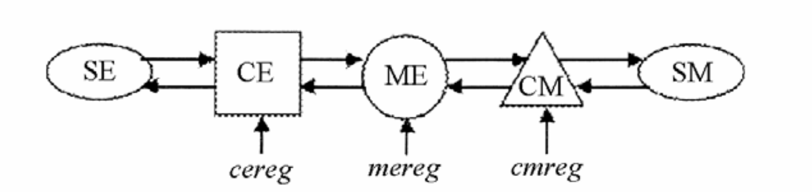


Fig. 2 – Elementary chain of electromechanical conversion.

3.2. Chain Presenting a Multi-Machine–Multi-Converter Systems

Some elements of conversion have as goal to assure an energizing conversion between *n* input sources and *p* output sources. Chains of conversion are thus coupled (Fig. 3). The EC can be composed in several coupled structures.

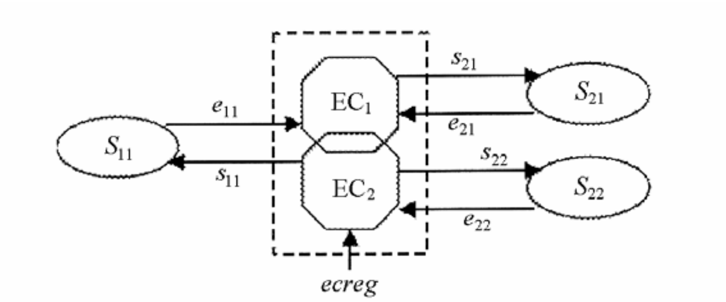


Fig. 3 – Example of coupling conversion.

In a coupling structure, some circuits and/or components are placed in common. This implies that these circuits or components should be of high rated power. The couplings allow the transfer of disruptions between chains of conversion that can lead some instability. But the possibility of distributing the energy between the various subsystems offers an incontestable advantage as for flexibility and reliability of the global system. Indeed, workings in damaged state are possible by eliminating all damaged subsystems.

4. Examples on Multi-Converter–Multi-Machine Systems

In order to explain the functioning of some MMS, this section contains

1° A system presenting an electric coupling: five legs Voltage Source Inverter (VSI) supplying two independent permanent magnets synchronous machines.

2° A system presenting a magnetic coupling: double stator permanent magnets synchronous machine supplied by two independent three phase VSI.

3° A system presenting electric and magnetic couplings: five legs inverter supplying double stator synchronous machine.

To simplify this study, it should be supposed that

a) the used machine is not saturated;

b) iron and all types of losses are neglected;

c) the inductances of the machine are constant;

d) the coils distributions are sinusoidal.

The proposed open loop control method applied to the used VSI is the technical Pulse Width Modulation (PWM) method.

4.1. Two Independent Synchronous Machines Supplied by a Five Legs VSI

Fig. 4 shows an example of an electrical coupling existing in a VSI. This inverter supplies two different permanent magnets synchronous machines (*A* and *B*) of different rated power (Zaiter *et al*., Aleppo, Syria, 2007; Bouscayrol *et al*., 2005).

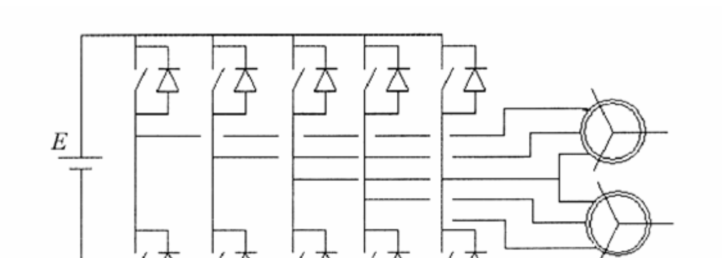


Fig. 4 – Two independent machines supplied by five legs VSI.

The two Park currents (i_d and i_q) of the equivalent model of each machine are presented in Fig. 5. As the used machines are of different rated power, these currents should take different values. In fact, the three phase current of each machine is shown in Fig. 6. These currents are also those supplied by the inverter, but, as this inverter has five legs, the current flowing in

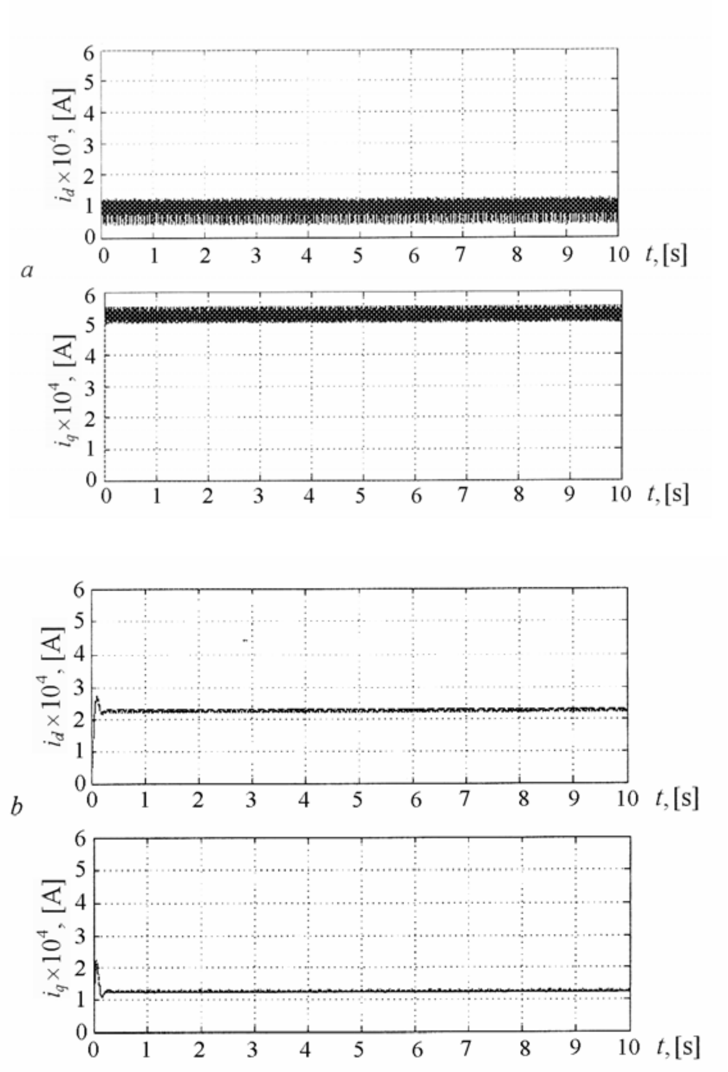


Fig. 5 – Park currents: *a* – Park currents in machine *A*;
b – Park currents in machine *B*.

the common leg should be equal to the sum of the third phase current of machine *A* and the third one of machine *B* (Fig. 7). Therefore, the common leg components should have a rated power greater than those of the other legs. Thus, five legs VSI can be connected to two machines of different or same rated power. These two machines develop different or same torques (Fig. 8).

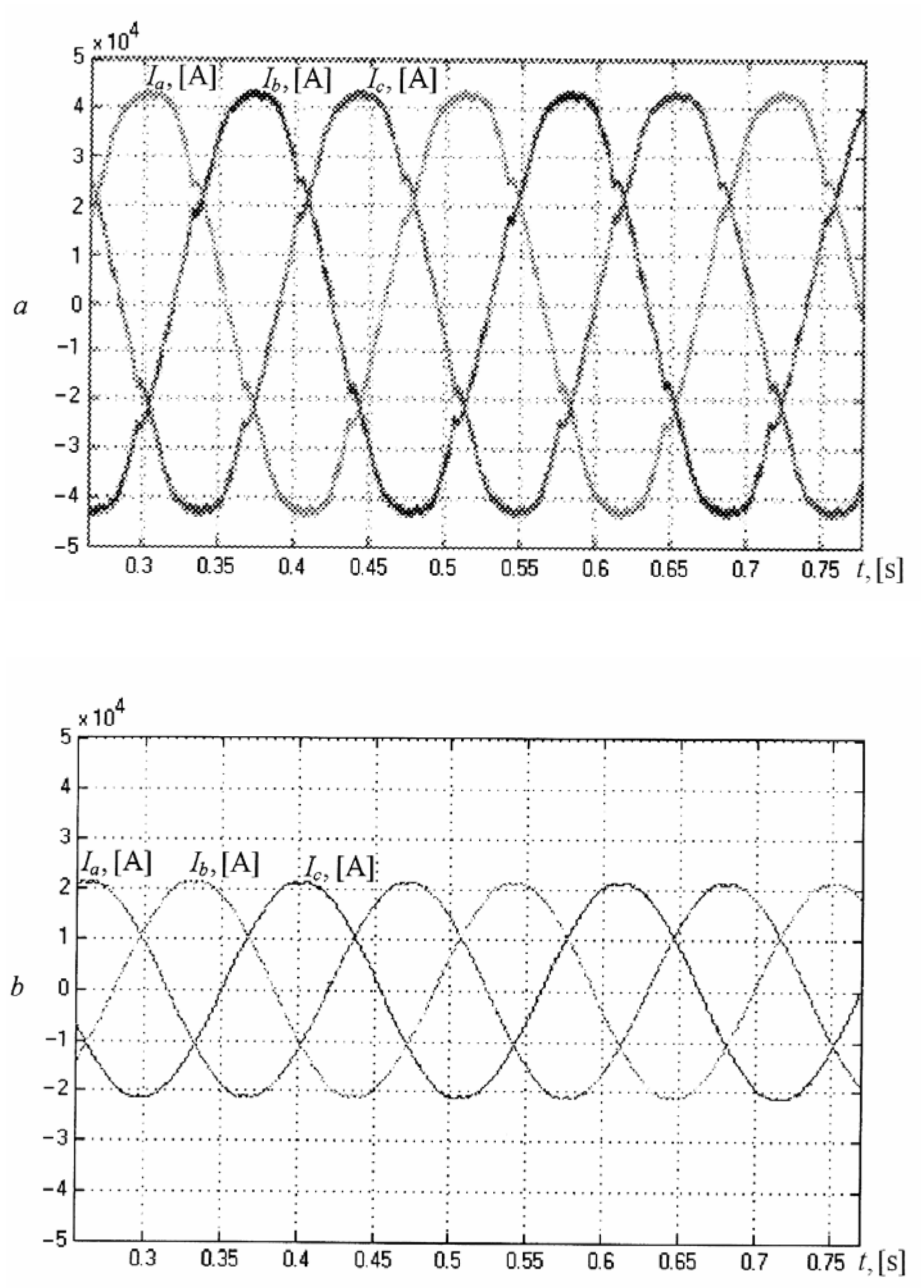


Fig. 6 – Machines stator currents: *a* – currents in machine *A*;
b – currents in machine *B*.

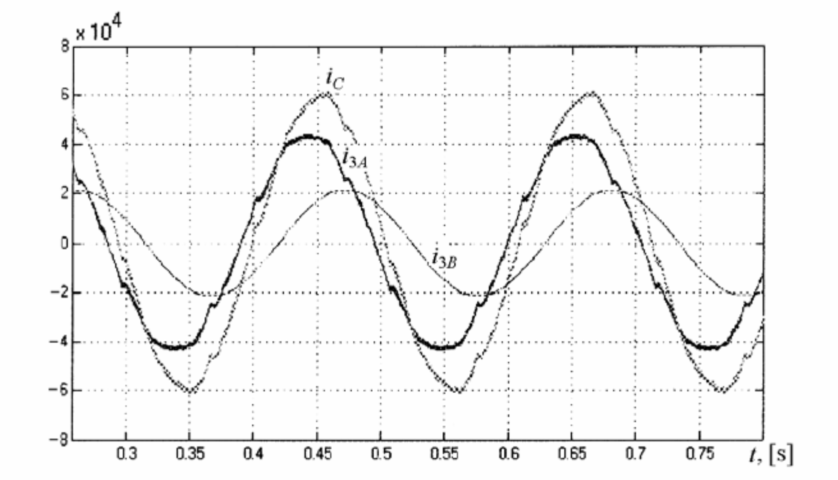


Fig. 7 – Currents i_{3A} and i_{3B} and the common leg current i_C.

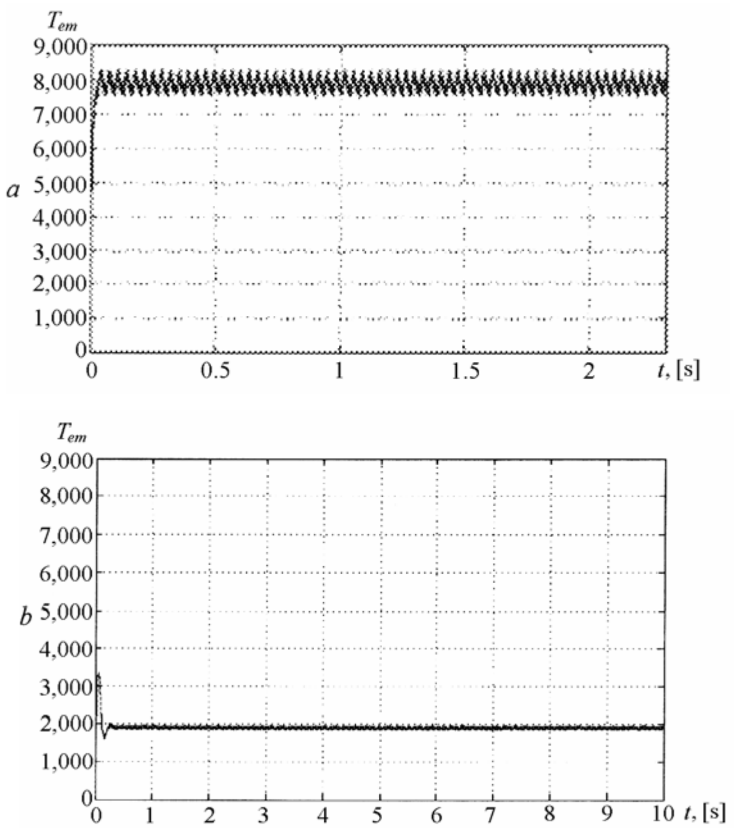


Fig. 8 – Torque in machines *A*, and *B*: *a* – torque in machine *A*;
a – torque in machine *B*

4.2. Double Stator Synchronous Machine Supplied by Two Independent PWM VSI

The studied machine is composed of two stars; each one is formed of three Y-connected windings. These stars can be shifted from each other by an electrical angle equal to γ. Each star is supplied by its own VSI (Fig. 9). The rotor contains permanent magnets. In this MMS the coupling is magnetic.

Fig. 10 shows the influence of the shifted angle on the current wave form. In fact, if the two stars are shifted, current ripples appear and can be dangerous for the two inverters and for the machine. These ripples, which appear only on the currents, do not affect the machine torque (Fig. 11).

The power division by using multi-star machines supplied by independent PWM VSI can not be applied except if the magnetic coupling between stars is weak (Moubayed, 1999; Moubayed *et al*., 1998). Or, in other case, the applied voltages to the homologous phases of the star windings should be instantaneously the same (inverters should be controlled by master–slave control strategy), and the star windings should not be shifted (El Ali *et al*., 2006; Moubayed *et al*., 1999).

To simplify this study, it should be supposed that

a) the used machine is not saturated;
b) iron and all types of losses are neglected;
c) the inductances of the machine are constant;
d) the coils distributions are sinusoidal.

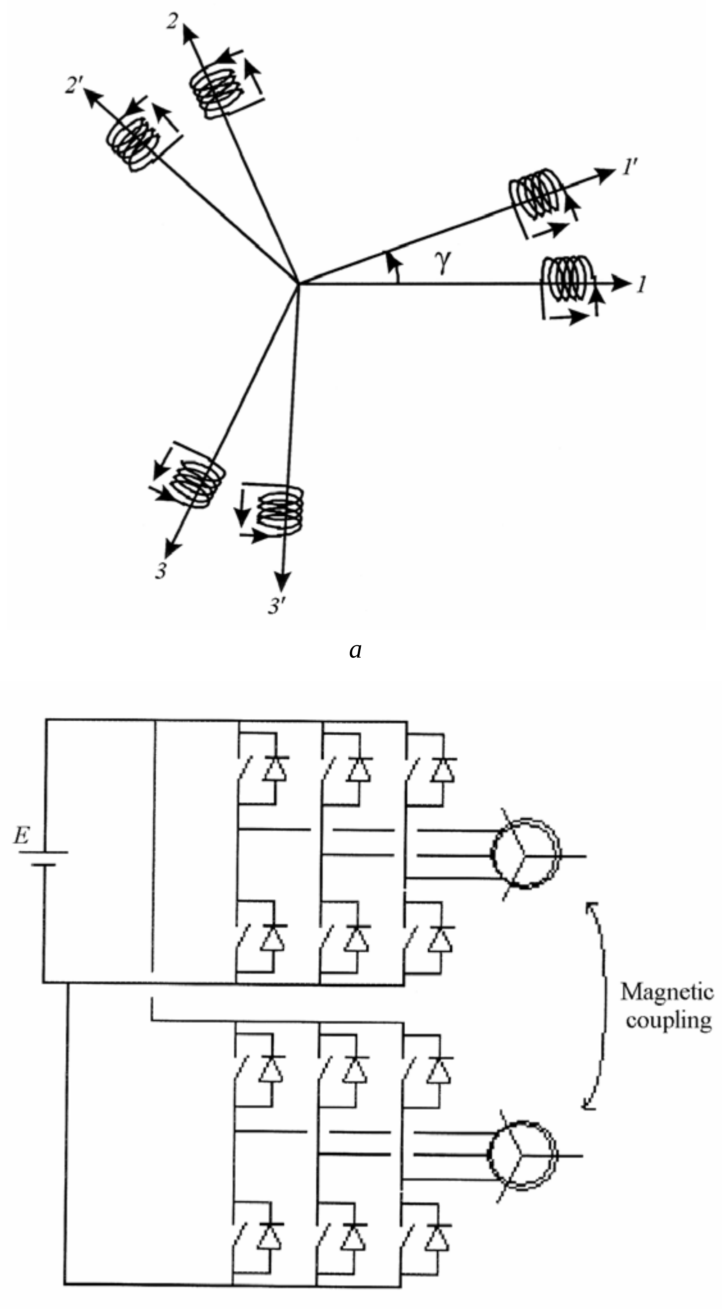
For the studied machine we note: i_k and $i_k^{'}$ are the currents flowing the k and k' phases of the two stators, (k = 1, 2 or 3), v_k and $v_k^{'}$ – the voltage across the k and k' phases of the two stators, e_k and $e_k^{'}$ – the emf of the k and k' phases of the two three phase windings; these emf are supposed to be sinusoidal; p is the number of pair of poles; l_s is the coil inductance, r – the winding resistance, $m\cos\xi$ is the mutual inductance between two windings delayed by an electric angle of ξ. The coefficient m is positive, $\left(m_{11}^{'} = m\cos\gamma\right)$.

The expressions of the voltages v_k and $v_k^{'}$ are:

$$v_k = ri_k + \frac{\mathrm{d}\phi_k}{\mathrm{d}t} + e_k, \quad v_k^{'} = ri_k^{'} + \frac{\mathrm{d}\phi_k^{'}}{\mathrm{d}t} + e_k^{'}, \tag{1}$$

where ϕ_k and $\phi_k^{'}$ are the generated flux in k and k' phases, respectively,

$$\begin{cases} \phi_k = \left(l_s + \dfrac{m}{2}\right)i_k + \dfrac{3m}{2}i_k^{'}\cos\gamma - \dfrac{m\sqrt{3}}{2}\left(i_{k+1}^{'} - i_{k+2}^{'}\right)\sin\gamma, \\ \phi_k^{'} = \left(l_s + \dfrac{m}{2}\right)i_k + \dfrac{3m}{2}i_k^{'}\cos\gamma + \dfrac{m\sqrt{3}}{2}\left(i_{k+1}^{'} - i_{k+2}^{'}\right)\sin\gamma. \end{cases} \tag{2}$$



a

b

Fig. 9 – Double stator synchronous machine supplied by two independent VSI:
a – double stator; *b* – multi converter – double stator machine.

The emfs e_k and $e_k^{'}$ take the form

$$e_k = E\sqrt{2}\sin\left[\omega t - \left(k-1\right)\frac{2\pi}{3}\right],\ \ e_k^{'} = E\sqrt{2}\sin\left[\omega t - \left(k-1\right)\frac{2\pi}{3} - \gamma\right], \qquad (3)$$

where ω is the electric speed.

The torque expression of the studied machine is

$$T = \frac{p}{\omega}\left[\left(e_1 i_1 + e_2 i_2 + e_3 i_3\right) + \left(e_1^{'} i_1^{'} + e_2^{'} i_2^{'} + e_3^{'} i_3^{'}\right)\right]. \qquad (4)$$

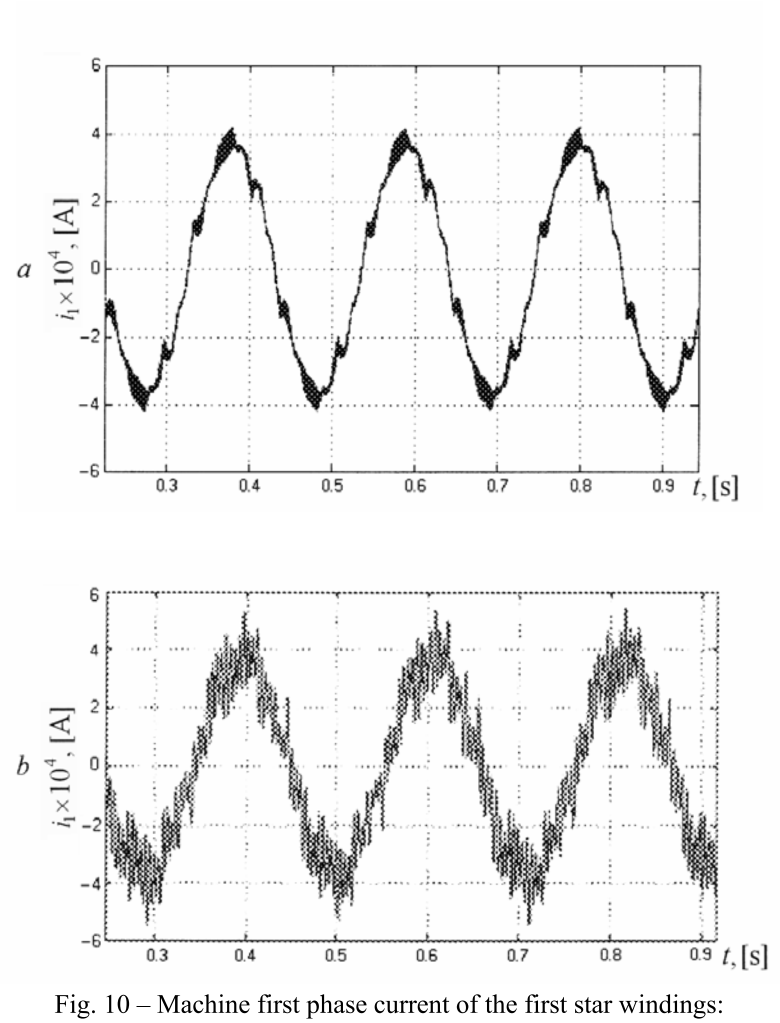


Fig. 10 – Machine first phase current of the first star windings:
a – non shifted stars; *b* – stars shifted by 30 degrees.

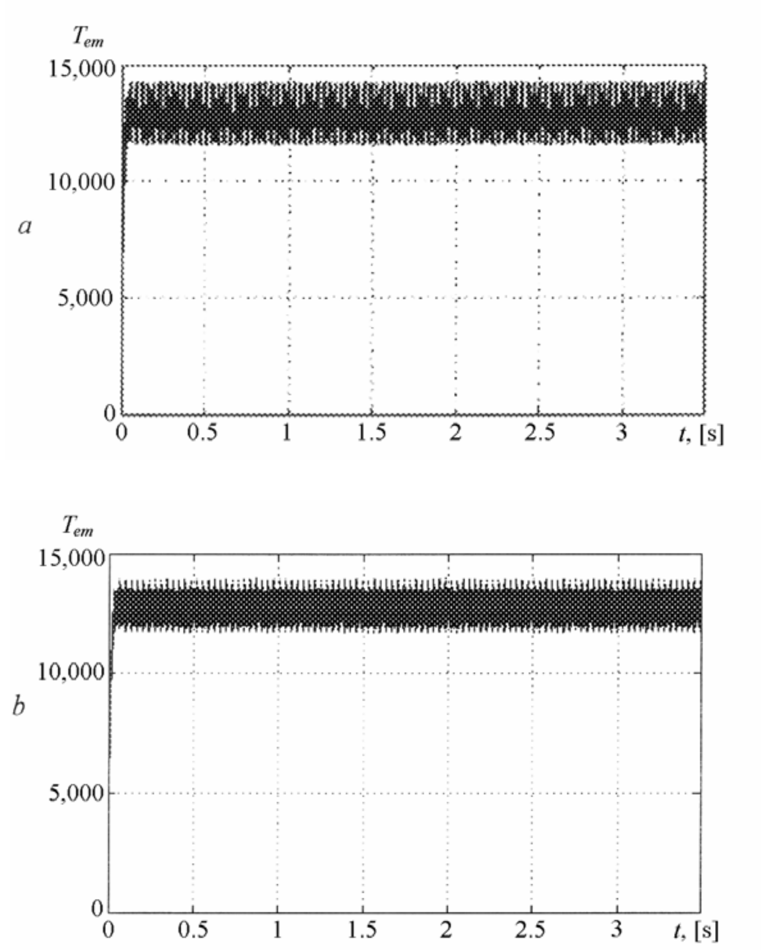


Fig. 11 – Machine torque: *a* – non shifted stars;
b – stars shifted by 30 degrees.

4.3. Double Stator Synchronous Machine Supplied by a Five Legs VSI

An example of electrical and magnetic couplings is presented in Fig. 12. This system is composed of one double stator synchronous permanent magnets machine (magnetic coupling) supplied by a five legs VSI (electrical coupling) (Zaiter *et al*., Amman, Jordan, 2007).

Fig, 13 shows the Park currents in each star windings of the studied machine. As the two stars are not shifted the currents wave forms are ripples free (Fig. 14 *a*). The inverter common leg should contain components of high power rating compared to those placed in the other legs (Fig. 14 *b*). The developed motor torque of the studied machine is represented in Fig. 15.

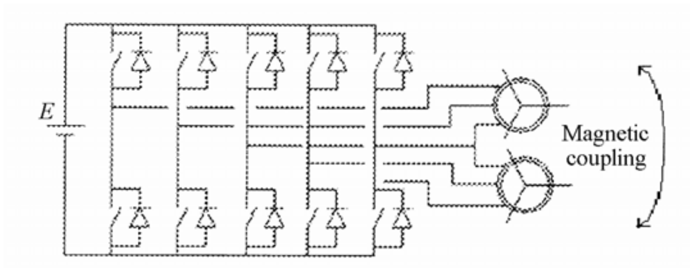


Fig. 12 – Double stator synchronous machine supplied by a five legs VSI.

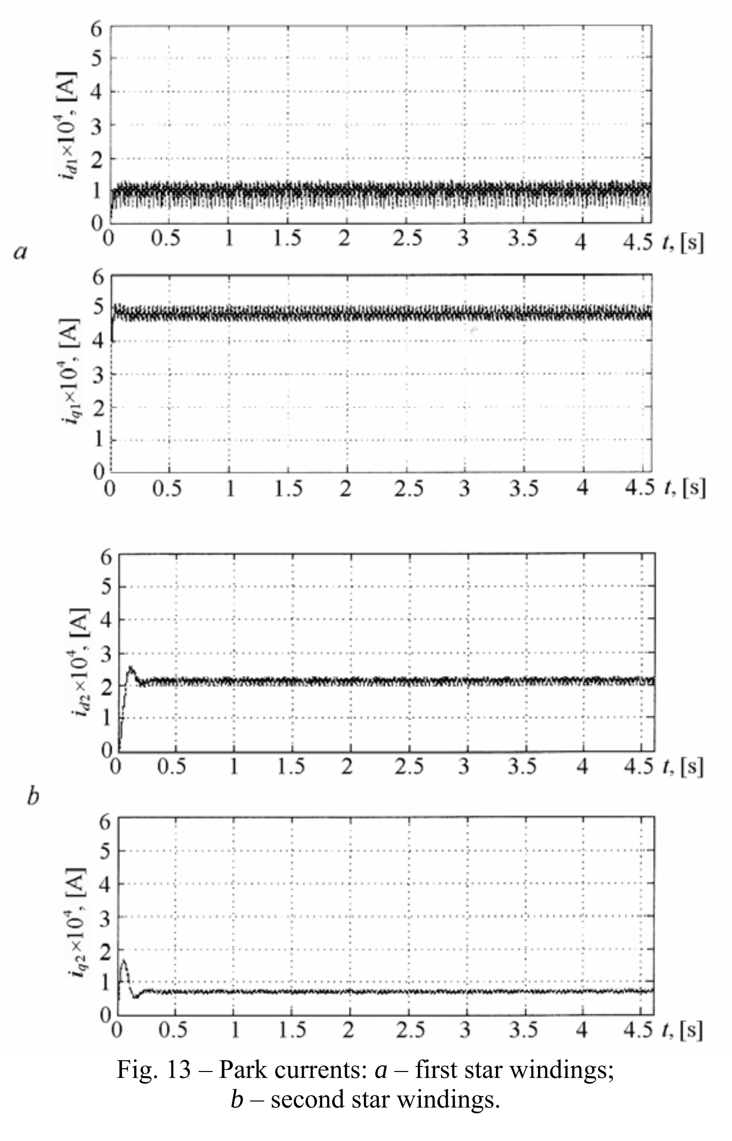
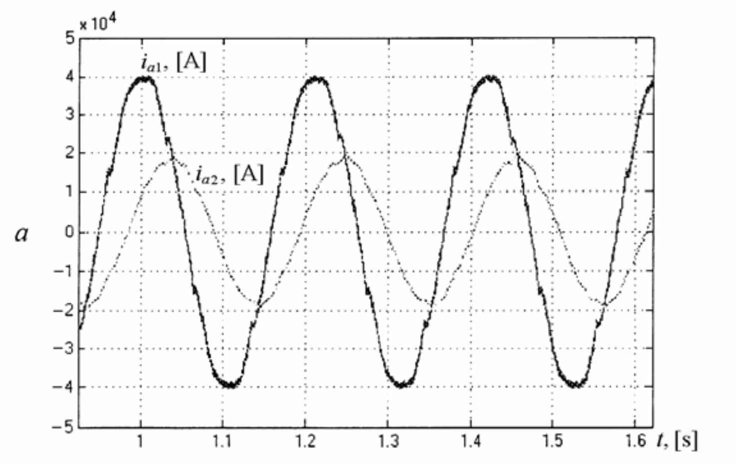


Fig. 13 – Park currents: *a* – first star windings;
b – second star windings.



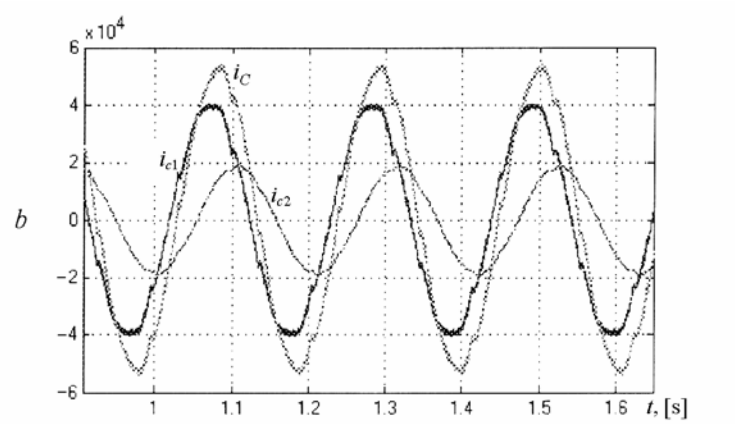


Fig. 14 – Currents in the machine and the inverter: *a* – first phase currents in stars 1 and 2; *b* – third phase currents and the common leg current i_C.

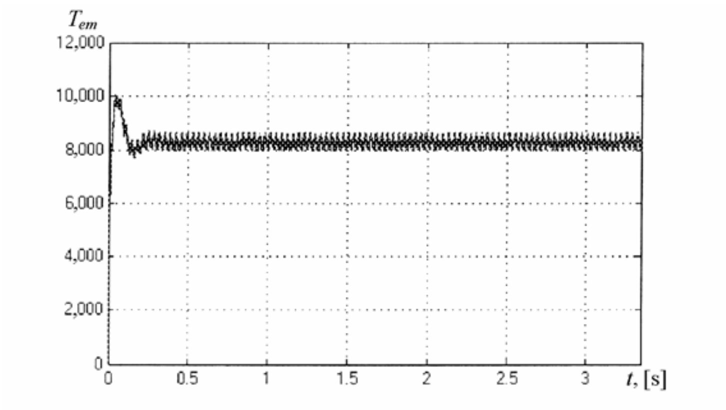


Fig. 15 – Machine torque.

5. MMS Control Methods

Consider the example of the DSSM supplied by two independent voltage source inverters. To remove or to minimize the phase current ripples which appear when the two star windings are shifted (Fig. 10 *b*) it is necessary to apply a control method on the system. The used method is the vector control. Current proportional regulator is used. The principle of this control method is defined according to following three strategies:

1. master–slave current control;
2. average current control;
3. independent current control.

In this section, these three control strategies will be applied to the Double Stator Synchronous Machine (DSSM) currents, therefore, indirectly to the machine torque.

5.1. Master–Slave Current Control

It consists in choosing one three phase windings as master; the other one will be the slave. In this study, the first star windings (a_1, b_1, c_1) is the master and the second windings (a_2, b_2, c_2) is the slave (Fig. 16).

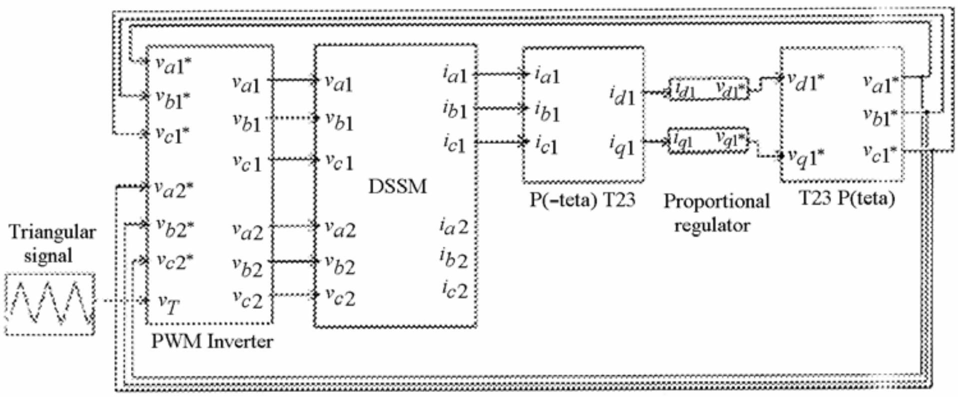


Fig. 16 – Master–slave current control.

This strategy aims to control the three phase currents of the master windings. The slave currents are not controlled. Therefore, the slave doesn't contribute to the regulation. But, as these two star windings are magnetically coupled, therefore, the ripples which appear in the slave currents should have important influence on the master currents. Then, these currents are hardly regulated. It is not preferable to use this master–slave strategy in current control.

5.2. Average Current Control

It consists in calculating the average currents of the Park currents of the two star windings and regulates these average currents. In effect, the three phase currents of each star are transformed to Park currents, i_{d1} and i_{q1} , for the first star, i_{d2} and i_{q2} , for the second one. Then, the average currents of i_{d1} and i_{d2} , and that of i_{q1} and i_{q2} are regulated separately (Fig. 17). These average values are used as inputs to the proportional regulators. This original strategy requires only two current regulators.

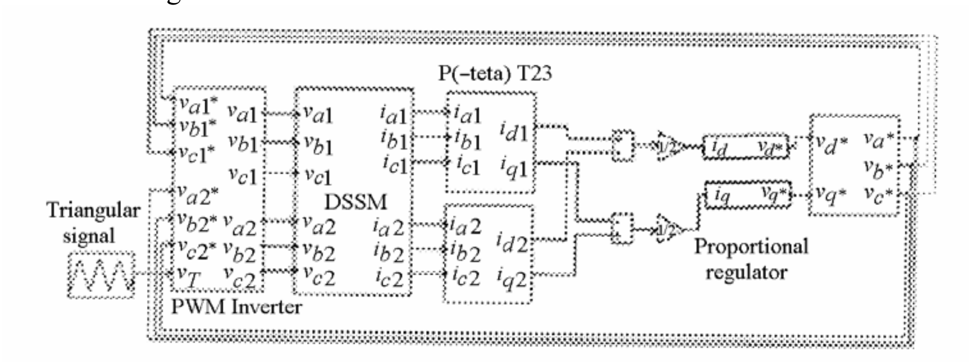


Fig. 17 – Average current control.

5.3. Independent Current Control

In this strategy, the two star windings are considered as masters (Fig. 18). The Park currents of each star are regulated separately. The outputs of the used regulators of these two masters are connected to the corresponding references. This strategy is very simple and reaches the objective in limiting the current ripples. Its disadvantage is the redundancy in the control loop. It requires four current regulators.

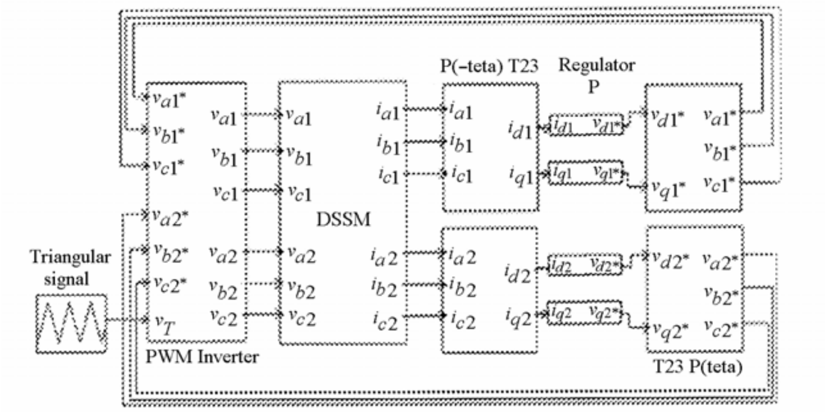


Fig. 18 – Independent control.

6. Simulation Results

The defined three strategies are applied to the Double Stator Synchronous Machine (DSSM). If the stators are none shifted, these strategies give the same results; therefore, they can not be compared. To evaluate the difference between these strategies, a 30° shifted angle between the two stators of the studied machine is used. This machine is supplied by two independent three phase VSI.

Fig. 19 *a* shows the phase currents without control. When the system functions in the master–slave strategy, the VSI references of the slave are not shifted by 30°, therefore, the phase currents contain ripples with high magnitude (Fig. 19 *b*). The simulation of the system using the average current strategy contributes to the presence of small ripples in the currents waveforms (Fig. 19 *c*), and that due to the same VSI references used in this strategy. Applying the independent control method on each stator, the ripples nearly disappear from the current waveforms (Fig. 19 *d*).

As conclusion, if the two stators of the studied machine are not shifted, any of these three control strategies can be used, but if the two stators are shifted, therefore, it is necessary to use the independent control strategy in order to protect the system (converter and machine) from any damage.

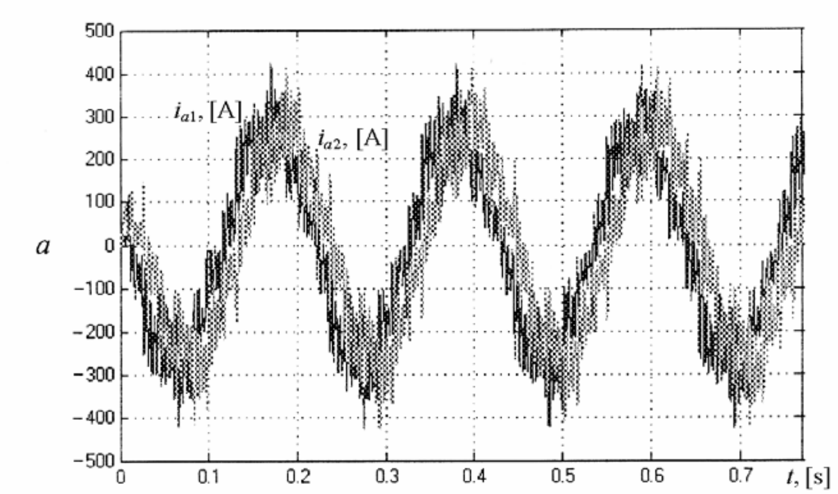


Fig. 19 – First phase currents in each stator: *a* – phase currents without control.

Fig. 20 *a* represents the torque waveform of the studied machine without control. Using the independent current control, the ripples amplitude that appear on the torque waveform decreases and disappears (Fig. 20 *b*) as result of the current control represented in Fig. 19 *d*.

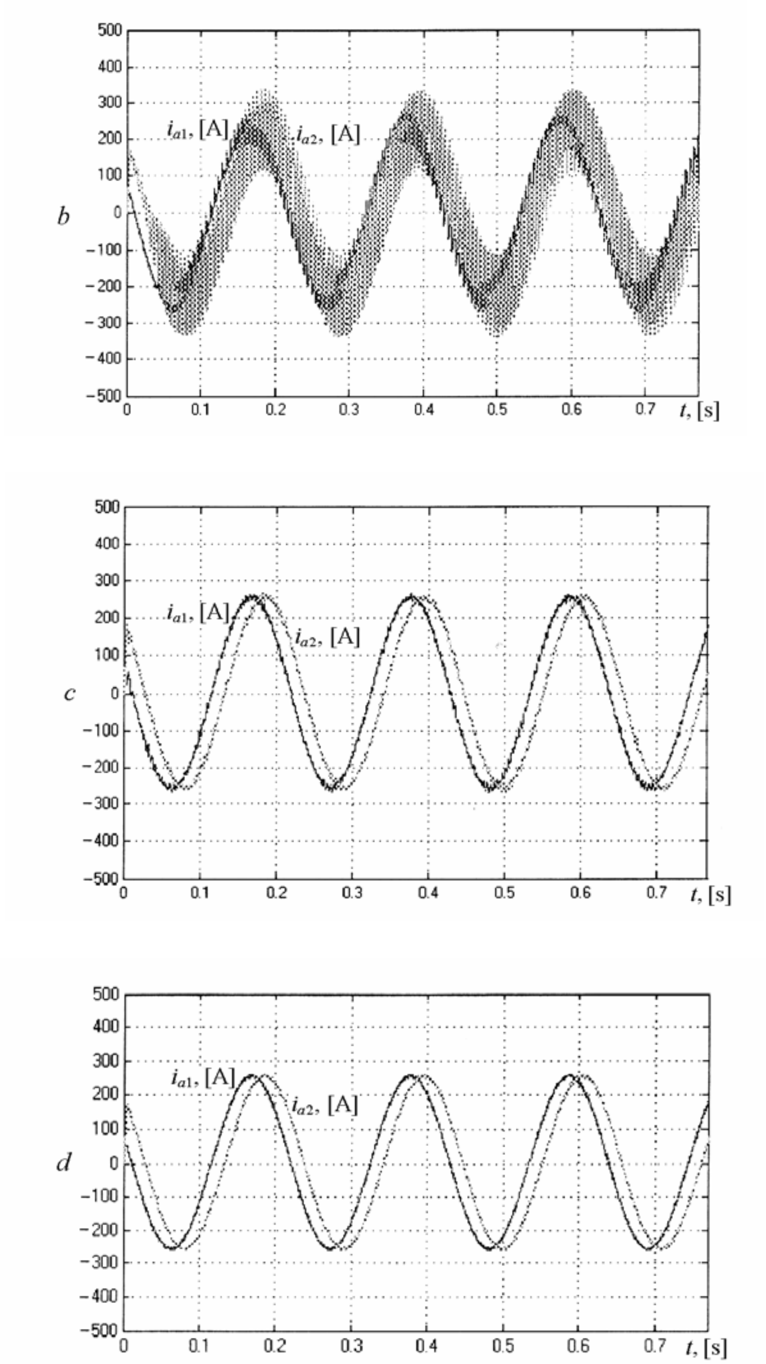
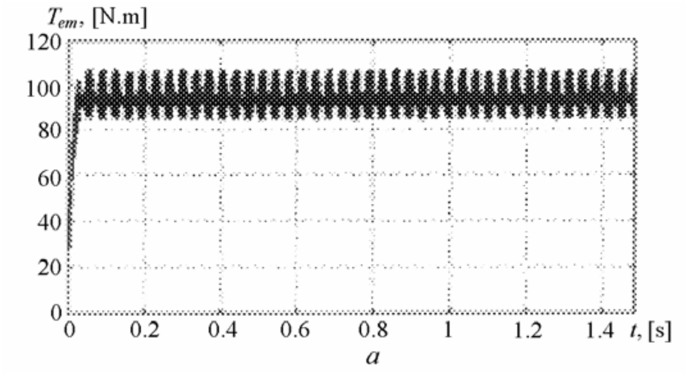


Fig. 19 – First phase currents in each stator: *b* – using the master–slave control; *c* – using the average current control; *d* – using the independent control.



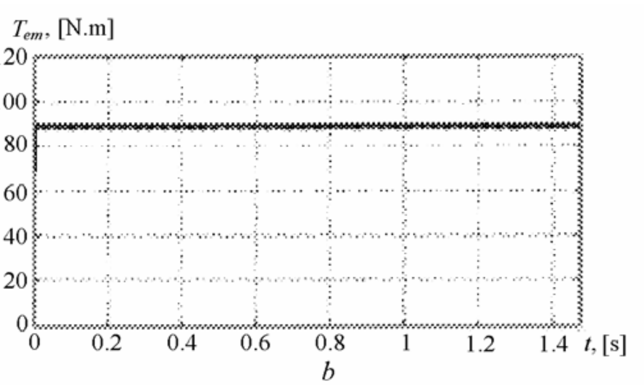


Fig. 20 – DSSM torque waveforms: *a* – torque without control;
b – torque using the independent control.

7. Conclusions

In this paper all structures of Multi-Converter–Multi-Machine Systems (MMS) are presented. The functions of the different parts constituting the chain of conversion of any electromechanical system are discussed. This presentation was followed by three examples of application of the MMS systems namely

a) Firstly, for a five legs VSI supplying two independent machines, the components constituting the common leg should have a high rated power compared to those of the other legs.

b) Secondly, when supplying a double stator synchronous machine by two independent VSI, ripples appear on the current wave forms. These ripples depend on the magnetic coupling existing between the two stators. To eliminate these ripples, the two star windings should not be shifted or the magnetic coupling existing between them should have as weak value.

c) Thirdly, to assure a safety functioning of the five legs VSI supplying a double stator synchronous machine, the common leg of the inverter should have a high power rating and the two stars of the used machine must be not shifted or must have a weak magnetic coupling between them.

Finally, if the two star windings of DSSM are shifted, three control strategies are used to regulate its currents and torque. The master–slave current control is not able to protect the system from ripples which appear on the currents and on the machine torque. For the average current control, only two current regulators are required, and the ripples are attenuated. Simulation results underline the importance of the independent current control strategy in eliminating these ripples. The disadvantage of this strategy, compared to the second one, is that it requires four current regulators.

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CONTROLUL CURENTULUI ŞI A CUPLULUI ÎN SISTEME MULTI-CONVERTOR ŞI MULTI-MAŞINĂ

(Rezumat)

Se prezintă metode originale şi eficiente de distribuţie a puterii între maşini şi convertoare de c.a. de putere ridicată. Puterea nominală unitară a convertoarelor şi/sau a maşinilor creşte. Astfel pot fi folosite comutatoare de putere cu frecvenţă mare de comutare. Apoi, teoretic, riplurile de curent şi de cuplu ar putea avea amplitudine redusă. Scopul acestei lucrări este de a analiza pseudo-sistemul multi-convertor şi/sau pseudo-sistemul multi-maşină. În primul rând se prezintă diferite structuri de multi-convertoare şi multi-maşini, precum şi un vocabular specific care s-a format pentru aceste structuri. Apoi se definesc elementele care formează un lanţ de conversie. Se prezintă simulările făcute pentru trei exemple de astfel de structuri. De asemenea, trei metode de control în curent şi cuplu sunt discutate şi comparate.