Indirect Fieled Oriented Control (IFOC)By The Application of The SynergeticTheory Applied to Induction Motor

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Abstract- The purpose of this paper is to introduce the synergic control theory for a design of a diagram of adequate and powerful control. Therefore and initially, the basic concepts of this technique are presented and followed by the stages of design to develop a single synergic controller speed and rotor flux in the diagram of field oriented control for induction motor squirrel cage that is deemed by its strength, high torque mass, and its relatively low cost ... etc, meanwhile, it benefited from the support of industry since its invention. Despite these advantages, these actuators are complex dynamic systems that exhibit a strong non-linearity, which makes them difficult to be controlled. So, the synergetic control is a solution for this problem because it is robust control despite the uncertainty on the model and external disturbances. A simulation results revealed some very interesting features.

Key-Words— Induction motor, field-oriented control, synergetic control theory.

I. INTRODUCTION

For many years, the DC machine has taken a special place and distinguished in various industrial applications. This thanks to its simplicity of control due to the natural decoupling between torque and flux, and also its unmatched dynamic performance that let such a machine used in different speeds in various processes. However, the sparks are due to brush-collector contact and the volume of the latter make use of this type of machine useless [1-2].

On the other hand, the asynchronous squirrel-cage which is famous for its strength, high torque mass, and its relatively low cost etc ...., Meanwhile, has enjoyed the favor of the industry since its Nicola Tesla invention by the end of last century [3].

However, the dynamics of this type of machine is found to be non-linear, multi-variable and strongly coupled resulting in rather poor performance in operation with the control V / F = constant. This is unlike the case of the DC machine which is considered as an optimum in point of view simplicity of control compare to the other machines in general that we try to find. This is due to the simplifications offered by the system brushes-collector [2-3].

On the other hand, thanks to the evolution witnessed in the field of power electronics components and the different control techniques applied to the induction machines with squirrel-cage, most of the recent industrial applications and control motor drivers are based on induction motor and make such processes as performed as the DC machine. In this sense, the first technique that was used is called "vector control". This technique allows obtaining a decoupled dynamic model similar to the model of the machine to separate DC excitation.[4-5-6].

In practice, the use of conventional correction schemes for vector control of induction motor cage where the model is nonlinear and variable parameters seems not so non-robust and efficient [5-7]. Indeed, it is known that such control is very sensitive to any changes in the motor rotor resistance, which is why research has for decades referred to other types of controllers more robust among others: those to changing patterns that were used in this paper.

This work is structured in three stages: The first step, will be devoted to the design of indirect field oriented control scheme based on a classical IP controller. So, in this context and to do this, the basic principles of this type of technical orientation of rotor flux will be presented.

In the second step, the basic concepts of synergetic theory will be used for the detailed design of synergetic control.

In the third step, the application of synergetic speed controller for induction motor.

Finally, numerical simulations and comparisons of results will be presented with the aim of validating the proposed approach.

II. CONTROL OF AN INDUCTION MOTOR

A. Model of the induction motor

The equations of the voltage PWM source inverter fed induction motor with current control, in the synchronous reference frame (d–q), using rotor fluxes as state variables are given by [8]:

$$v_{ds} = \sigma L_s \frac{d\iota_{ds}}{dt} + R_s\, \iota_{ds} - \sigma L_s \omega_s \iota_{qs} - \frac{L_m}{T_r}\, \omega_r \Phi_{qr}$$

$$v_{qs} = \sigma L_s \frac{d\iota_{qs}}{dt} + R_s\, \iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r}\, \omega_r \Phi_{dr}$$

$$\frac{d\Phi_{dr}}{dt} = \frac{-1}{T_r}(\Phi_{dr} - L_m \cdot \iota_{ds}) + \omega_{sl} \cdot \Phi_{qr} \qquad (1)$$

$$\frac{d\Phi_{qr}}{dt} = \frac{-1}{T_r}(\Phi_{qr} - L_m \cdot \iota_{qs}) + \omega_{sl} \cdot \Phi_{dr}$$

$$\frac{d\Omega}{dt} = \frac{1}{J} \cdot \left(T_{em} - T_L - f_r \cdot \Omega\right)$$

$$T_{em} = \frac{3}{2}\frac{pL_m}{L_r} \cdot (\Phi_{dr} \cdot \iota_{qs} - \Phi_{qr} \cdot \iota_{ds})$$

For a rotor-flux orientation, the regulator imposes the orientation of the rotor flux (Φ_r) with respect to the d-axis, giving $\Phi_r = \Phi_{dr}$ and $\Phi_{qr} = 0$. Substituting these relations in (2), leads to the field-oriented model of the motor which is given by the following equation system:

$$v_{ds} = \sigma L_s \frac{d\iota_{ds}}{dt} + R_s\, \iota_{ds} - \sigma L_s \omega_s \iota_{qs} - \frac{L_m}{T_r}\, \omega_r \Phi_r \qquad (2.a)$$

$$v_{qs} = \sigma L_s \frac{d\iota_{qs}}{dt} + R_s\, \iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r}\, \omega_r \Phi_r$$

$$\frac{d\Phi_r^*}{dt} + \frac{1}{T_r} \cdot \Phi_r^* = \frac{L_m}{T_r} \cdot \iota_{ds}^* \qquad (2.b)$$

$$\omega_{sl}^* = \frac{L_m \cdot \iota_{qs}^*}{T_r \cdot \Phi_r^*}$$

$$T_{em}^* = \frac{3}{2}\frac{pL_m}{L_r}\Phi_r^* \cdot \iota_{qs}^*$$

The field-oriented controller is based on the inversion of the above equation system. The command variables (i_{ds}^*, i_{qs}^*, v_{ds}^*, v_{qs}^*) are generated here respectively by regulators as it is shown in figure.1.

The rotor flux is estimated by means of stator current and speed measurements (direct method) as follows:

$$\frac{d\iota_{ds}}{dt} = \frac{1}{\sigma L_s}\left[v_{ds} - \left(R_s + \left(\frac{L_m}{T_r}\right)^2 \right) \cdot \iota_{ds} + \right.$$
$$\left. + \sigma L_s \omega_s \iota_{qs} + \frac{L_m}{T_r}\omega_r \Phi_r \right] \qquad (3)$$
$$\frac{d\iota_{qs}}{dt} = \frac{1}{\sigma L_s}\left[v_{qs} - \left(R_s + \left(\frac{L_m}{T_r}\right)^2 \right) \cdot \iota_{qs} \right.$$
$$\left. - \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r}\omega_r \Phi_r \right]$$

The corresponding position is given by:

$$\theta_e = \int (p \cdot \Omega + \omega_{sl}^*)\, dt \qquad (4)$$

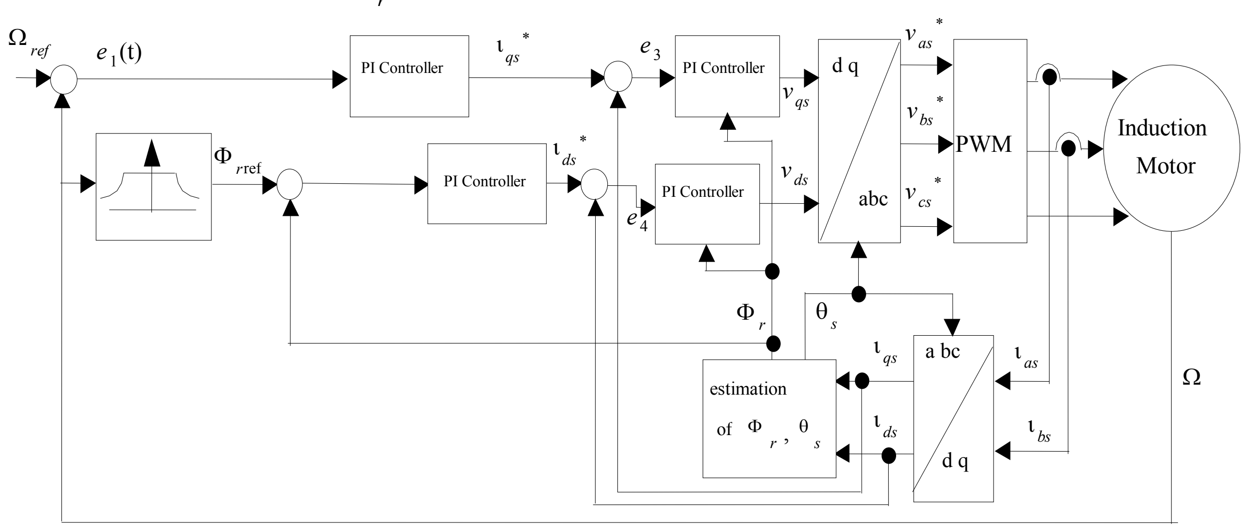


Fig. 1: Vector control scheme of an induction motor.

III. SYNERGETIC CONTROL

Synergetic Control Theory [8][9]exploits the capability of open systems to self-organize. The theory invokes a holistic philosophy of controlled dynamic interactions between energy, matter, and information which is implemented through a combination of both positive and negative feedback. The philosophy of synergetic control design is based on the principle of dynamic expansion and contraction of the state space of the controlled system.

The expansion of the state space enriches the system dynamics by providing additional information that is the key to improving the performance of the closed-loop system. In contrast to expansion, the contraction of the state space that is performed by the control action eliminates the unwanted dynamics of the system or reduces excessive degrees of freedom. At the control design stage, these unwanted dynamics are removed by introducing dynamic constraints that are represented as invariant manifolds in the state space of the system.

The synergetic control design procedure follows the ADAR method (Analytical Design of Aggregated Regulators) [8]. The main steps of the procedure can be summarized as follows. Suppose the system to be controlled is described by a set of nonlinear differential equations of the form

$$\dot{X} = f(t, x, u) \qquad (5)$$

Where X is the state vector, u is the control input vector and t is time. Start by defining a macro-variable as a function of the state variables:

$$\Psi = \Psi(x) \qquad (6)$$

The control will force the system to operate on the manifold $\Psi = 0$. The designer can select the characteristics of this macro-variable according to the control specifications (e.g. limitation in the control output, and so on). In the trivial case the macro variable can be a simple linear combination of the state variables.

The same process can be repeated, defining as many macro-variables as control channels. The desired dynamic evolution of the macro-variables is

$$T\dot{\Psi} + \varphi(\Psi_s) = 0; T > 0 \qquad (7)$$

Where T is a design parameter specifying the convergence speeds to the manifold specified by the macro variable.
The chain rule of differentiation gives

$$\dot{\Psi} = \frac{d\Psi}{dx}\dot{x} \qquad (8)$$

Combining (8), (10), (11) we obtain

$$T\frac{d\Psi}{dx}f(t, x, u) + \Psi = 0 \qquad (9)$$

Equation (9) is finally used to synthesize the control law u. Summarizing, each manifold introduces a new constraint on the state space domain and reduces the order of the system, working in the direction of global stability.

The procedure summarized here can be easily implemented as a computer program for automatic synthesis of the control law or can be performed by hand for simple systems, such as the speed control for induction motor used for this study.

IV.APPLICATION OF SYNERGETIC SPEED CONTROL FOR INDUCTION MOTOR

Synergetic control theory for applications in power electronics is described in [8] [10] here the same concepts are used to synthesize a controller for controlling an induction motor, the model is represented by the system of equations (1).

To find the desired control law, the first step in the design of the synergistic control is the choice of appropriate macro-variables; in general the macro-variable can be a function of state variables.

Our objective is to obtain a control law of a state function coordinate (Ω, Φ) which provides reference values that is required to the motor speed reference Ω_{ref} and a reference flux Φ_{ref}. Therefore a torque control must be satisfied.

We use the method described above to solve the problem, i.e To find a control law u (Ω, Φ). The first step is the selection of macro- variables. In general the macro-variable can be any function (non-linear functions including) of state variables.

We have three components ω_r, V_{ds} and V_{qs}, which allows us to impose the following invariants: technological (ω_r= Cst) and electromagnetic (Φ_{dr} =Cst, Φ_{qr}= 0)[11].

Expressions of laws controls:

We have in the model of the command with the fieled oriented control (2) two main components of command (v_{ds} v_{qs}) and consequently, we introduce only two manifolds ($\psi_1$et ψ_2) defined as follows [8]:

$$\omega_r = \omega_s + \frac{L_m}{T_r}\frac{I_{qs}}{\varphi_{r\,ref}}, \varphi_{qr} = 0 \qquad (10)$$

$$\Psi_1 = i_{ds} - \varphi_1(\omega_r, \Phi_{dr}) \qquad (11)$$

And

$$\Psi_2 = i_{qs} - \varphi_2(\omega_r, \Phi_{dr}) \qquad (12)$$

Ψ1 and Ψ2 must satisfy the following equations:

$$\begin{aligned} T_1\dot{\Psi}_1 + \Psi_1 &= 0 \\ T_2\dot{\Psi}_2 + \Psi_2 &= 0 \end{aligned} \qquad (13)$$

$T_1>0$,$T_2>0$.

The derivation of Ψ1 gives:

$$\dot{\Psi}_1 = \dot{i}_{ds} - \dot{\varphi}_1 \qquad (14)$$

By introducing equation (14) in the first functional equation (13) we get:

$$T_1(\dot{i}_{ds}-\dot{\varphi}_1)+\Psi_1=0 \quad (15)$$

In addition, replacing $\dot{i}_{ds}$ by its expression in the initial system (3), we obtain:

$$T_1\left(\frac{-R_s}{\sigma L_s}i_{ds}+\omega_s i_{qs}+\frac{L_m}{L_r T_r \sigma L_s}\varphi_{dr}+\frac{V_{ds}}{\sigma L_s}-\dot{\varphi}_1\right)+i_{ds}-\varphi_1=0 \quad (16)$$

So:

$$V_{ds}=\left[(R_s-\frac{\sigma L_s}{T_1})i_{ds}-\sigma L_s\omega_s i_{qs}-\frac{L_m}{L_r T_r}\varphi_{dr}+\frac{\sigma L_s\varphi_1}{T_1}+\sigma L_s\dot{\varphi}_1\right] \quad (17)$$

On the other hand, the derivation of Ψ2 gives:

$$\dot{\Psi}_2=\dot{i}_{qs}-\dot{\varphi}_2 \quad (18)$$

So the second functional equation (13) gives:

$$T_2(\dot{i}_{qs}-\dot{\varphi}_2)+\Psi_2=0 \quad (19)$$

Substituting $\dot{i}_{qs}$ by its expression in the initial system (3), we obtain:

$$T_2\left(\frac{-R_s}{\sigma L_s}i_{qs}+\omega_s i_{ds}+\frac{L_m}{L_r\sigma L_s}\omega_r\varphi_{dr}+\frac{V_{qs}}{\sigma L_s}-\dot{\varphi}_2\right)+i_{qs}-\varphi_2= \quad (20)$$

So,

$$V_{qs}=\left[(R_{sm}-\frac{\sigma L_s}{T_2})i_{qs}+\sigma L_s\omega_s i_{ds}+\frac{L_m}{L_r}\omega_r\varphi_{dr}+\frac{\sigma L_s\varphi_2}{T_2}+\sigma L_s\dot{\varphi}_2\right] \quad (21)$$

Internal controls, $\varphi_1(\omega_r,\Phi_{dr})$; $\varphi_2(\omega_r,\Phi_{dr})$ and consequently their derivatives $\dot{\varphi}_1$, $\dot{\varphi}_2$, will be specified by a second group of macro-variables given by:
$i_{ds}=\varphi_1$ and $i_{qs}=\varphi_2$

So,

$$\frac{d}{dt}\omega_r=\frac{1}{J}\frac{PL_m}{L_r}(\Phi_r\varphi_2)-\frac{C_r}{J}-\frac{K_f}{J}\omega_r$$

$$\frac{d\varphi_r}{dt}=\frac{L_m}{T_r}\varphi_1-\frac{1}{T_r}\varphi_r \quad (22)$$

For this decomposed system (22), we introduce other macro- variables Ψ_3, Ψ_4 to impose the desired references and which will be calculated later.

Basic synergistic law:

Introducing macro-variables of the [12] [8][9][13] [14] :

$$\Psi_3=k_1(\omega_{ref}-\omega)+k_2(\Phi_{ref}-\Phi_r)$$
$$\Psi_4=k_3(\omega_{ref}-\omega)+k_4(\Phi_{ref}-\Phi_r) \quad (23)$$

Those macro-variables must satisfy the two differential homogeneous conditions following:

$$T_3\dot{\Psi}_3+\Psi_3=0, T_3>0$$
$$T_4\dot{\Psi}_4+\Psi_4=0, T_4>0 \quad (24)$$

By derivation:

$$\dot{\Psi}_3=-k_1\dot{\omega}-k_2\dot{\Phi}_r$$
$$\dot{\Psi}_4=-k_3\dot{\omega}-k_4\dot{\Phi}_r \quad (25)$$

Then (24) is written:

$$-T_3(k_1\dot{\omega}+k_2\dot{\Phi}_r)+\Psi_3=0$$
$$-T_4(k_1\dot{\omega}+k_2\dot{\Phi}_r)+\Psi_4=0 \quad (26)$$

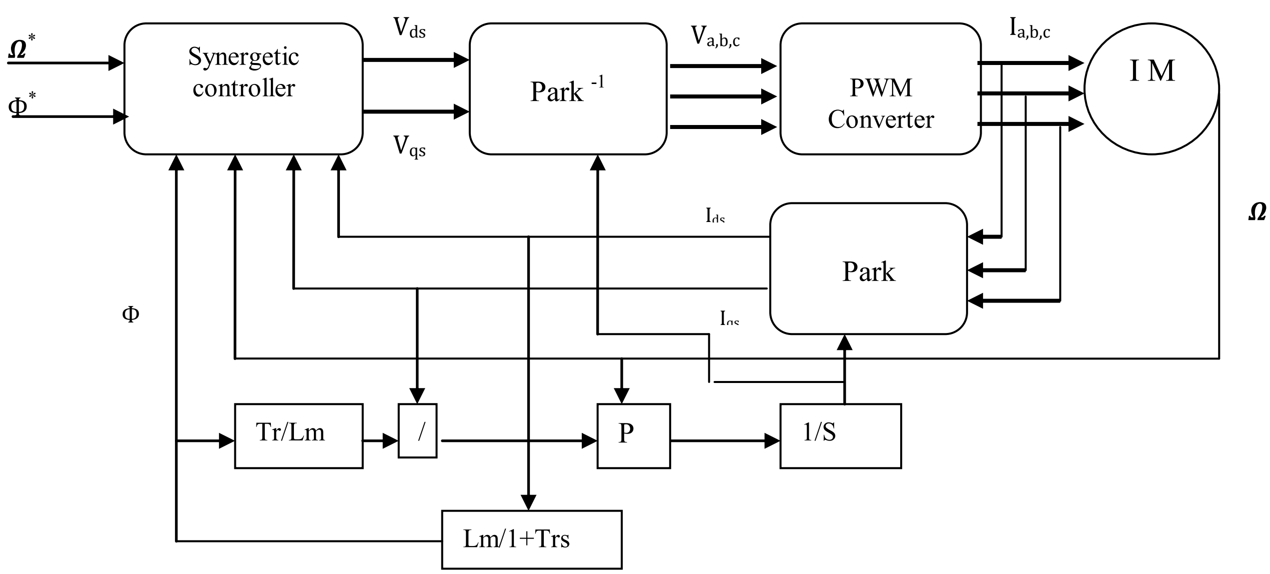


Fig. 2: Synergetic control scheme of an induction motor.

By substituting, $\dot{\omega}$ $\dot{\Phi}_r$, by their expressions in the decomposed system (21) we get:

$$T_3(k_1(\frac{1}{J}\frac{P^2L_m}{L_r}(\Phi_r\varphi_2)-\frac{PC_r}{J}-\frac{K_fP}{J}\omega_r)+k_2(\frac{L_m}{T_r}\varphi_1-\frac{1}{T_r}\varphi_r))+\Psi_3=0 \quad (27)$$

$$T_4(k_3(\frac{1}{J}\frac{P^2L_m}{L_r}(\Phi_r\varphi_2)-\frac{PC_r}{J}-\frac{K_fP}{J}\omega_r)+k_4(\frac{L_m}{T_r}\varphi_1-\frac{1}{T_r}\varphi_r))+\Psi_4=0 \quad (28)$$

By resolving this system we obtain the internal controls φ_1 and φ_2 according to the different state variables and references.

There after by replacing them in the expressions of V_{ds} V_{ds}, it will be thus determined according to the variables of state and reference (speed and rotor flux). The diagram of such control is given in figure 2.

V. VALIDATION OF THE SYNERGETIQUE CONTROLLER

In order to verify the effectiveness of the synergetic controller compared to the PI one, a simulation of the dynamic of the process is done by considering the following tests:

The first test concerns a no-load starting of the motor with a reference speed Ω_{ref} = 100 rad/sec. Then a torque load (T_L = 10 Nm) is applied at t = 1 sec, with $K_1=K_2=K_4=1$, $K_3=0$, $T_1=T_2=T_4=T_3=10^{-4}$, The results are shown in “fig.3 and 4”.

The second concerns a no-load starting of the motor then a torque load (T_L = 10 Nm) is applied at t = 1sec with variation speed between (100, 160, 50, 0,-50 rad/s).The results are shown in “fig.5 and 6”.

Note that the parameters of the induction motor used are given in Appendix.

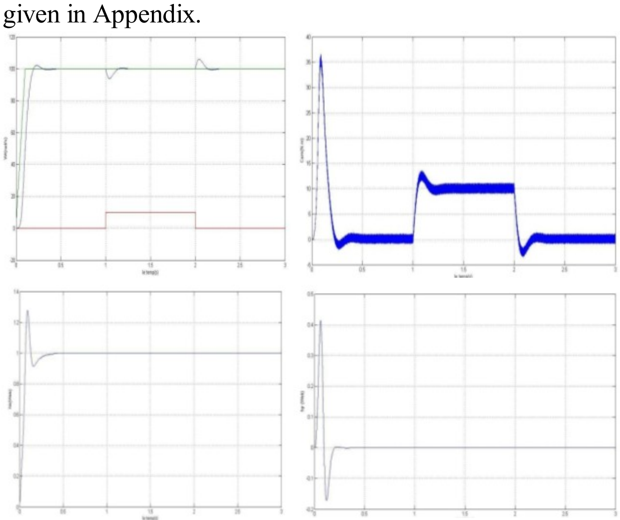


Fig. 3: Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm with PI controller.

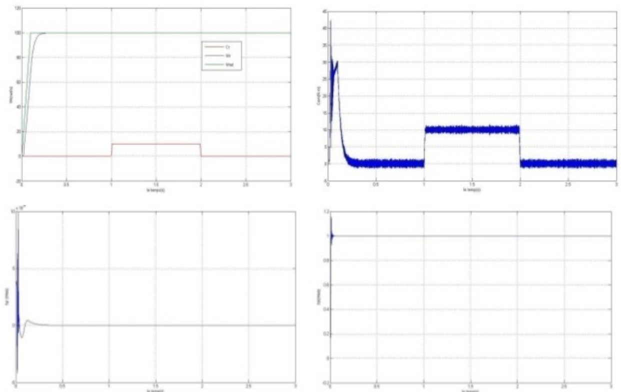


Fig. 4: Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm with synergetic controller

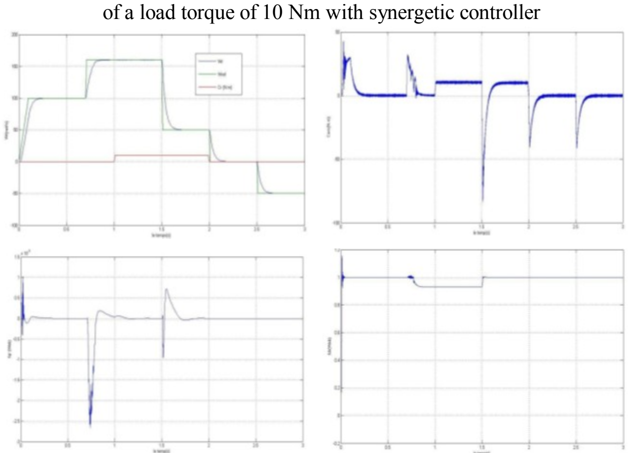
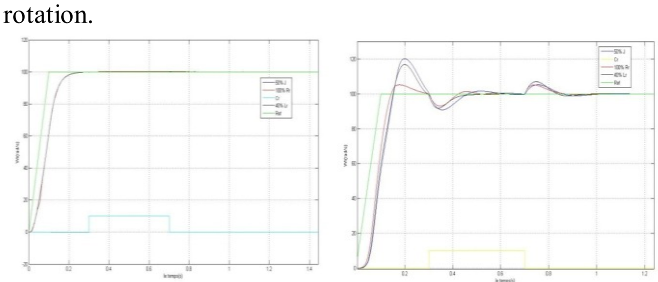


Fig. 5: Dynamics simulation of induction machine with a perturbation of a load torque of 10 Nm variation speed between (100, 160, 50, 0,-50 rad/s) with synergetic controller.

From the results of simulation of the figure (3, 4), it is clear that the field oriented control is established by setting the flux responses $\Phi_{qr} = 0$, $\Phi_{dr} = 1$ wb, despite the load variations, and speed follows its value of reference with the presence of external disturbance impacts, this last is rejected during the synergetic controller application, which proves the robustness of this last with presence of external disturbances even with variation or change of the direction of speed rotation.



Synergetic controller PI controller

Fig .6: Comparison between the two speed controllers with application of variations parametric and external disturbance.

From the obtained waveforms in figure 6, it is clearly shown that the robustness of our system toward parameter's variations and external perturbation is ensured in all the synergetic control processes which confirms the ability of these kind control techniques to ensure the tracking and the robustness as it is cited by numerous other works..

VI. CONCLUSION

The proposed approach has revealed very interesting features. In fact, the combination of the nonlinear control with the field oriented control maintains an effective decoupling between speed and flux for the whole range of speed which allows to obtain high dynamic performances for constant flux operation similar to that of DC motors**.** Further, these high performances are maintained above the nominal speed for the constant power operation, which is not the case in the conventional field oriented control. The addition of the synergetic controller has improved the robustness towards modeling uncertainties and external disturbances.

VII. APPENDIX: MACHINE PARAMETERS

Squirrel-cage induction motor of 1.5 Kw, 220 V,P= 2 poles, 1420 tr/min, 50 Hz.

$R_s = 4.85\ \Omega$; $R_r = 3.805\ \Omega$; $L_s = 0.274$ H ; $L_r = 0.274$ H; M = 0.258 H ; J = 0.031 $Kg.m^2$ f = 0.00114 Nms

X. REFERENCES

[1] P. Barret, «Régime transitoires des machines électrique tournantes», Edition EYROLLES, 1982.

[2] B.K.Bose, « Technology Trends in Microcomputer Control of Electrical Machines » IEEE Trans. Ind. Electron, vol.35, N°1, 1998, pp.160-177.

[3] B. GABRIEL, «Commande Vectorielle de Machine Asynchrone en environnement temps réel MATLAB/SIMULINK»,PFE, C.N.A.M. mars2001.

[4] F .blaschke, « The principle of field orientation as applied to the new transvector », Siemens review, vol .34, pp.217, 222,1972.

[5]Y.Fu « commandes découplées et adaptatives de machines asynchrones », Thèse de doctorat ,Universités de Montpellier ,1991.

[6]L. Barazane, «Commande Vectorielle d'une Machine Asynchrone alimenté en courant», Thèse de Magister, ENP, Alger, 1993.

[7] Y. Fu « commandes découplées et adaptatives de machines asynchrones », Thèse de doctorat ,Universités de Montpellier ,1991.

[8] A. A .Kolesnikov.'' Synergétique : processus d'autoorganisation et commande''.(En Russe) Taganrog 2004, Russie.

[9] I. Kondratiev and R. Dougal. '' General Synergetic Control Strategies for Arbitrary Number of Paralleled Buck Converters Feeding Constant Power Load: Implementation of Dynamic Current Sharing''. IEEE ISIE 2006, July 9-12, 2006, Montreal, Quebec, Canada

[10] Young-Dae Son, Tae-Won Heo, Enrico Santi, Antonello Monti. '' Synergetic Control Approach for Induction Motor Speed Control''. The 30th Annual Conference of the IEEE Industrial EIectronics Society, November 2 - 6, 2004, Busan, Korea.

[11] I. Kondratiev, R. Dougal, E. Santi, G. Veselov. '' Synergetic Control for DC-DC Buck Converters with Constant Power Load''. 3rd Annual IEEE Power Eleclronics Specialists Conference Aachen, Germany, 2004.

[12] Zhenhua Jiang, Roger A. Dougal. '' Synergetic Control of Power Converters for Pulse Current Charging of Advanced Batteries From a Fuel Cell Power Source''. pp1140-1150. IEEE Transactions on power electronics, Vol. 19, No. 4, July 2004.

[13] A. Lidozzi, L. Solero, P. Taddia. ''Synergetic Control for Axial-Flux PM Motor Drives'' pp2561-2568. IAS 2005. 0-7803 9208-6/05/$20.00 IEEE 2005.

[14] A. Monti, R. Dougal, E. Santi, D. Li, K. Proddutur. "Compensation for step-load variations when applying synergetic control," Proc. IEEE Applied Power Electronics Conference (APEC'03), pp. 334-340, Feb. 2003