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J. Electrical Systems 2-1 (2006): 29-51

Journal of Electrical Systems

Regular paper

Modeling, Control and Analyze of Multi-Machine Drive Systems using Bond Graph Technique

In this paper, a system viewpoint method has been investigated to study and analyze complex systems using Bond Graph technique. These systems are multi-machine multi-inverter based on Induction Machine (IM)*, well used in industries like rolling mills, textile, and railway traction. These systems are multi-domains, multi-scales time and present very strong internal and external couplings, with non-linearity characterized by a high model order. The classical study with analytic model is difficult to manipulate and it is limited to some performances. In this study, a "systemic approach" is presented to design these kinds of systems, using an energetic representation based on Bond Graph formalism. Three types of multi-machine are studied with their control strategies. The modeling is carried out by Bond Graph and results are discussed to show the performances of this methodology.*

Keywords: Induction Multi-machine-Multi-inverter, Adjustable Speed Drive, Bond Graph, Causality analysis.

1. INTRODUCTION

A classic method for adjustable speed motors drive was the single independent (IM) used in several industrial applications with a good operating stability. However, this technique associates to every machine its own inverter; this solution makes a duplication of components (power electronics, control electronics, instrumentation environment) and the connecting problems for mobile systems. Several industrial applications: Mills, textile, railway Traction, robotics… [1-4] present electric and mechanical coupling, imposing several constraints on each drive. These constraints complicate the design, the analysis, the analytic modeling of theses systems and their control. This class of systems, which is Multi-machine Multi-inverter, needs a behavioral analysis in order to offer a functioning stability of the global system that can be affected by the electrical and mechanical couplings. These systems require complex control strategy to equilibrate the functioning of all machines used in the process. These systems are considered as complex systems, they present several non-linearity, and with different strong coupling they are also multi-scale time,

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multi-domains and present high order model system. These specifications complicate the design, the study and the global system analysis. In this context, the design of this class of system with an «Approach system" is very interesting using a global systemic modeling available for the design by the analysis and simulation. The studied systems present different energizing domain couplings, so it is interesting to use a formalism representation for modeling. Bond Graph technique is one of the powerful tool used for the systemic modeling, it is an energetic representation based on the flux and effort elements, multi-domains and offer a compartmental analysis and syntheses using the causality propriety. Using the strong advantages of Bond Graph: energetic flux (Bond) multi-fields (Transformer [TF, MTF], Gyrator [GY, MGR]), the zero junction, the one junction and the causality, we can model any complex system [6, 7]. The simulation of bond Graph models is possible using 20-sim Software. Actually some societies like Alstom, General Motors, Renault and Peugeot are using this method for the design. In this paper, Section 1 is devoted to the different structures of multi-machine multi-inverter systems. A system based on induction machine used for railway traction is presented in Section 2; another system used in the motorization of mobile robots is studied in Section 3. Systemic design method using the causality propriety of the Bond Graph is devoted in Section 4.

2. MULTI-MACHINE MULTI-INVERTER SYSTEMS PRESENTATION

One of the essential industrial exigencies is the reduction of design time, the price, the maintenance and the optimization of the volume of embarked systems. These exigencies have given the opportunities to develop a new class of drives called Multi-machine- Multi-inverter Systems (MMS) well used in many industrial applications mainly in high power applications. MMS are composed of an inverter feeding several machines or many inverters associated with some machines, in other case a combination of these two possibilities. The fundamental characteristic of all MMS is the existence of at least one coupling established by the energetic variable between the different inverters or machines, the possible couplings are mainly electric, magnetic or mechanical. The multi-element concept distinguishes three fundamentals types of MMS [8].

2.1 Common filter systems or multi-inverter systems

The common filter MMS or multi-inverter structure possess the same DC feeding source, this one can be obtained from another DC source via a filter, to reduce the harmonic current reduction produced by the inverter. In other applications the DC source is given from an alternative grid via a rectifier. This filter fed n inverters feeding n machines associated to mechanical loads. In addition to the internal coupling in the induction machine between the flux and the torque, this type presents mechanical coupling imposed by the application and an electric coupling by the filter. The structure is frequently used in processes of sheet metal and textiles [9, 10]. These inverters also require complex control algorithms; the general control strategy used for multi-machine systems is the Filed Oriented Control (F.O.C) with Pulse Width Modulation (P.W.M) technique [10].

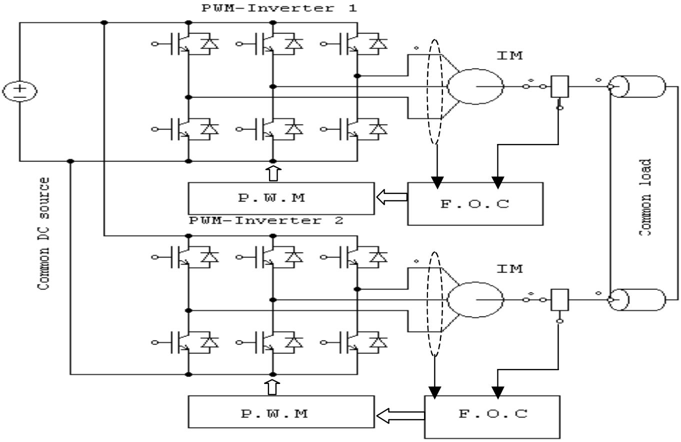

Figure 1. Common filter multi-machine system.

2.2 Parallel structure or mono-inverter multi–machine

The principle of this structure is to feed by one inverter several machines without any disequilibria the functioning of all machines is the same. The production cost and maintenance of this system is more attractive compared to conventional structure when each machine is fed by its own inverter and benefit of its own regulation. However, it presents strong electric coupling in the common inverter and mechanical coupling in the coupled loads. We can distinguish two control strategies, the mean control and the master-slave. The mean control takes in to account the two motors by recreating the corresponding imaginary "average motor" with the application of an identical coefficient for each motor (k=0.5). The MMS system will be controlled by a classic FOC control, it is therefore necessary to have the real averages inputs or by an observer, for this control we consider the average on the speeds and the currents, in this case we can optimize the numbers of sensors [11, 12]. The second method takes into account only one motor called ’’master motor’’. The same voltage imposed by the control on the «master motor» feeds slave motor. The master-slave strategy allows the minimization of the control algorithm, the optimization of the inverters and the sensors. To reduce the disequilibria of the motors we can also define the alternative master-slave control.

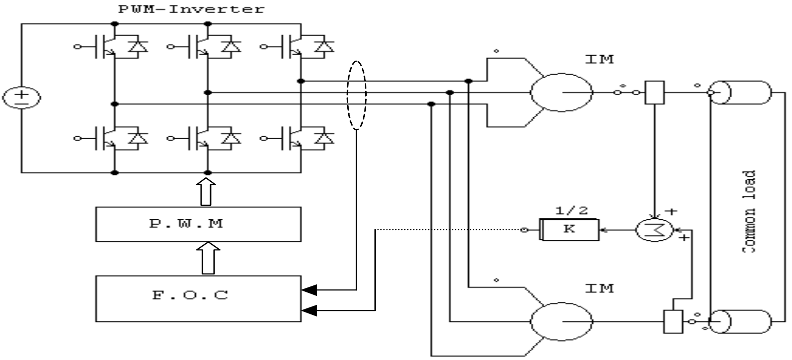

Figure 2. The mean control strategy of the multi-machine system

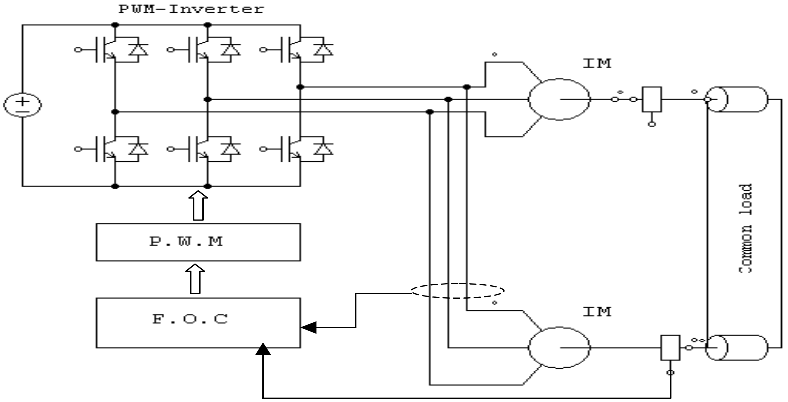

Figure 3. The master-slave control strategy of the multi-machine system

2.3 The (m, n) multi-machine structure

Another intermediate structure between the two structures is the m-legs inverter feeding n machines. The principle is that one inverter leg can generate an alternative voltage phase from the DC voltage, so a multi-phase (m legs) inverter can fed n machines, in this case several machines can have some common phases. A famous application of these systems is the robotics. In the motorization of a mobile robot, using two asynchronous machines, we can feed the two induction machines by a 4-legs inverter [13].

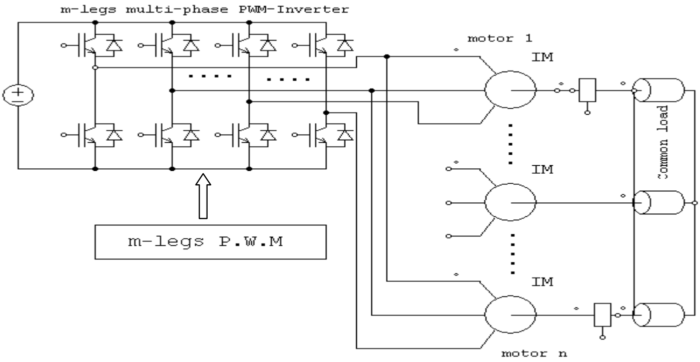

Figure 4. m-legs inverter n-machines system.

3. SYSTEMIC MODELING AND COMPARTMENTAL ANALYSIS OF A RAILWAY TRACTION SYSTEM

The studied system is represented on the Fig.5. This system is composed by 12 induction motors especially designed for traction, fed by six PWM-inverters connected to the catenaries through an (R.L.C) filter. In this application, several requirements and constraints are imposed: good torque performances dynamics, elimination of harmonic pollution in the network is required, in order to guarantee the absence of frequencies able to disrupt the railway signaling and good stability of the train. Due to complexity of this system: 12 motors, strong electrical and mechanical coupling, energetic interaction between each element of this systems, the high model of the system l…, only a global systemic model is able to analyze the functioning of the global system, to ameliorate the design, and to establish to good strategy control to avoid the destruction of the system. In this system we can show two fundamentals structures of the MMS, the multi-inverters (two inverters, two machines) and the parallel one (one inverter, two machines). For the second structure we can define two basic control strategies, the mean control and the master-slave control. The general control strategy used for multi-machine systems is the Flux Oriented Control (F.O.C) method; recently the Direct Torque Control (D.T.C) strategy was applied by the same author for multi-machine systems and gives concurrencies results compared to the F.O.C [14-15]. In this paper, the tramway studied and analyzed is controlled by the FOC method, the principal strategy is not described, and it was doing with bloc diagrams or SIDOPS+ 20-Sim-software language. The tram is composed of four bogies three of them are motors; each motor bogie is composed of four driven wheels, by an asynchronous motor through a speed reducer. The driver through the handle modulates the effort of traction to apply to tram bogies, the operation consist so to modulate the electromagnetic torque of motors.

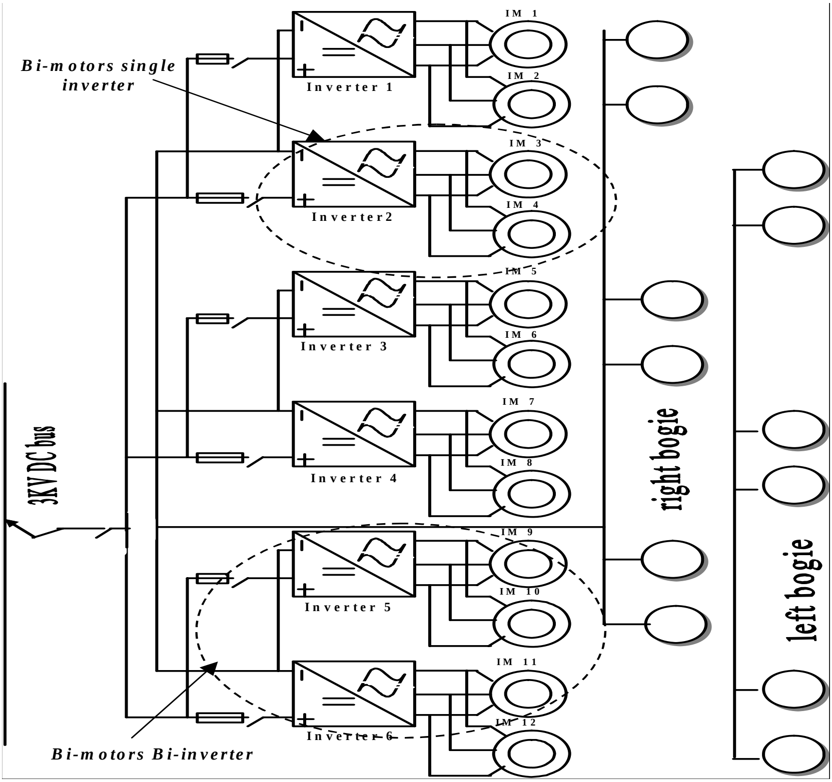

Figure 5. General presentation of a railway traction chain

Different structures of railway traction systems, depending on the network supply voltage and catenaries, from a country to an anther are presented and compared in [19].

3.1. Bond Graph Modeling of the different tramway part

The tramway system consists of these essential elements: The feeding source, the input filter, the inverters, the inductions motors and the mechanical chain. The input filter is used to eliminate the PWM-inverter harmonics and to guarantee continuous voltage to the inverters; this feeding system is realized through a weak area contact assumed by the pantograph. The input filter is an (R_f, L_f, C_f), this element is a resonant circuit which can makes instabilities of the system, the corresponding Bond Graph model is represented on Fig.6.

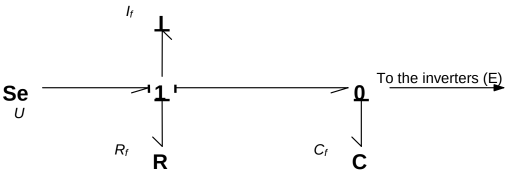

Figure 6. Bond Graph model of the input filter

The PWM-inverter transforms a DC voltage in a three phase alternative voltage using the PWM technique, by Bond Graph method technique we can model any converter using the invariant topology or the variable topology [6], if we consider that a switching element convert a voltage to an another voltage, we can model it by transformation or a modulated transformation [MTF]. The PWM-inverter output voltages are given by Eq. (1).

$$\begin{cases} V_{s1} = \dfrac{2.E}{3}(2.C_1 - C_2 - C_3) = \alpha.E \\ V_{s1} = \dfrac{2.E}{3}(C_1 - 2.C_2 - C_3) = \beta.E \\ V_{s1} = \dfrac{2.E}{3}(C_1 - C_2 - 2.C_3) = \gamma.E \end{cases} \tag{1}$$

(C_i, i=1, 3) are the switching signals and the coefficients (α,β,γ) are equivalent to the duty cycles. According to Eq. (1). the Bond Graph model of the inverter is given by Fig.7.

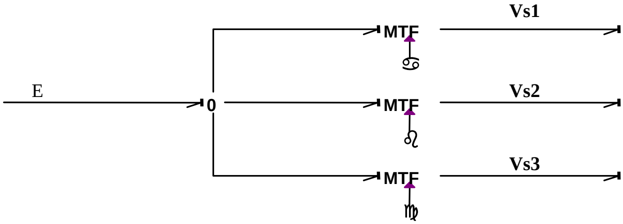

Figure 7. Bond Graph Model of the inverter.

The modeling of the induction motor is carried out in the (α,β) frame using the Park Transformation. The inputs bi-phase system is obtained from Eq. (2).

$$\begin{cases} X_\alpha = \sqrt{\dfrac{3}{2}}\left(X_1 - \dfrac{1}{2}X_2 - \dfrac{1}{2}X_3 \right) \\ X_\beta = \dfrac{1}{\sqrt{2}}\left(X_2 - X_3 \right) \end{cases} \tag{2}$$

(X_α, X_β) are the stator or rotor variables (voltage, current, flux…) in the (α,β) frame and (X_1, X_2, X_3) are the variables in the three-phase system (stator or rotor).

The bi-phased system can be generated from the following model:

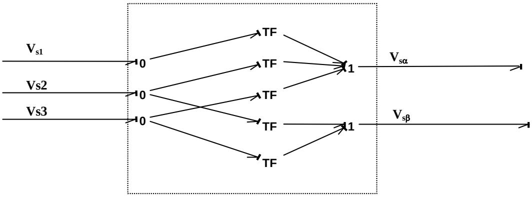

Figure 8. Bond Graph model of the Concordia transformation.

We can obtain the same transformation using the multi-port element.

The general model of the induction machine in (α, β) frame is a 5-order model given by Eq. (3).

$$\begin{cases} V_{s\alpha} = (R_s + L_s.\dfrac{d}{dt}).i_{s\alpha} + L_m.\dfrac{di_{r\alpha}}{dt} \\ V_{r\alpha} = (R_r + L_r.\dfrac{d}{dt}).i_{r\alpha} + L_m.\dfrac{di_{s\alpha}}{dt} \\ V_{s\beta} = L_m.\dfrac{di_{s\alpha}}{dt} + L_m.\varphi.i_{s\beta} + (R_r + L_r.\dfrac{d}{dt}).i_{r\alpha} + L_r\varphi.i_{r\beta} \\ V_{r\beta} = -L_m\varphi.i_{s\alpha} + L_m.\dfrac{di_{s\beta}}{dt} - L_r.\dot{\varphi}.i_{r\alpha+}(R_r + L_r.\dfrac{d}{dt}).i_{r\beta} \\ J\dfrac{d\omega}{dt} = T_{em} - T_r - T_f \end{cases} \tag{3}$$

The electromagnetic torque is given by Eq. (4).

$$T_{em} = p\frac{L_m}{L_r}(\Phi_{r\alpha}i_{s\beta} - \Phi_{r\beta}i_{s\alpha}) \tag{4}$$

From these equations we can deduce the Bond Graph model of the bi-phase equivalent induction machine [21].

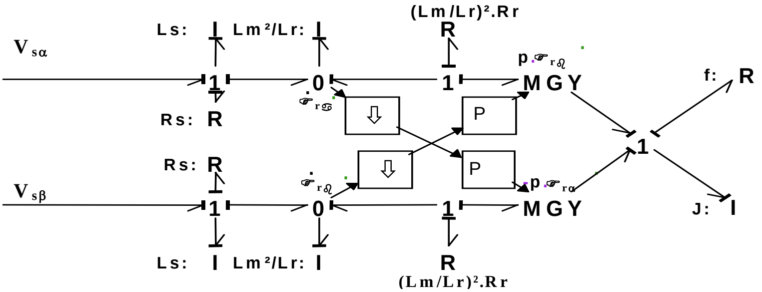

Figure 9. Bond Graph model of the induction machine in the (α,β) frame.

The studied locomotive consists of two bogies; each of them is constituted of two motor parts. One is preserved in the model to implant the two half parts of the same bogie. Indeed this model adjusts well for the analysis of effects introduced in the behavior of the system by various phenomena or disruptions. The mechanical chain consists of the two following parts:

- The mechanical transmission composed of mechanical mating and a reducer.
- The wheel - Rail contact is iron-iron type defining a law of adhesion that is generally weak, or even the slip, therefore the wheel transmits to the rail the totality of the traction strength.

The transmission chain corresponds to a configuration with reduction gear, which is joined rigidly to the frame of bogie, which is considered the stationary reference of the system. This mechanical model is developed by Alstom society; figure 10 shows the transmission chain, from the rotor of the motor to the wheel [3].

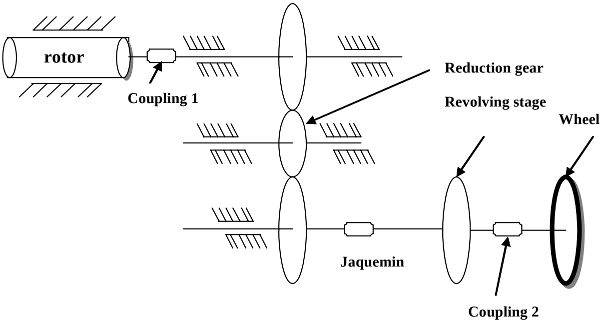

Figure 10. Transmission chain schematic.

On the figure below we give the transmission chain Bond Graph model [21].

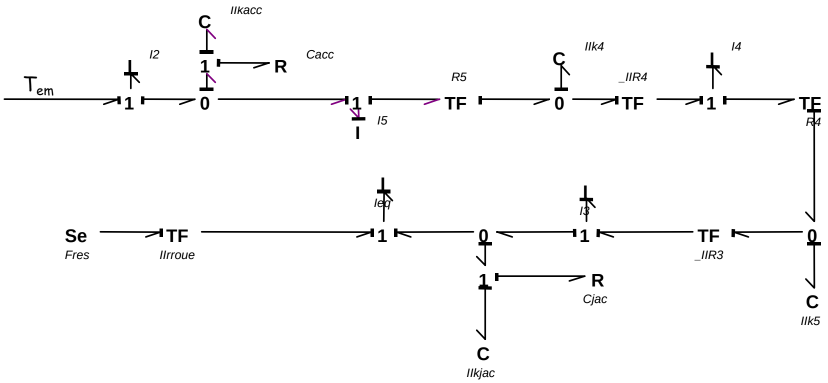

Figure 11. Bond Graph Model the mechanical transmission chain.

To determinate the resonant frequency of the mechanical chain, we fed the Bond Graph model with a sinusoidal perturbation with a variable frequency considered as the electromagnetic torque given by the induction machine (1000+100sin (2πf)). Different simulations have been done corresponding to different frequencies, the analysis of these results, shows that the resonant frequency is about 18 Hz [20]. This study is interesting to choose input filter value because the mechanical resonance frequency can be transmitted to the input filter through the different parts of the global system and making much instability problems. Recently another method, based on linearized Bond Graph coupled to another software simulation designed especially for the stability analyze of the Bond Graph model (ARCHER), was applied to analyze the stability of the railway traction [21].

The influence of the resonance frequency on the functioning of the system is shown on Fig.13. In this simulation, an input filter at its frequency resonance feeds the inverter, we conclude that this frequency is injected through the global system and it appears with big oscillations of the electromagnetic torque of the machine. To avoid the mechanical chain destruction, we must choose the input filter value corresponding to resonant frequency not at the functioning motors speeds rang.

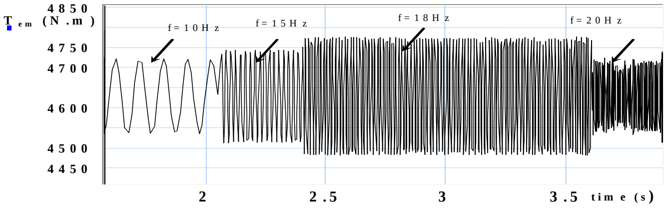

Figure 12. Temporal response of the electromechanical torque.

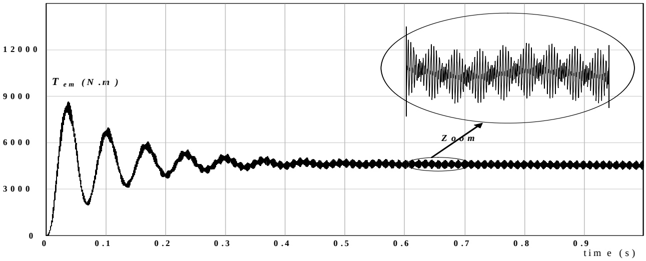

Figure 13. Response of the electromechanical torque when the speed reference is equal to the input filter frequency resonance

3.2. Modeling of the different multi-machine structures of the railway traction chain

As it was shown on Fig. 5, the system includes two types of the multi-machine structure, the parallel one and the multi-inverter one.

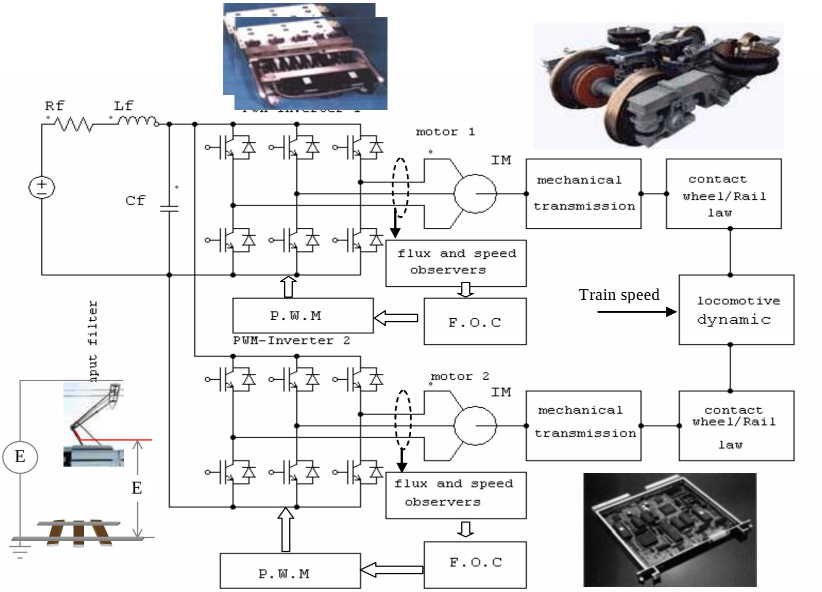

Figure 14. Bi-machine bi-inverter multi-machine system with independent control strategy.

3.2.1 *Study of the bi-motor bi-inverter structure*

The bi-motor bi-inverter system with strong mechanical and electrical couplings structure controlled by master-slave F.O.C method is shown on Fig.14. The inverters used in this structure are a classical two level voltage inverters supplied by a common DC voltage source through an RLC input filter. The master-slave-control (M.S.C) applied for this structure consists in driving only one of two motors; the other one behavior is not considered by the control. Figure 15 gives the Bond Graph model, where the bloc-diagram (IM) represents the sub-system: induction machine corresponding to the Bond graph model of the Fig.9. The Bond Graph model shows these couplings and the energy flux circulation with a homogenous representation. The association of these sub-systems gives the global systemic model of the tramway. Different simulations are carried out for correct and unbalanced functioning points, when we introduce some electrical or mechanical perturbations.

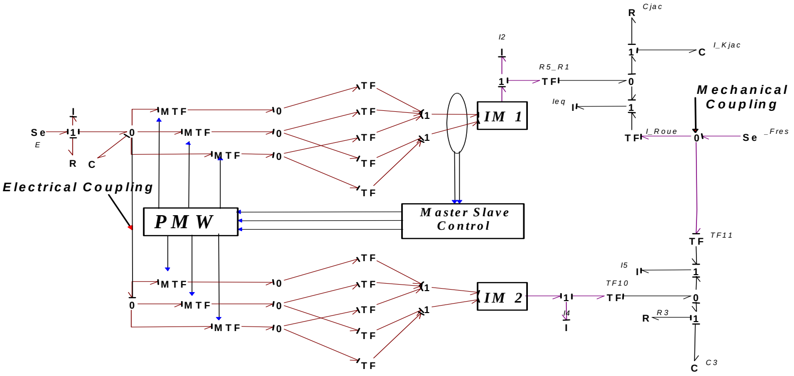

Figure 15. Bond Graph Model of the bi-inverters- bi machines structure.

Figure 16, shows the behavior of the input filter (Voltage U_{cf} and current I_{lf}).

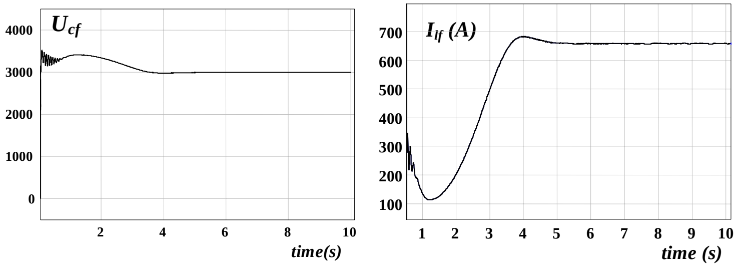

Figure 16. Inputs filter behavior for a correct functioning.

The study of the input filter is an essential analysis of the global system since the electrical resonance can be transmitted to the mechanical chain and makes its destruction. Figure 17 shows the evolution of the electromagnetic torques of the two motors. The electromagnetic torques of two motors are the same and presents in the transient mode an enormous increase, this can makes many problems in the mechanical coupling. In this study it is interesting to analyze the unbalanced functioning of the system, we have made a mechanical disturbance, which can be a bad contact between the wheel and the rail. Figure 18 shows the electromagnetic torques responses of two motors when the disturbance occurs.

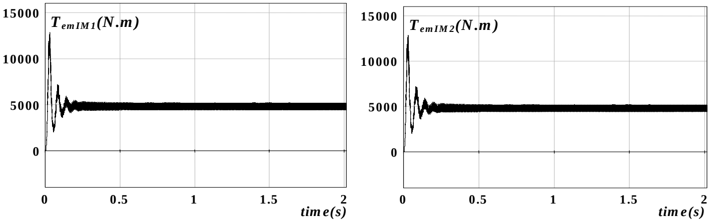

Figure 17. Evolution of the electromagnetic torques of the motors.

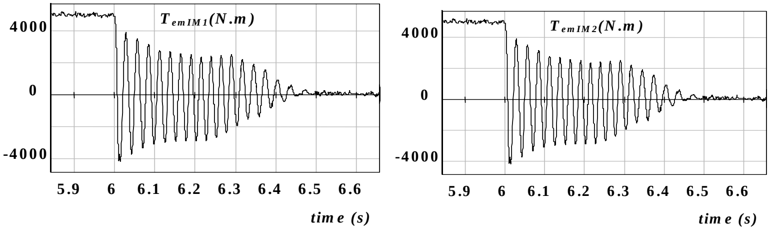

Figure 18. Evolution of the electromagnetic torques with mechanical disequilibria functioning point.

Figure 18 presents the electromagnetic torques responses corresponding to an electrical disturbance (disconnection of the pantograph), theses big oscillations can destruct all the mechanical chain.

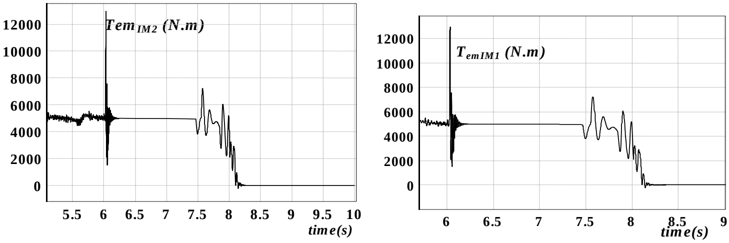

Figure 19. Evolution of the electromagnetic torques for an electrical disequilibria functioning point.

We can observe that at the introduction of the mechanical disturbance, the electromagnetic torques make some oscillations during 0.5s before becoming zero, but when we introduce the electrical disturbance a great increases appears which can be the cause of the destruction of the system.

Using Bond Graph technique and the 20-Sim software we can find some similar results obtained by complicated and very expensive software reserved for complex systems [10], [16].

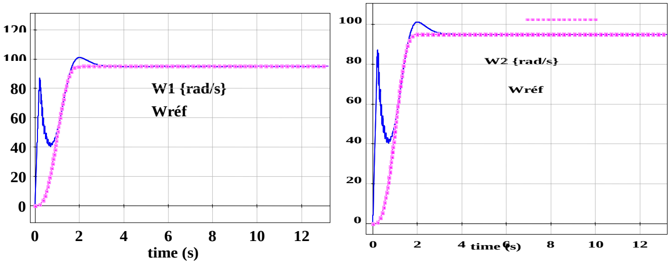

Figure 20. Variation of the machines angular speeds.

Figures 17 and 20 represent the evolution of the electromagnetic torques and the speeds of the motors. These figures give the simulations of the torques of the two induction machines, fed by two inverters and a same input filter of which the frequency of resonance is the nominal frequency of the machine working. These motors have the same electric and mechanical parameters, in these conditions, the simulations show that they have the same electromagnetic torques of 5Kn and the same speeds that follow their reference ω_{ref} = 95 rd/s with an overtaking that can be reduced by an appropriated adjustment of the parameters of the regulator.

3.2.2 *Study of the bi-motor single inverter structure*

Figure 21 gives the second structure composed by a single inverter feeding two induction machines, driven by the F.O.C control with a mean control strategy (the inputs control references or signals are obtained by computing the mean signals from the two machines, we can obtain a mean motor by the collect of average of different calculated values). Others control strategies like master-slave control, switching master-slave control or differential control with their flux and speeds observers are studied in [16], [18].

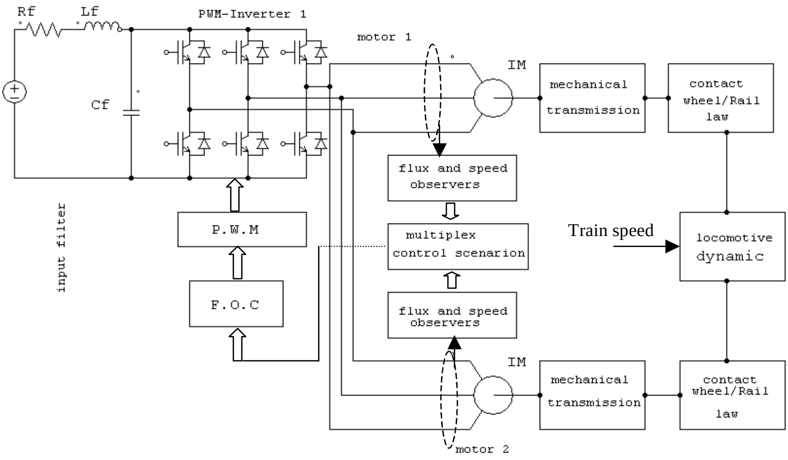

Figure 21. Bi-motor mono-inverter structure with master/slave or mean control strategy.

On the Fig.22, we present the global Bond Graph model, signal modulating the inverter are obtained from a F.O.C mean control method.

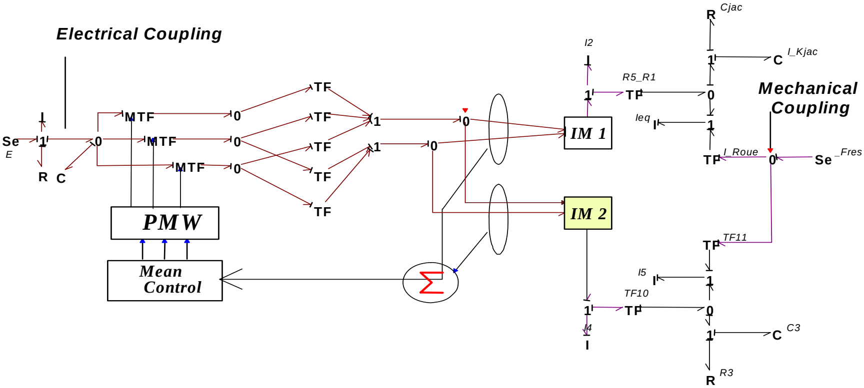

Figure 22. Bond Graph model of the mono-inverter – bi-machines MMS.

For this structure we have also analyzed the system for the same unbalanced working scenario showed in the first structure to compare the performances of each them. Figure 23 represents the evolution of the electromagnetic torques of the machines at the introduction of the same mechanical disturbance in the first structure.

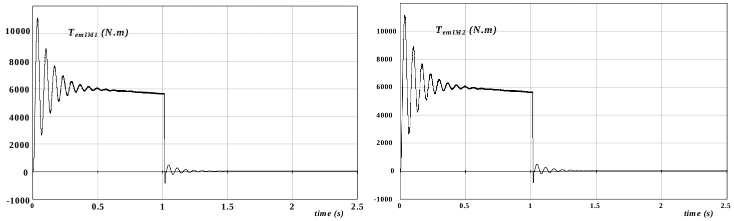

Figure 23. Evolution of the electromagnetic torques for a mechanical disequilibria functioning point.

Figure 24 shows the electromagnetic torques of two motors when an electrical disturbance occurs on the input filter.

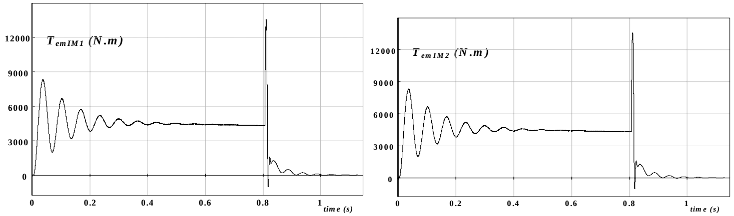

Figure 24. Evolution of the electromagnetic torques for an electrical disequilibria functioning point.

We conclude that the electromagnetic torques responses present a few oscillations during 0.25s when we introduce a mechanical perturbation. When the disconnection of the pantograph is made, the electromagnetic torques present a great increase which can make the destruction of the system.

This global test can illustrate the dynamical performances of the proposed two structures, and can give an idea to the conception of the system. The simulation results confirm, therefore, the robustness of the second structure against these perturbations; also its simplicity of construction can be a reason to the choice of the single inverter structure.

For the balanced functioning, the performances of the system are represented of the figures below (filter parameters, electromagnetic torques and the speeds motors), theses performances are the same compared to those obtained by bi-inverter-bi-motor system with independent or master-slave control strategy. In these conditions we can optimize the general feeding chain and the control strategies by the use of the single-inverter-bi-motor system.

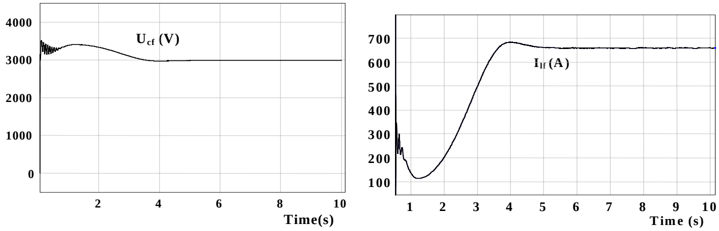

Figure 25. Variation of the characteristic sizes of the input filter: balanced functioning.

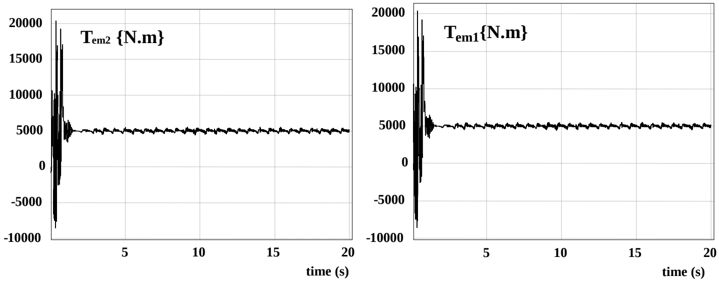

Figure 26. Variation of the electromagnetic torques of two machines: balanced functioning.

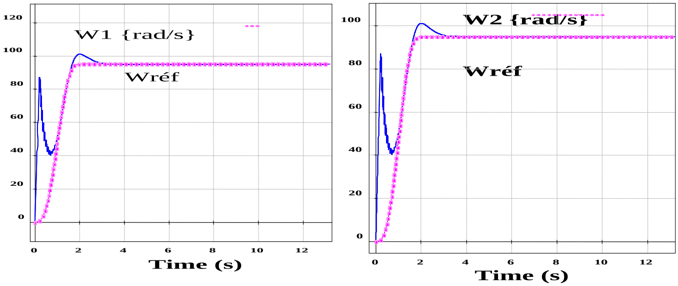

Figure 27. Speeds machines evolution for a balanced functioning.

4. APPLICATION TO THE ASYNCHRONOUS MOTORIZATION OF A MOBILE ROBOT

Among the MMS structures presented we have shown the m-legs n-machines structure. In this part we study an example of 4-legs-bi-machines structure, which is the most common structure used in the asynchronous motorization of mobile robots [3], [12]. This structure is made of two wheels, motorized by two induction machines feted by 4-legs inverter.

In the Bond Graph model, the two wheels will be modeled by an “I” storage element. The 4-legs inverter will be modeling by 4 modulated transformers (MTF). The mechanical coupling is realized by the contact of the wheel with the land, and modeling by an effort source “Se”. Compared to the classical 3 legs inverter, the PMW technique used generates four duty cycles.

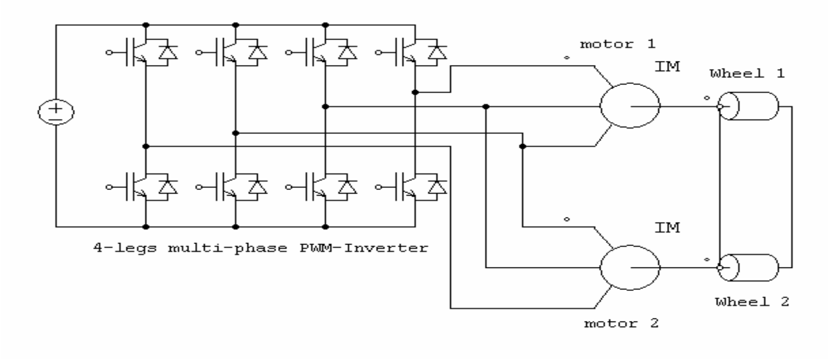

Figure 28. Bi-machine-4 legs MMS structure of the asynchronous motorization of a mobile robot.

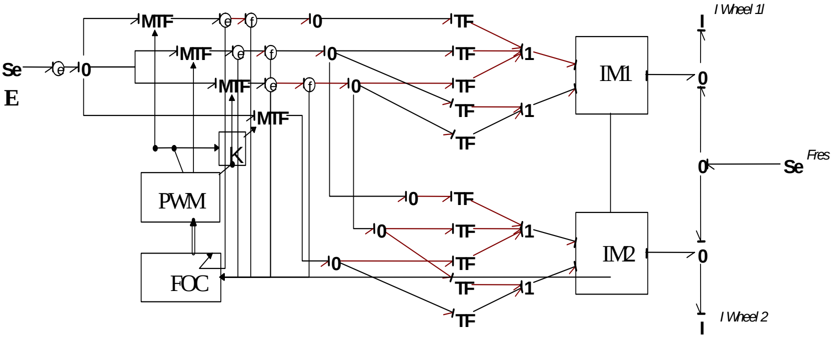

Figure 29. Bond Graph Model of the bi - machines 4 legs of inverter- structure.

In the following figure, we give an example of a trajectory followed by the robot and of their speed references.

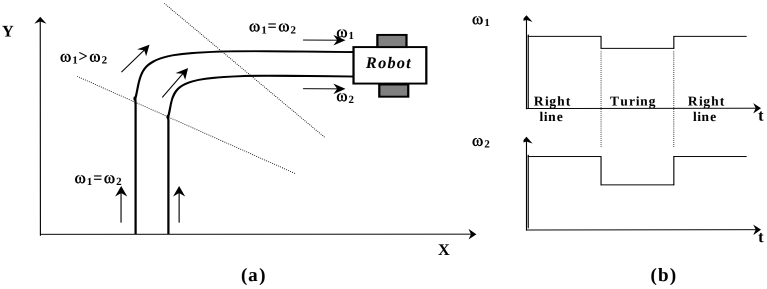

Figure 30. (a): trajectory (b): speed references

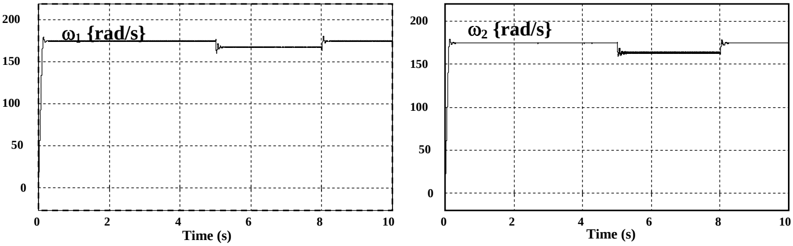

Figure 31. Evolution of the angular speeds of two machines

In simulations of this system, we deduce the dynamic behavior of the control variables and the correct Bond Graph modeling.

5. SYSTEMIC DESIGN BY THE ANALYSIS OF THE BOND GRAPH CAUSALITY

The “Causality” is one of the fundamental propriety of the Bond Graph used for the systemic design and analysis. In this part we give an example of the design method using the causality propriety of the Bond Graph technique, we choose the input (R.L.C) filter, which makes some stability problems. In fact, in systemic approach we can use this element to analyze the global behavior of the system, to verify the good physical associations between the sub-systems and to add the missing elements in order to ameliorate the design. We demonstrate also how the respect of physical causality (integral) guarantees the fundamental laws of the elements association exchanging the energy. Using also the causality loops and ’’Mason Law’’, we can deduce the analytic model from any Bond Graph model. In order to describe the relations of "action and reaction" and to write laws associated to elements under mathematically causal solvent, it is necessary to determine variables that are imposed to elements (data) and those that impose these elements (consequences). The case where causality is not unique: Fig.32 (a, b), generates implicit equations that can causes some numerical problems in simulation (Fig.33). It is necessary to make explicit these equations, by breaking the algebraic loop (indicated by the causality loop, Fig.32(c) between the implied elements by adding dynamic elements that fix the causality propagation.

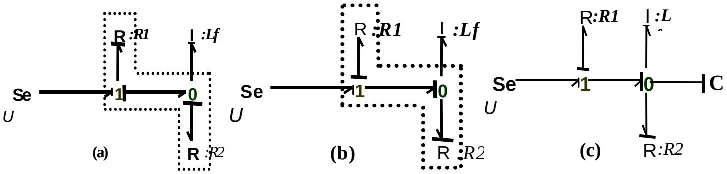

Figure 32. Example of causality uniqueness between the R1 and R2 elements (a, b), unique causality(c).

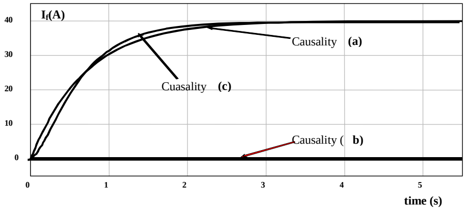

Figure 33. Effect of the affectation of the causality on the flux (I_f) variable (current in the filter).

In this example we have introduced a capacitor ’’C’’ element to the zero junction to fix the causality of the resistances elements ’’R’’. In fact, the added elements often correspond to real or parasitic physical phenomena disregarded in the modeling. A derivative causality on the dynamic elements ’’C’’ or ’’I’’ generates implicit equations when we determine the state representation of the system, to carry out the simulation of models having this type of causality it is necessary to use a solver accepting the implicit equations or to modify the model to suppress the derivative causality by adding some supplementary dynamic elements as for the case of non-uniqueness of the causality [9], [11], [20].

CONCLUSION

In this paper, heterogeneous complex systems called Multi-machine Multi-inverter are studied with a “system viewpoint methodology” based on Bond Graph technique. Due to the different fields of energy conversion, the non-linearity and the different dynamics and the high model order of the system, the use of a global homogeneous formalism is essential for studying the global system. The Bond Graph allows unifying in the same formalism different fundamental domains of the physics; this facilitates the interdisciplinary of system design, which is very important for high power system with strong couplings like MMS systems. The studied systems are well used in different industrial applications mainly in high power where we must avoid any disequilibria functioning, that way we have emphasized on the demonstration of the flux energy circulation. The first studied application is the asynchronous railway traction with Field Oriented Control applied to the master-slave and mean control method, and we have demonstrated that the mono-inverter-bi-motor system is equivalent to the bi-inverter-bi-motor one. The other application is the motorization of a mobile robot consists of 4 legs inverter feeding two induction motors. The causality analysis is an important step in the "approach system" design using all energetic formalism representation and can be considered as a challenge method for the system design and analysis, in electrical engineering.

Acknowledgement

The author thanks very much, Professor Bernard De Fornel and Professor Maria-Pietrzak David from LEEI-ENSEEIHT-INP Toulouse for their scientific discussions and benefit remarks about the multi-machine systems subject. Thanks also to Professor Xavier Roboam Researcher Director at CNRS-France, head of team "system" of LEEI-ENSEEIHT-INPT for his contribution to LSE laboratory "control-systems" team in multi-fields systems design methodologies.

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Nomenclature: list of symbols

L_s, L_r, L_m : Are respectively the stator, rotor inductances and mutual cyclic inductance.

$V_{s/r\alpha,\beta}$:Stator/Rotor voltage in the stationary (α,β) axis

$i_{s/r\alpha,\beta}$:Stator/Rotor currant in the stationary (α,β) axis

$\phi_{s/r\alpha,\beta}$:Stator/Rotor flux in the stationary (α,β) axis

R_s, R_r : Stator/ Rotor resistances

J : Moment of inertia of induction motor

T_{em} : Electromagnetic torque,

T_f : Friction torque (f friction coefficient)

Tr : Load torque.

ω : The electrical speed of the machine.

P : The number of the pair pole in the machine