IJST, Transactions of Electrical Engineering, Vol. 39, No. E2, pp 183-192
Printed in The Islamic Republic of Iran, 2015

IMPROVING SPEED PERFORMANCES OF INDUCTION MOTOR BY USING SYNERGETIC CONTROL THEORY*

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Abstract– The use of micro-controllers in actuators provides extended flexibility for on-line data acquisition and sophisticated control implementation. However, attempts to utilize the excellent features of induction motor that is deemed by its strength, robustness, high torque, and relatively low cost in actuators face a fundamental control design challenge. The purpose of this paper is to introduce the synergic control theory, and apply it to design a speed controller for an induction motor and optimize the parameters of the controller to improve its responses convergence with higher performances and minimum chattering compared to sliding mode control. This paper presents technological invariant manifold based on vector control design with rotor field oriented control (RFOC) for induction motor; the design uses Synergetic Control theory to create an analytical control law which ensures asymptotic stability of the closed-loop operation, eliminate the influences of both external disturbances and parameters variations. To validate this approach, simulation study is carried out, and shows some very interesting features.

Keywords– Induction motor, field-oriented control, synergetic control theory, electric traction, nonlinear control

1. INTRODUCTION

Motion control deals with the design and implementation of controllers for mechanically moving objects. It plays an important role in modern industry such as improving machine accuracy and productivity in the mechanical manufacturing way.

In the application of actuators that use induction motors (IM) in electrical traction, Electrical vehicles (EV) control systems is a promising approach, because IM is a low cost, reliable, and robust motor [1] that is widely used in electromechanical systems (EMS) with a wide range of rotation frequencies and angles. In addition, the use of micro-controllers in actuators provides extended flexibility for on-line data acquisition and sophisticated control implementation. However, attempts to utilize these excellent features of IM in actuators face a fundamental control design challenge. One of the problems is that IM itself is an electromechanical plant with sophisticated dynamics. The challenging properties of the IM that complicate the control design are high nonlinearity and a high order of a dynamic model describing the behavior of IM in different operating modes. Another problem is that the load of the actuator is uncertain: exhibiting either a wide range of variation, or nonlinear behavior, or both.

Among numerous control strategies developed for IM, however, those that treat IM as one control channel system are the most popular. For instance, the principle of constant V/Hz control relates the amplitude of stator voltage to the frequency of feeding voltage [2]. In addition, these control strategies are

*Received by the editors January 6, 2014; Accepted June 23, 2015.
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usually designed using simplified linear models that are unable to reflect the real physics of the processes in adequate ways [3]. Moreover, control design methods either “compensate” or ignore nonlinearity, multi-connectivity, and some of the available control channels. Indeed, such methods put significant limitations on achievable qualitative characteristics of IM such as the region of stability, the range of regulation, and the stiffness of the mechanical characteristic. Correspondingly, all of the above mentioned, limits the capabilities of IM in actuators. In order to fully utilize capabilities of IM in actuators, a vector control should be designed that controls several interrelated coordinates such as frequency of rotation, angular position, torque, magnetic flux, current, etc., and takes into account nonlinearity of the IM model and the load [4, 12].

Synergetic control theory is a new direction in control science that uses the natural nonlinear qualities of dynamic objects based on the principle of direct self-organization. This principle clearly reveals the objectives of control laws and deeply changes the emphasis of modeling by focusing attention on result rather than process. Control, as a measure of purposeful influence of a person on a power system and as a reflection of his aims and requirements, should weave together all the aspects of the system’s functionality [5].

This paper presents invariant manifold based vector control design with rotor field oriented control (RFOC) for induction motor. The design uses Synergetic Control Theory to create an analytical control law which ensures asymptotic stability of the closed-loop operation, and suppresses the influence of the external disturbance with optimization of the parameters of the controller to improve the speed performance of the IM.

2. CONTROL OF INDUCTION MOTOR

a) Model of the induction motor

For control purposes the model is often expressed in an arbitrary two axis rotating reference frame. This makes it easier for the control designer to fix the reference frame to a particular motor quantity and adjust the model accordingly.

The equations of the induction motor, in the synchronous reference frame (d–q), using rotor fluxes as state variables are given by [6]

$$
\begin{aligned}
v_{ds} &= \sigma L_s \frac{d\,\iota_{ds}}{d\,t} + R_s\,\iota_{ds} - \sigma L_s \omega_s \iota_{qs} - \frac{L_m}{T_r}\omega_r \Phi_{qr} \\
v_{qs} &= \sigma L_s \frac{d\,\iota_{qs}}{d\,t} + R_s\,\iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r}\omega_r \Phi_{dr} \\
\frac{d\varphi_{dr}}{dt} &= \frac{-1}{T_r}(\varphi_{dr} - L_m i_{ds}) + \omega_{sl}\varphi_{qr} \\
\frac{d\varphi_{qr}}{dt} &= \frac{-1}{T_r}(\varphi_{qr} - L_m i_{qs}) + \omega_{sl}\varphi_{dr} \\
\frac{d\Omega}{dt} &= \frac{1}{J}(C_{em} - C_r - K_f \Omega) \\
C^*_{em} &= \frac{3}{2}\frac{PL_m}{L_r}(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds} \\
\sigma &= 1 - \frac{L^2{}_m}{L_s L_r}; T_r = \frac{L_r}{R_r}
\end{aligned}
\tag{1}
$$

For a rotor-flux orientation, the regulator imposes the orientation of the rotor flux (Φr) with respect to the d-axis, giving Φr = Φdr and Φqr = 0. Substituting these relations in (2), leads to the field-oriented model of the motor which is given by the following equation system

$$
\begin{aligned}
&v_{ds} = \sigma L_s \frac{d\iota_{ds}}{dt} + R_s\, \iota_{ds} - \sigma L_s \omega_s \iota_{qs} \\
&v_{qs} = \sigma L_s \frac{d\iota_{qs}}{dt} + R_s\, \iota_{qs} + \sigma L_s \omega_s \iota_{ds} + \frac{L_m}{T_r}\, \omega_r \Phi_r \\
&\frac{d\varphi^*_r}{dt} + \frac{1}{T_r}\varphi^*_r = \frac{L_m}{T_r} i^*_{ds} \\
&\omega^*_{sl} = \frac{L_m}{T_r}\frac{i^*_{qs}}{\varphi^*_r} \\
&C^*_{em} = \frac{PL_m}{L_r}\varphi^*_r i^*_{qs}
\end{aligned}
\tag{2}
$$

The field-oriented controller is based on the inversion of the above equation system. The control variables (ids*, iqs*, vds*, vqs*) are generated here respectively by regulators as it is shown in Fig. 1.

The rotor flux is estimated by means of the stator current and speed measurements (indirect method) as follows [13]:

$$
\begin{aligned}
&\frac{dI_{ds}}{dt} = \frac{1}{\sigma L_s}\left[v_{ds} - \left(R_s + \left(\frac{L_m}{T_r}\right)^2 \right) \right] + I_{ds} + \sigma L_s \omega_s I_{qs} \\
&\frac{dI_{qs}}{dt} = \frac{1}{\sigma L_s}\left[v_{qs} - \left(R_s + \left(\frac{L_m}{T_r}\right)^2 \right) \right] + I_{qs} - \sigma L_s \omega_s I_{qs} + \frac{L_m}{T_r}\omega_r \phi_r
\end{aligned}
\tag{3}
$$

The corresponding position is given by

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

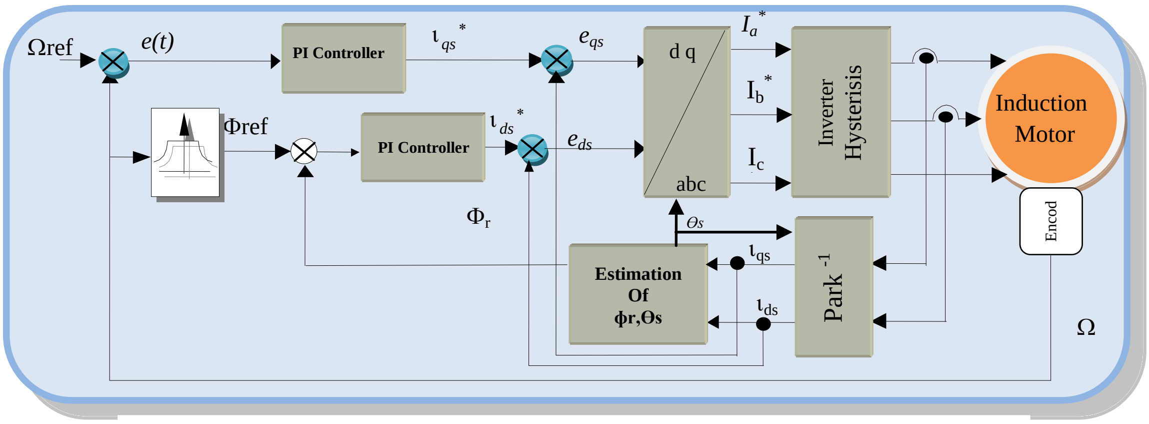

Fig. 1. Vector control schema of induction motor

In our case, hysteresis PWM control will be adapted, so the Eq. (2) will be replaced by

$$
\begin{aligned}
&I_{ds} = \frac{\phi_{dr}}{L_m} + \frac{T_r}{L_m}\frac{d\phi_{dr}}{dt} \\
&I_{qs} = \frac{T_r}{L_m}\omega_{sl}\phi_{dr} \\
&C_{em} = \frac{PL_m}{L_r}\phi_{dr} I_{qs} \\
&\frac{d\Omega}{dt} = \frac{1}{J}(C_{em} - C_r - K_f \Omega) \\
&\Omega = P\omega
\end{aligned}
\tag{5}
$$

3. SYNERGETIC CONTROL

Synergetic Control Theory 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 [7].

The philosophy of synergetic control 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 which is the key to improving the performance of the closed-loop system. In contrast to the expansion, the contraction of the state space that is performed by the controller 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.

In order to apply the ideas of Synergetic in control theory, it is necessary to keep the conceptual correspondence to the main qualities of self organization: nonlinearity – open systems – coherence. For control tasks the most important quality is that the system must be open [8].

In the initial statement, the control system is described by the differential equations of the object

$$\dot{x}(t) = F(x, u, q, M) \tag{6}$$

It includes state coordinates x(t) and some external forces consisting of sought controls u(t), setting actions q(t) and possibly the disturbing actions M(t). In order to move from the system "object - external forces" to forming the self-organization equations we must exclude these forces in an appropriate way. To do that we should extend the initial equations of the system "object - external forces" in such a way that excluded forces would become internal for the system. Therefore, for the new extended system its equations can become the self organization equations, i.e. as a result of this extension, we can move to self organization of the system [8].

In synergetic control theory the requirements put on dynamic and static qualities of the systems being synthesized are represented in the form of a set of invariants. Invariants enter into the structure of invariant manifolds formed in the phase space of the object according to the method of synergetic synthesis. These manifolds serve as attractors of the closed-loop system [9].

In the IM three invariants groups can be determined: electromagnetic, energetic and technological.

Technological invariant characterizes the desired static or dynamic state of the controlled variables like torque, angle and mechanical speed.

Energetic invariants are correlated between object's coordinates characterizing mode of work (minimal energy losses, minimal energy consuming) [10].

For the constancy or stabilization of the magnetic state of our system Electromagnetic invariants can be used.

The main steps of the procedure can be summarized as follows [11]. Suppose the system to be controlled is described by a set of nonlinear differential equations of the form

$$\dot{X} = f(t, x, u) \tag{7}$$

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

$$\Psi = \Psi(x) \tag{8}$$

The control will force the system to operate on the manifold Ψ=0. The designer can select the characteristics of this macro-variable according to the control specifications (e.g. limitation in the controller 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

$$T\dot{\Psi} + \varphi(\Psi) = 0; \qquad T > 0 \tag{9}$$

where T is a design parameter specifying the convergence speeds to the manifold specified by the macro variable.

(10)

The chain rule of differentiation gives

$$\dot{\Psi} = \frac{d\Psi}{dx}\dot{x} \tag{10}$$

Combining (7), (8) and (9), we obtain

$$T\,\frac{d\Psi}{dx} f\,(t, x, u) + \Psi = 0 \tag{11}$$

Equation (11) is finally used to synthesize the control law u. To summarize, each manifold introduces a new constraint on the state space domain and reduces the order of the system, working in the direction of 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.

4. APPLICATION OF SYNERGETIC SPEED CONTROL FOR INDUCTION MOTOR

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 the state variables.

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

The above described method to solve the problem is used, 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, I_{ds} and I_{qs}, which allow us to impose the following invariants: technological (ω_r= Cst) and electromagnetic (Φ_{dr} =Cst, Φ_{qr}= 0).

-Expressions of law controls

In the first step, the synergetic controller is applied only to the speed control loop which presents a technological invariant (speed control) in this paper. For magnetic stability control of the system, the electromagnetic invariant can be added, so the synergetic controller will be used in flux control loop, this step is perspective for future work.

In order to reduce the static error, an integral term of the error on ω is added to Ψ

$$\psi = k_1(\omega_{ref} - \omega) + k_2\int(\omega_{ref} - \omega)dt \tag{12}$$

Ψ must satisfy the following equation:

$$T\dot{\psi} + \psi = 0 \qquad \text{With } T>0 \tag{13}$$

$$\psi = 0 \tag{14}$$

Equation (13) defines the evolution of the macro-variable ψ into the invariant manifold (14).

Under control (13), manifold (14) becomes an attractor in the state space of the closed-loop system. As a result, from an admissible arbitrary initial location in the state space, the system moves towards the manifold and then along the manifold to the equilibrium point.

The stability of the system's motion towards the manifold is determined by using Lyapunov function.

$$V = \frac{1}{2}\Psi^2 > 0 \tag{15}$$

$$\dot{V} = -\frac{\Psi}{T} < 0 \quad if \quad T > 0 \tag{16}$$

Equation (16) shows that the stability of the motion towards the attractor is exponentially asymptotically stable, as long as the parameter T is greater than zero. The coefficient T corresponds to the stability asymptotic conditions of Eq. (13).

The derivation of Ψ gives

$$\dot{\psi} = k_1\dot{\omega} + k_2(\omega_{ref} - \omega) \tag{17}$$

So
$$\dot{\omega} = \left[-\frac{\psi}{T} - k_2(\omega_{ref} - \omega)\right]\frac{1}{k_1} \tag{18}$$

Substituting the expression of Eq. (18) in the speed equation system (5), we obtain

$$C^*_{em} = \left[-\frac{\psi}{T} - k_2(\omega_{ref} - \omega)\right]\frac{PJ}{k_1} + C_r + K_f P\omega \tag{19}$$

The implementation schema of this control technique is given in Fig. 2.

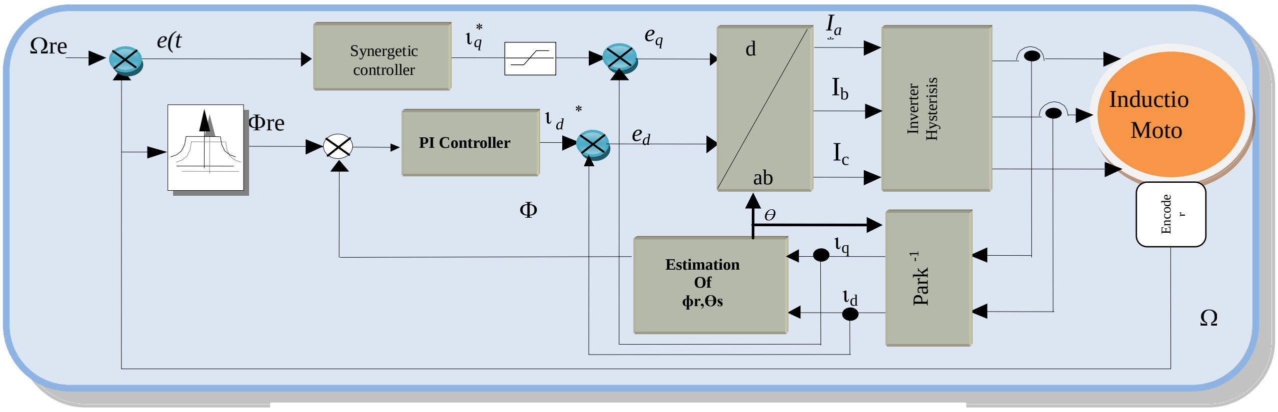

Fig. 2. Synergetic control schema of induction motor

5. VALIDATION OF THE SYNERGETIC CONTROLLER

In order to verify the performances of the synergetic controller and its capability to suppress an external disturbance, a simulation of the process dynamic is done by considering the following two 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, the results are shown in Fig. 3.

The second concerns a no-load starting of the motor then a torque load (T_L = 10 Nm) is applied at t = 1sec with speed variation between (100, 200, -50 rad/s).The results are shown in Fig. 4.

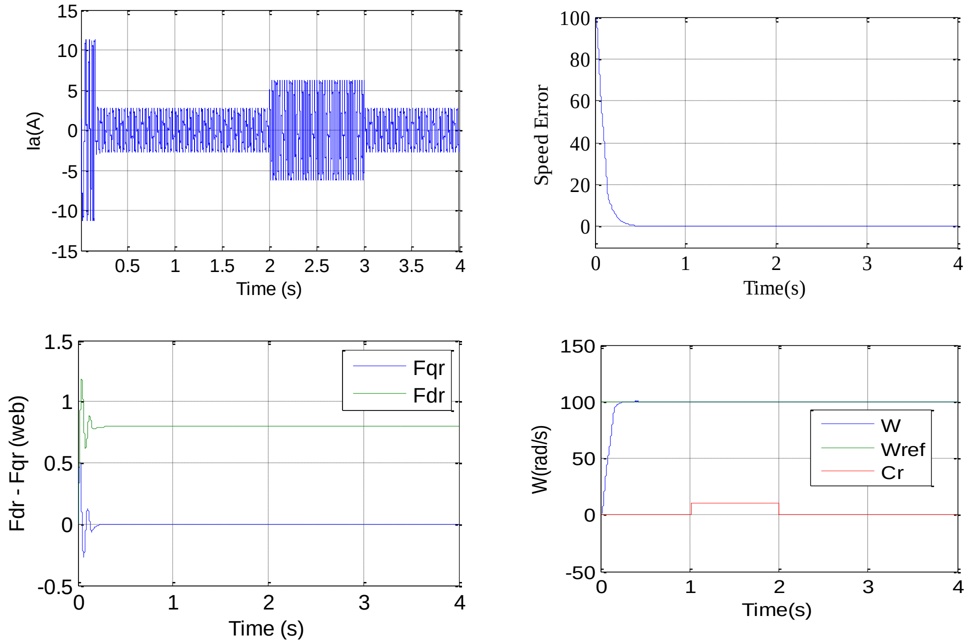

Fig. 3. Dynamics simulation of synergetic control a torque load of 10 Nm

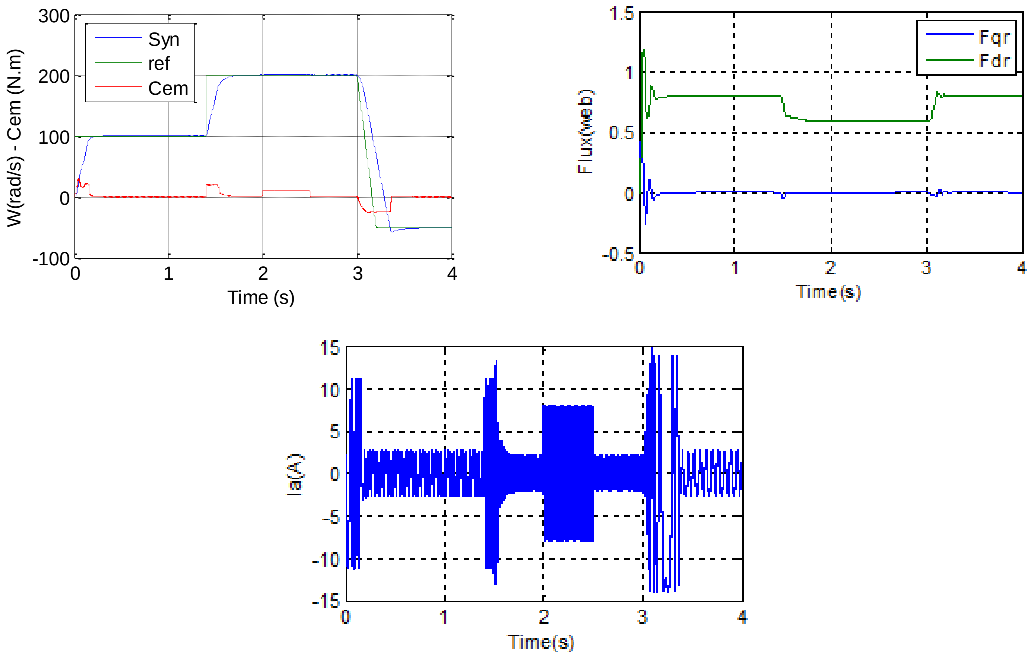

Fig. 4. Dynamics simulation of synergetic control with speed variation between (100, 200,-50 rad/s)

The parameters of the induction motor used are given in Appendix.

The results shown in Figs. 3 and 4 show that the field oriented control is established by setting the flux responses $\Phi_{qr} = 0$, $\Phi_{dr} = 0.8$ wb, despite the load variations, and speed follows the reference value with minimum impacts induced by external disturbance between (1<t<2sec), which proves the robustness of this technique even with variation or change of the speed rotation direction.

From the two tests, it can be seen that the velocity is not influenced by the external disturbance, neither for the constant reference (100rad/s) nor for speed reference variation.(100,200,-50 rad/s), it can be seen that the specified value of the rotor flux linkage is achieved which confirms that the technological invariant is reached. While the behavior of the stator current from the two figures is the same without exceeding the current limit of the motor (18A), the behavior of the current between t = 2 sec and t = 3 sec is due to the application of load torque which presents a call of power from the motor, and at t=1.5sec is due to the increasing speed from 100 to 200 rad/s, so electromagnetic torque is rising, and at t=3sec a high variation is seen which is due to resistant torque to meet the speed set point and reverse the rotation sense from 200 to -50rad/s.

To operate the motor above its nominal speed field weakening technique is used (Fig. 4), by reducing the rotor flux so the IM behavior is the same as DC motor, the higher efficiency operating range of the drive can be extended beyond the nominal speed, this technique allows the motor speed to be quadrupled under certain operating conditions.

To perform this technique, an optimization of the controller parameters is done in the Figs. 5 and 6, where a variation of the parameters of control setting is made to view its impact on the behavior of the motor control.

Starting from Fig. 5, it is seen that increasing in the parameter k_1 improves the speed response of the system and a high starting torque is seen which is interpreted by increasing in the control energy, so the convergence rate will be higher. However; a decreasing in this last minimizes the control energy so the speed response is smaller. Otherwise in Fig. 6 arise in the parameter T improves the pursuit and therefore minimizes the static and dynamic error and ensures asymptotic stability of the closed-loop, but limitation (sat bloc) is needed to keep best control of the system. Decrease in T can maintain the same response -see Iqs*plot- without limitation (sat bloc) but in this case the choice of an optimal value is required. The convergence rate of the dynamical system and hence the algorithm is determined by the value of the parameter T, since T can be any positive number. The decrease in T can help to keep the transition process under control.

The performed simulation shows that the closed-loop system is stable, robust against uncertain load disturbances.

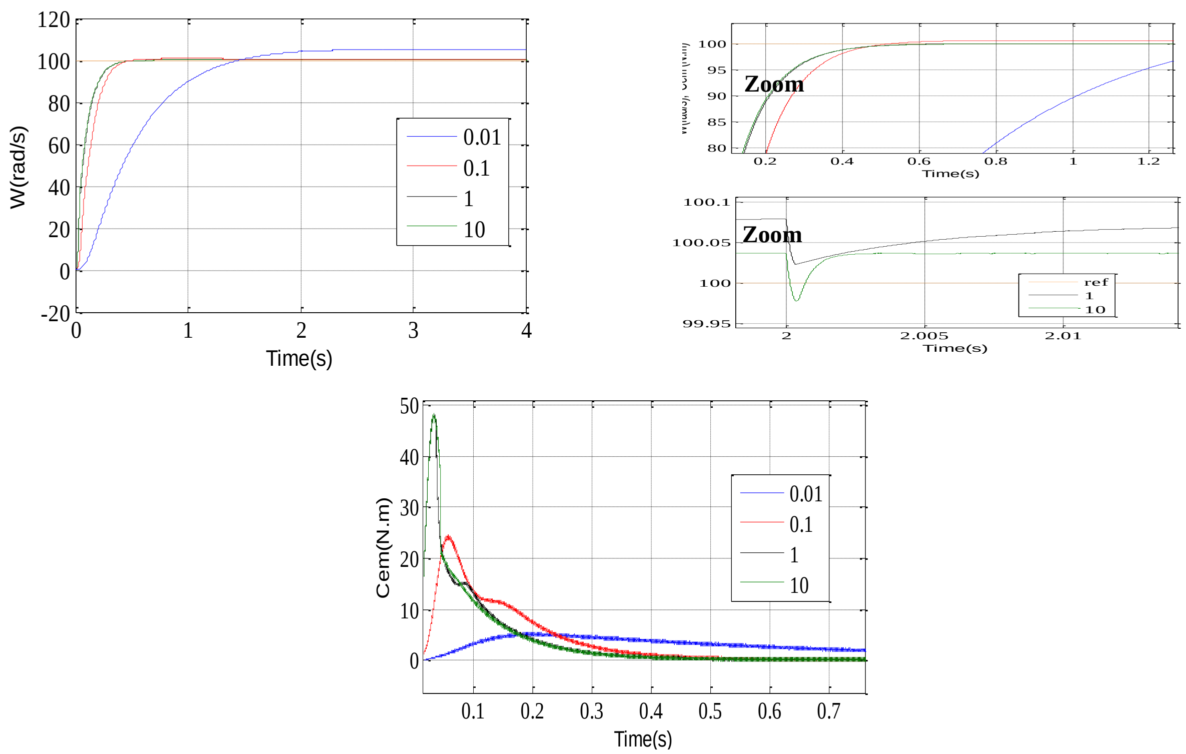

Fig. 5. Dynamics simulation of synergetic control with the variation impact of parameter k_1

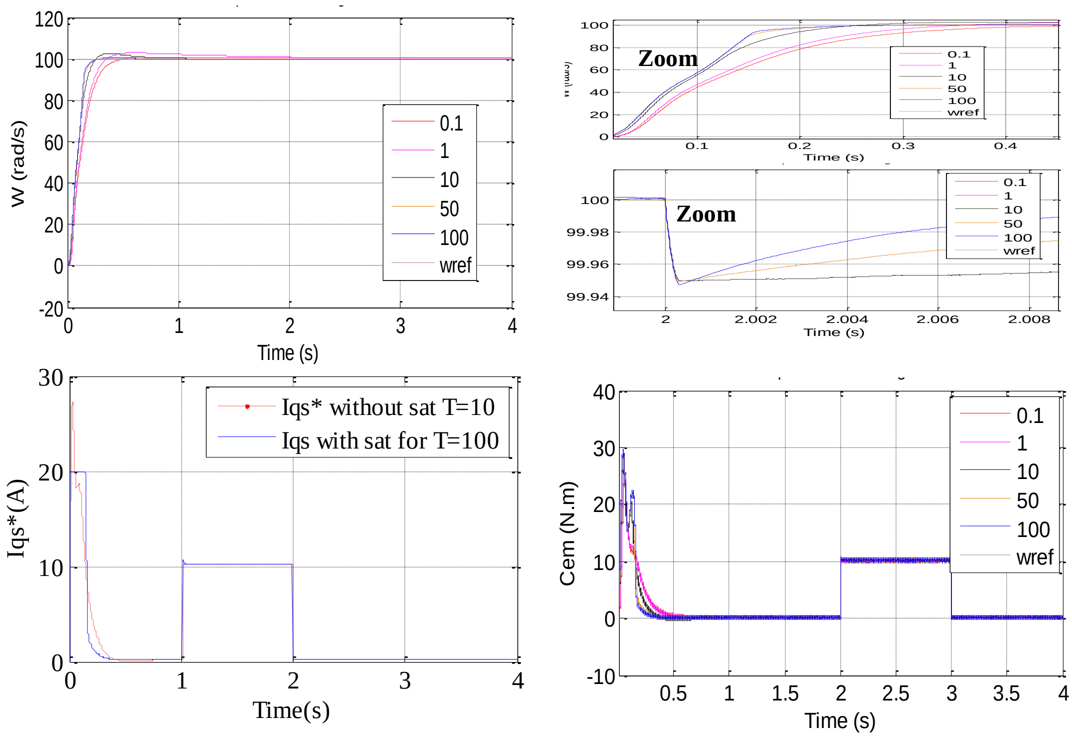

Fig. 6. Dynamics simulation of synergetic control with the variation impact of parameter T

6. CONCLUSION

In this paper we presented a synergetic control theory design for an induction motor which operates under a widely variable uncertain load and can be used in traction motion. The proposed synergetic 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 high dynamic performances for constant flux operation to be obtained, similar to that of DC motor. 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. The application of Synergetic Control Theory exhibits controllable rate of convergence which can be made faster or slower than the rate of other algorithms.

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 Ω ; R_r = 3.805 Ω ; L_s= 0.274 H ; L_r =0.274 H; L_m = 0.258 H ; J = 0.031 Kg.m^2;K_f = 0.00114 Nms.

NOMENCLATURE

ω_r	the rotor speed, in actual (mechanical) radians per second; W_s: Supply frequency;
ω_{ref}	reference rotor speed.
C_{em}	electromagnetic torque; C_r: Load torque.
P	number of poles; J : Inertial constant.
I_d,I_q	direct- and quadrature-axis components of the induction motor armature current.
V_d,V_q	direct- and quadrature-axis components of the induction motor voltage.
R_s,R_r	stator and rotor resistance.
L_s,L_r	stator inductance. L_m: Mutual inductance.

REFERENCES

1. Muenchhof, M., Beck, M. & Isermann, R. (2009). Fault-tolerant actuators and drives-Structures, fault detection principles and applications. *Annual Reviews in Control,* Vol. 33, No. 2, pp. 136-148.
2. Robyns, B., Labrique, F. & Buyse, H. (1995). Performance analysis of a simplified indirect field oriented control algorithm for small power induction actuators. *Mathematics and Computers in Simulation*, Vol. 38, No. 4-6.
3. Ioannides, M. G. Papazis, S. A. & Ioannidou, F. G. (2003). Implementation of scalar control scheme for variable frequency induction motor actuator system. *Sensors and Actuators A: Physical*, Vol. 106, No. 1-3.
4. Kondratiev, I., Dougal, R. & Veselov, G. (2010). Synergetic control for marine actuators. ONR grant N00014-08-1-0080.
5. Kondratiev, I., Roger A. Dougal, R. (2001). Application of the synergetic control approach in energy systems for hybrid electric vehicles. *Proceedings of IECEC'01, 36th Intersociety Energy Conversion Engineering Conference*, Savannah, Georgia.
6. Yahi, A. & barazane, L. (2014). Application of fuzzy sliding approach for speed control in field oriented process and to reduce chattering of an induction motor. *Journal of Electrical Engineering*, Vol. 14, No. 1.
7. Kondratiev, I. (2009). *Synergetic control: Converter based autonomous DC power distribution systems*. Lambert Academic Publishing AG & Co. KG.
8. Kolesnikov, A. A. (2009). Nonlinear system’s synthesis – the central problem of modern science and technology: synergetics conception. Part II: Strategies of Synergetics control. *2nd Chaotic Modeling and Simulation International Conference*, Chania Crete Greece.
9. Kolesnikov, A. A. (2002). *Synergetic control for electromechanical systems*. US office Naval Research under Grant N00014-00-1-031.
10. Kondratiev, I., Dougal, R., Santi, E. & Veselov. G. (2004). Synergetic control for DC-DC buck converters with constant power load. *3rd Annual IEEE Power Eleclronics Specialists Conference Aachen*, Germany.
11. Yahi, A., Barazane, L. & Khwaldeh, A. (2011). Indirect field oriented control (IFOC) by the application of the synergetic theory applied to induction motors. *Proceedings of the 9th International Symposium on Mechatronics and its Applications (ISMA13)*, Amman, Jordan.
12. Kianinezhad, R., Nahid-mobarakeh, B., Betin, F. & Capolino, G. A. (2009). Robust sensorless vector control of induction machines. *Iranian Journal of Science & Technology, Transaction B, Engineering*, Vol. 33, No. B2, pp. 133-147.
13. Ben Azza, H., Jemli, M., Boussak, M. & Gossa, M. (2011). Implementation of sensorless speed control for two-phase induction motor drive using ISFOC strategy. *Iranian Journal of Science & Technology, Transaction B, Engineering*, Vol. 35, No, B2, pp. 63-74.