Speed control based on variable gain PI controller and rotor resistance estimation of an indirect vector controlled induction machine drive

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Abstract – **This paper presents an original variable gain PI (VGPI) controller for speed control and rotor resistance estimation of an indirect vector controlled (IVC) induction motor drive.**

First, a VGPI speed controller is designed. Its simulated performances in speed control and rotor resistance estimation are compared to those of a classical PI controller.

Simulation of the IVC induction motor drive using VGPI for speed control shows promising results. The motor reaches the reference speed rapidly and without overshoot, trapezoidal commands under no load are tracked with zero steady state error and almost no overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt with.

For rotor resistance estimation, the variation of the integrator gain from zero to a terminal value results in the elimination of the transient state estimation error. The proposed VGPI resistance estimator provides excellent tracking performance.

***Keywords* – Induction motor, indirect vector control, variable gain PI controller, rotor resistance estimation.**

I. INTRODUCTION

With the apparition of the indirect field oriented control (FOC), indirect vector controlled (IVC) induction motor drives are beginning to become a major candidate in high performance motion control applications due to their relative simple configuration compared to direct vector scheme which requires flux and torque estimators [1]. In the complex machine dynamics, this decoupling technique permits independent control of the torque and the flux [2].

Indirect FOC however is parameter sensitive [3-7]. Motor heating and saturation causes detuning in the decoupling operation and introduces errors in the torque and field motor output values. The design of robust controllers allowing parameter variation compensation of the decoupling operation is then necessary.

PID classical controllers find some difficulties in dealing with the detuning problem.

In this paper, an original variable gains PI controller is presented. This controller is used for speed control and rotor resistance estimation of an indirect field oriented induction machine drive.

II. VGPI CONTROLLER STRUCTURE

The use of PI controllers to command an induction motor speed is often characterised by an overshoot in tracking mode and a poor load disturbance rejection. This is mainly caused by the fact that the gains of the controller cannot be set to solve the overshoot and load disturbance rejection problems simultaneously.

Overshoot elimination setting will cause a poor load disturbance rejection, and rapid load disturbance rejection setting will cause important overshoot or even instability in the system.

To overcome this problem, we propose the use of variable gains PI controllers. A variable gain PI (VGPI) controller is a generalisation of a classical PI controller where the proportional and integrator gains vary along a tuning curve as given by Fig. 1. Each gain of the proposed controller has four tuning parameters:

- Gain initial value or start up setting which permits overshoot elimination.
- Gain final value or steady state mode setting which permits rapid load disturbance rejection.
- Gain transient mode function which is a polynomial curve that joins the gain initial value to the gain final value.
- Saturation time which is the time at which the gain reaches its final value.

The degree n of the gain transient mode polynomial function is defined as the degree of the variable gain PI controller.

If e(t) is the signal input to the VPGI controller then the output is given by :

$$y(t) = K_p e(t) + \int_0^t K_i e(\tau) d\tau \qquad (1)$$

with

$$K_p = \begin{cases} \left(K_{pf} - K_{pi}\right)\left(\dfrac{t}{T_s}\right)^n + K_{pi} & \text{if} \quad t < T_s \\ K_{pf} & \text{if} \quad t \geq T_s \end{cases} \qquad (2)$$

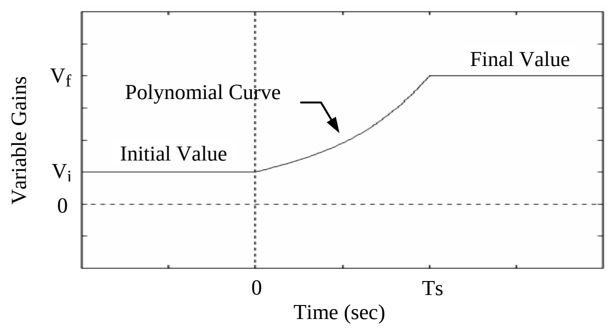

Fig. 1. Variable PI Gains Tuning Curve

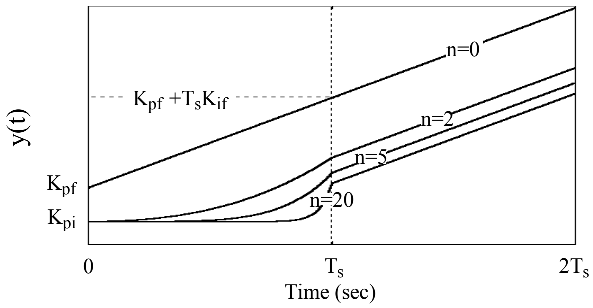

Fig. 2. VGPI step response for different values of the degree n

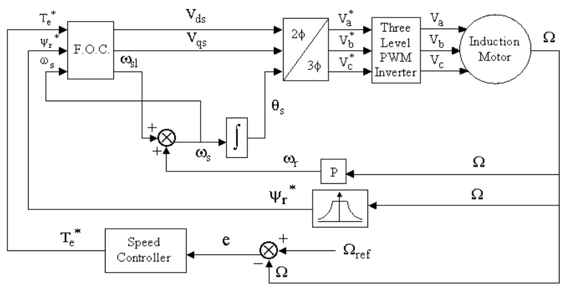

Fig. 3. Indirect field orientation control block diagram

$$K_i = \begin{cases} K_{if}\left(\dfrac{t}{T_s}\right)^n & \text{if} \quad t < T_s \\ K_{if} & \text{if} \quad t \geq T_s \end{cases} \tag{3}$$

Where K_{pi} and K_{pf} are the initial and final value of the proportional gain K_p, and K_{if} is the final value of the integrator gain K_i. The initial value of K_i is taken to be zero. It is noted that a classical PI controller is a VGPI controller of degree zero.

The VGPI unit step response is given by:

$$y(t) = \begin{cases} K_{pi} + \left(K_{pf} - K_{pi} + \dfrac{K_{if}}{n+1}t\right)\left(\dfrac{t}{T_s}\right)^n & \text{if} \quad t < T_s \\ K_{pf} + K_{if}\left(t - \dfrac{n}{n+1}T_s\right) & \text{if} \quad t \geq T_s \end{cases} \tag{4}$$

Fig.2 gives the unit step response of a VGPI controller for different values of the degree n.

If $t<T_s$ (transient region), the classical PI unit step response is a linear curve beginning at K_{pf} and finishing at $K_{pf} + T_s K_{if}$, whereas the VGPI unit step response ($n \neq 0$) varies along a polynomial curve of degree n+1 beginning at K_{pi} and finishing at $K_{pf} + T_s K_{if}/(n+1)$.

If $t \geq T_s$ (permanent region), the unit step responses of a PI and a VGPI controller are both linear with slope K_{if}.

From these results, one can say that a VGPI controller has the same properties than a classical PI controller in the permanent region with damped step response in the transient region.

A VGPI controller could then be used to replace a PI controller when we need to solve the load disturbance rejection and overshoot problems simultaneously.

III. VGPI CONTROLLER IN SPEED CONTROL OF AN IVC MOTOR DRIVE

In order to show the effect of varying the gains of a PI controller on IVC motor drive speed control performances, some simulation work have been performed using the IVC induction motor drive structure illustrated by Fig.3 where the controller block is first replaced by a classical PI controller and then by a VGPI controller.

The parameters of the motor used in the simulation are given in Table 1. The reference speed used is $\Omega_{ref} = 1000$ rpm.

The classical PI controller is tuned using successive trials method. The machine is started up with a load of 10 Nm with the application of a 2 Nm load disturbance at t=2s. After making a compromise between speed overshoot and load disturbance rejection problem, the classical PI gains obtained are $K_p = 0.6$ and $K_i = 2$.

Unlike the classical PI controller, tuning of the VGPI controller does not need compromising. Speed overshoot caused by high integrator gains could be eliminated by increasing either the saturation time or the degree of the controller. One can choose the final value of the integrator gain needed for the application and then tune the other controller parameters so as to eliminate speed overshoot. Here is a proposed method of tuning a VGPI controller.

1. Choose a first degree VGPI controller with a high value of K_{if} (rapid load disturbance rejection).
2. Choose an initial value of the saturation time T_s.
3. Determine K_{pi} and K_{pf} for speed overshoot elimination by using the following steps ::
   - ♦ Consider K_p to be constant and simulate the controlled system for a small initial value of K_p.
   - ♦ Increase K_p gradually and simulate the controlled system again until speed overshoot gets to its optimum. Simulation shows that as K_p increases, speed overshoot decreases until an optimal value is obtained, then it begins to increase again. Choose K_{pi} to be the value of K_p that gives optimal overshoot.
   - ♦ Simulate the controlled system for an initial value of K_{pf} equal to the chosen value of K_{pi}.
   - ♦ Increase gradually the value of K_{pf} and simulate the controlled system again until speed overshoot is totally eliminated or gets to its optimal value. Simulation shows that as K_{pf} increases, speed overshoot decreases until a total elimination or gets to an optimal value. If overshoot is totally eliminated then K_{pf} is obtained and the controller is tuned.
4. If overshoot is not totally eliminated, then the value of the saturation time T_s is not sufficiently high, increase it gradually without exceeding a limiting value and repeat step 3 until overshoot is totally eliminated.
5. If at the limiting value of T_s overshoot is still not eliminated, then the degree of the controller is not high enough. Increase it and repeat the controller tuning again.

Using this tuning method with $K_{if} = 14$, the tuned VGPI controller is given by:

$$K_p = \begin{cases} 0.4 + 1.5\,t & \text{if} \;\; t < 1 \\ 1.9 & \text{if} \;\; t \geq 1 \end{cases} \qquad K_i = \begin{cases} 14\,t & \text{if} \;\; t < 1 \\ 14 & \text{if} \;\; t \geq 1 \end{cases} \tag{5}$$

TABLE 1
INDUCTION MACHINE PARAMETERS

2 pairs of poles, 50Hz	$R_s = 4.85\,\Omega$	$L_s = 274\,\text{mH}$
220/380 V, 6.4/3.7 A	$R_r = 3.805\,\Omega$	$L_r = 274\,\text{mH}$
2 hp , 1420 rpm	$L_m = 258\,\text{mH}$	
$J = 0.031\ \text{kgm}^2$	$f = 0.00114\ \text{Nms}$	

Fig.4.a and 4.b show the settling performance and the disturbance rejection capability of the classical PI and the proposed VGPI controller. Initially the machine is started up with a load of 10Nm. At 2s, a 2Nm load disturbance is applied during a period of 2s.

For the classical PI controller, the speed of the motor reaches Ω_{ref} at 1.8s after making an overshoot of 4.4%. The controller rejects the 2Nm load disturbance after 1.6s with a maximum speed dip of 24.8 rpm (2.58%).

For the VGPI controller, the speed of the motor reaches Ω_{ref} at 0.44s without overshoot. The controller rejects the 2Nm load disturbance in less than 0.6s with a maximum speed dip of 8.3 rpm (0.83%).

Fig.4.c and 4.d show the speed tracking performance of the VGPI and classical PI controllers under no load. The slope of the trapezoidal command speed is 2500 rpm/s. For both controllers, the slope of the trapezoidal command speed is correctly tracked.

In the case of the classical PI controller, the motor speed crosses Ω_{ref} by making a 8.05% overshoot before it returns to it after more than 1.6 seconds.

In the case of the VGPI controller, the motor speed crosses Ω_{ref} by making a 4.94% overshoot before it returns to it after 1.2 seconds.

Simulations given by fig.4.e to 4.o examine the robustness of the classical PI and the VGPI controllers to machine parameters variation.

Fig.4.e and 4.f show the controllers reaction to moment of inertia variation. The motor's speed is simulated, under no load, for moments of inertia equal to J and $J \times 2$. Simulation results show that multiplying J by 2 affects both the time to peak and the overshoot values. In the case of the classical PI controller, the time to peak value changes from 0.24s to 0.38s and the overshoot value changes from 12.5% to 20.4%. In the case of VGPI controller, the time to peak value changes from 0.26s to 0.36s and the overshoot value changes from 4.52% to 8.12%.

Fig.4.g to 4.o shows the reaction of the classical PI and the proposed VGPI controller to rotor resistance variation. The motor is started up with a load of 10 Nm. The rotor resistance is supposed to double at 2sec.

Rotor resistance variation is shown to affect the rotor flux orientation. For both controllers the following results are obtained :

- At rotor resistance rated value, the rotor flux is oriented along the direct axis as assumed by the field orientation scheme (ψ_{qr}=0)
- At 200% of rotor resistance rated value, the rotor flux is deviated clockwise from the direct axis with an angle of 7.49° causing then a detuning problem in the field orientation scheme.
- The controllers compensate the detuning problem by increasing the torque command to 161% of its rated value.

The classical PI controller rejects the rotor resistance disturbance after 1.7s with a speed dip of 70 rpm (7%). The proposed VGPI controller rejects the rotor resistance disturbance in less than 0.7s with a maximum speed dip of 23.5 rpm (2.35%).

By comparing these results, one can say that varying the gains of a classical PI controller transforms it to a high performance robust controller. A linear variation of the gains (first degree VGPI controller) gave important amelioration. One can mention the settling time value which was almost divided by four or the speed overshoot which was totally eliminated. Better performances could be obtained using higher degree VGPI controllers.

IV. VGPI CONTROLLER IN ROTOR RESISTANCE ESTIMATION

In the previous section it has been shown by simulation that the variation in the rotor resistance affects the rotor flux orientation and causes F.O.C. detuning problem. This problem could be eliminated by adding to the command system a rotor resistance estimation block whose function is to feed the field orientation scheme with the estimated instantaneous value of the rotor resistance.

Rotor resistance estimation could be done using a characteristic function F defined as:

$$F = \frac{1}{\omega_s}\left(\left(V_{ds} - K\frac{di_{ds}}{dt}\right)i_{qs} - \left(V_{qs} - K\frac{di_{qs}}{dt}\right)i_{ds}\right) + K\left(i_{ds}^2 + i_{qs}^2\right) \quad (6)$$

where $K = L_s - L_m^2 / L_r$ and L_s, L_r, L_m are rotor parameters, i_{ds}, i_{qs}, v_{ds}, v_{qs} and ω_s are motor currents, voltages and electrical synchronous speed.

This function can also be obtained from a modified expression of the reactive power with the introduction of flux orientation conditions as follows:

$$F = \frac{L_m}{L_r\omega_s}\frac{d\psi_r}{dt}i_{qs} - \frac{L_m}{L_r}\psi_r i_{ds} \quad (7)$$

In permanent mode, this equation becomes:

$$F_0 = -\psi_r^{*2} / L_r \quad (8)$$

The error function $\Delta F = F - F_0$ reflects the rotor resistance variation [8],[9] and can be used as a correction function for the adaptation of the rotor time constant $T_r = L_r / R_r$ in the speed control [10]. The adaptation is made using a closed loop control of the characteristic function F which works parallel to the speed control. The input to the F controller is the measured difference ΔF and the output is the estimated variation ΔT_r given by:

$$\Delta T_r = T_{r\_ini} - T_{r\_est} \quad (9)$$

Where T_{r_ini} and T_{r_est} are respectively the initial and estimated value of the rotor time constant.

In order to show the effect of varying the gains of a PI controller on rotor resistance estimation performances, some simulations have been executed using the IVC induction motor drive structure with rotor resistance adaptation illustrated by Fig. 5. The F-controller block is first replaced by a classical PI controller and then by a VGPI controller. The speed controller used in the two cases is the VGPI given by equation 5.

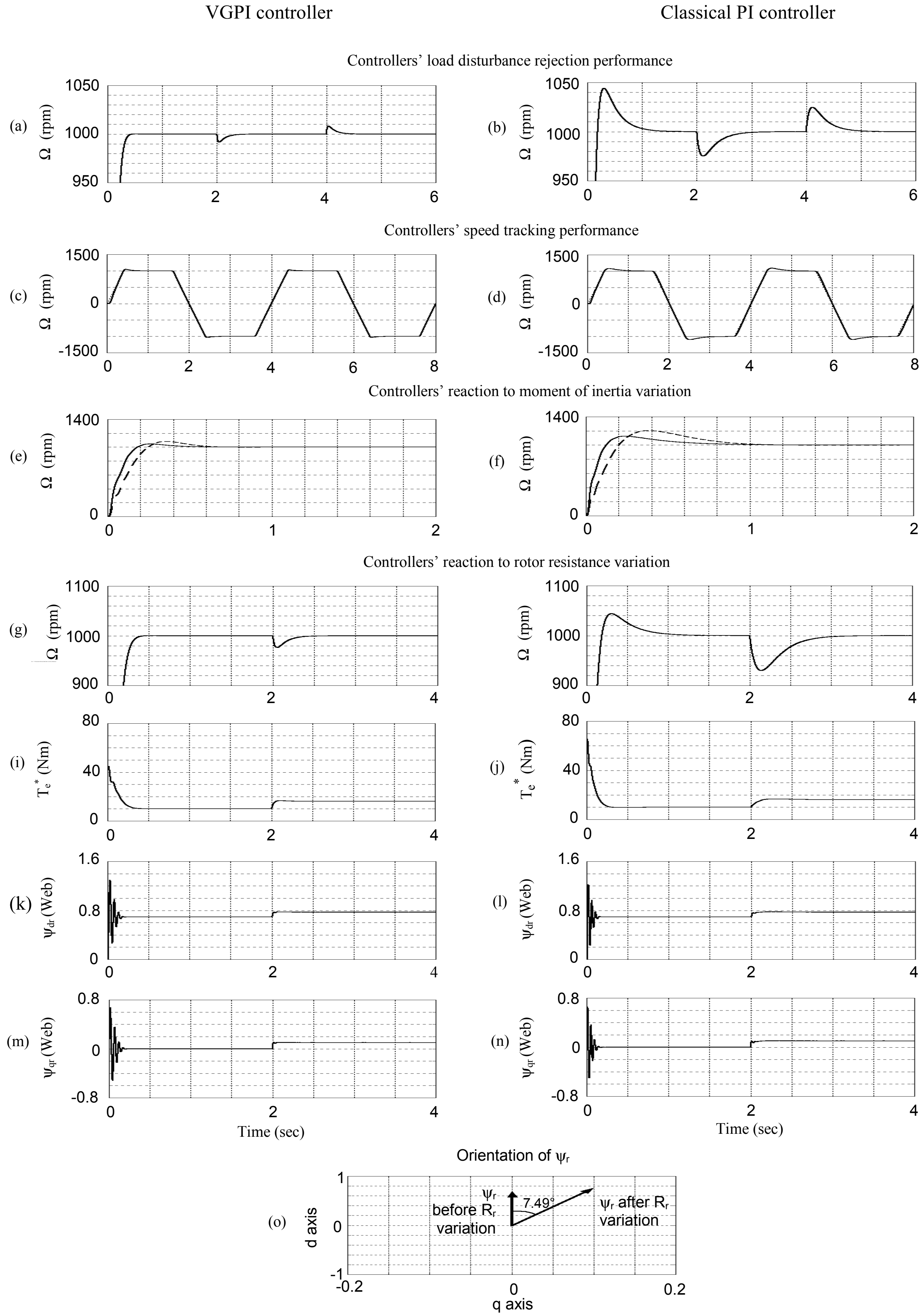

Fig. 4. Performances comparison between the VGPI and the classical PI controller in the case of load disturbance rejection, speed tracking, moment of inertia variation and rotor resistance variation.
(e – f) —— J, – – – 2×J

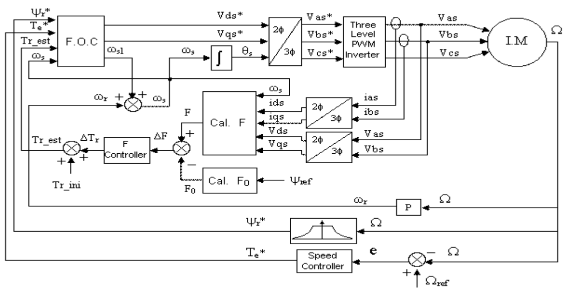

Fig. 5. Indirect field orientation control block diagram with rotor resistance adaptation

The functions F and F_0 used in the rotor resistance estimation structure are calculated using the reference value ψ_r^* and the measured variables i_{ds}, i_{qs}, v_{ds}, v_{qs} and ω_s.

Tuning the VGPI and the classical PI F-controllers is done using successive trials method. The machine is supposed to start with a load of 10 Nm. The rotor resistance changes at 1 sec from 100% of its rated value to 200% linearly till 2 sec. this value is maintained for 2 sec and then decreases back to 100% at the same rate.

The gains of the classical PI F-controller are given by $K_p = 0$ and $K_i = 1.2$

The gains of the VGPI F-controller are given by:

$$K_p = 0 \ , \quad K_i = \begin{cases} 3\,t^3 & \text{if } t < 1 \\ 3 & \text{if } t \geq 1 \end{cases} \qquad (10)$$

Fig.6 illustrates a simulated performance comparison between the Variable Integrator (VI) and the classical Integrator rotor resistance estimator.

In permanent mode, simulation shows that both F-controllers have nearly the same performances. The error function ΔF is rapidly eliminated resulting in:

- Fast convergence of the rotor resistance estimation.
- Elimination of the detuning problem ($\psi_{qr} = 0$).
- Elimination of the rotor resistance variation effect in speed control.
- Elimination of the command torque compensation for rotor resistance variation.

In transient mode however there is a difference between the performances of the two F-controllers.

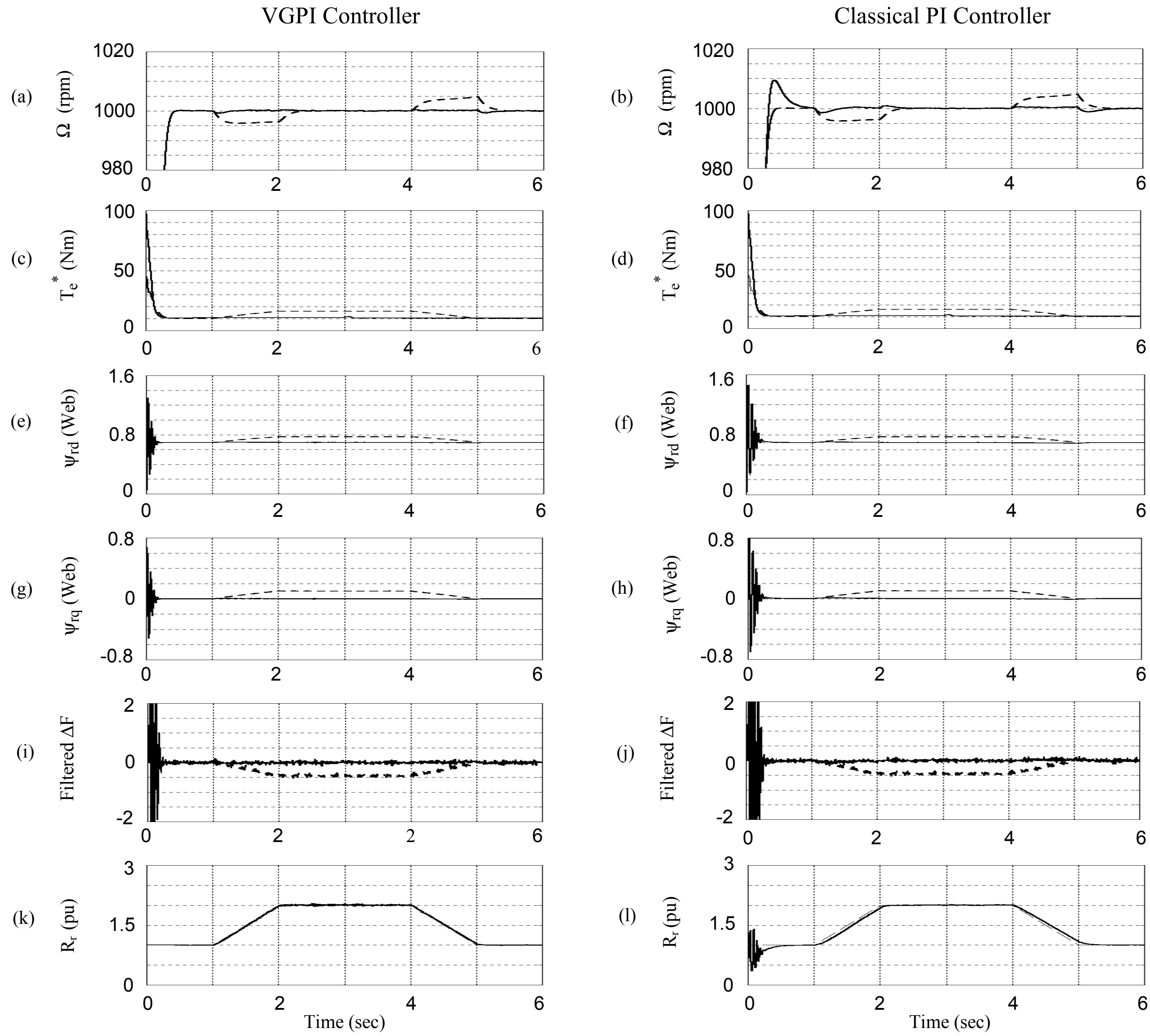

Fig. 6. Performance comparison between the VGPI and the classical PI rotor resistance estimator
(a – j) – – – Before rotor resistance adaptation, —— After rotor resistance adaptation
(k – l) – – – Real value, —— Estimated value

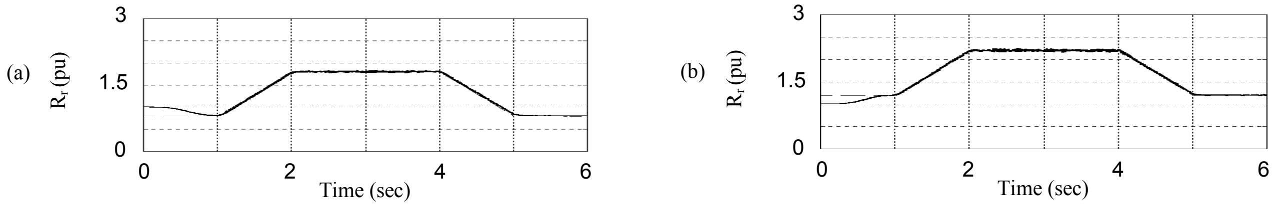

Fig. 7. VGPI rotor resistance estimation in the case of over estimation and under estimation of T_{r_ini}.
– – – Real value, —— Estimated value

The VGPI rotor resistance estimator converges rapidly on the real value without overshoot whereas the PI estimator oscillates during 0.5 sec between 39% and 145% of the real value. These oscillations introduce a 9% overshoot on the speed control.

Fig.7 illustrates a simulated rotor resistance estimation using a VGPI controller in the case of over estimation and under estimation of T_{r_ini}. The simulation results demonstrate that rotor resistance estimation does not depend on the rotor constant initial value used in the rotor resistance estimation operation.

V. CONCLUSION

In this paper an original variable gain PI controller has been introduced. The dynamical performances of a VGPI controller in speed control and rotor resistance estimation of a voltage fed IVC induction machine drive have been studied and compared with those of a classical PI controller.

Simulation results demonstrated that VGPI controller outperforms the classical PI controller, both in speed control and in rotor resistance estimation operation.

In speed control, the given first degree VGPI controller totally eliminates overshoot and improves the performances of a classical PI controller by a minimal factor of 2 (settling time is divided by 4, load disturbance rejection time and speed dip are almost divided by 3, rotor resistance variation rejection time and speed dip are almost divided by 3). These performances could be significantly improved by using a higher degree VGPI controller.

In rotor resistance estimation, a third degree Variable Integrator estimator provides excellent rotor resistance tracking performance. It eliminates both the oscillations obtained on a classical Integrator rotor resistance tracking and the resulting speed overshoot.

In conclusion it seems that classical PI controllers could be transformed to high performance robust controllers just by varying their gains. Our perspective is to develop a variable gain Fuzzy Logic controller for speed control and rotor resistance estimation of an IVC induction motor drive.

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