FULL PARAMETER INDEPENDENCE IN A FIELD-ORIENTED CURRENT-FED SYNCHRONOUS MACHINE WITH TWO EXCITATION WINDINGS

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ABSTRACT - *Field orientation of rotating field machines is influenced by various machine parameters. Most unpleasant are those parameters which vary during machine operation, such as the stator and rotor resistances. Permanent influences of resistance variation in steady state operation could have serious consequences. Also transitory influences are often disturbing. In this paper a control method for a current-fed synchronous machine is presented in which both permanent and transitory parameter influences are suppressed as much as possible.*

1.INTRODUCTION

We introduce a current-fed (I) rotating field synchronous machine (S) with a rotor damper winding system (subscript d) and a rotor excitation winding system (subscript r). The last system consists of 2 windings perpendicular to each other, which can be used as two separate excitation windings. We refer to this machine as the IS(2) in contrast with the conventional current-fed synchronous machine with only one excitation winding (IS(1)). The three-phase stator winding (subscript s) and the damper winding system can be transformed in equivalent two-phase windings. Using the two-dimensional vector theory a set of equations in the (damper winding) flux reference coordinate system, indicated by ψ (see Fig. 1), can be derived for the IS(2). It should be noted that for the sake of simplicity the leakage inductance $l_{\sigma d}$ of the damper winding system is neglected. Fig. 2 shows the corresponding block diagram.

$$\psi = l \cdot i_\mu \tag{1}$$

$$i_\mu = i_s^{\psi 1} + i_r^{\psi 1} + i_d^{\psi 1} \tag{2}$$

$$0 = i_s^{\psi 2} + i_r^{\psi 2} + i_d^{\psi 2} \tag{3}$$

$$-r_d \cdot i_d^{\psi 1} = \dot{\psi} \tag{4}$$

$$-r_d \cdot i_d^{\psi 2} = \psi\, \dot{\varphi}^r \tag{5}$$

$$i_s^{\psi 1} = i_s \cdot \cos \varepsilon_s^{\psi} \tag{6}$$

$$i_s^{\psi 2} = i_s \cdot \sin \varepsilon_s^{\psi} \tag{7}$$

$$\varepsilon_s^{\psi} = \varepsilon_s^s - \varphi^s \tag{8}$$

$$\varphi^s = \varphi^r + \rho^s \tag{9}$$

$$i_s = \sqrt{\left(i_s^{s1}\right)^2 + \left(i_s^{s2}\right)^2} \tag{10}$$

$$\varepsilon_s^s = \arctan i_s^{s2}/i_s^{s1} \tag{11}$$

$$i_s^{s1} = i_s^{s1*} \tag{12}$$

$$i_s^{s2} = i_s^{s2*} \tag{13}$$

$$i_r^{\psi 1} = i_r \cdot \cos \varepsilon_r^{\psi} \tag{14}$$

$$i_r^{\psi 2} = i_r \cdot \sin \varepsilon_r^{\psi} \tag{15}$$

$$\varepsilon_r^{\psi} = \varepsilon_r^r - \varphi^r \tag{16}$$

$$i_r = \sqrt{\left(i_r^{r1}\right)^2 + \left(i_r^{r2}\right)^2} \tag{17}$$

$$\varepsilon_r^r = \arctan i_r^{r2}/i_r^{r1} \tag{18}$$

$$i_r^{r1} = i_r^{r1*} \tag{19}$$

$$i_r^{r2} = i_r^{r2*} \tag{20}$$

$$m_{el} = \psi \cdot i_s^{\psi 2} = -\psi \cdot \left(i_r^{\psi 2} + i_d^{\psi 2}\right) \tag{21}$$

$$\dot{\rho}^s = \frac{1}{t_{mech}} \int (m_{el} - m_{load})\, dt \tag{22}$$

The current-regulated voltage-source-inverter to supply the stator winding system and the two ac/dc converters to supply the two excitation windings are assumed to be ideal as indicated by (12), (13) and (19), (20). As can be seen from (2) and (3) and Fig. 1 the combination of all current vectors in the machine results in a vector quadrangle. How-

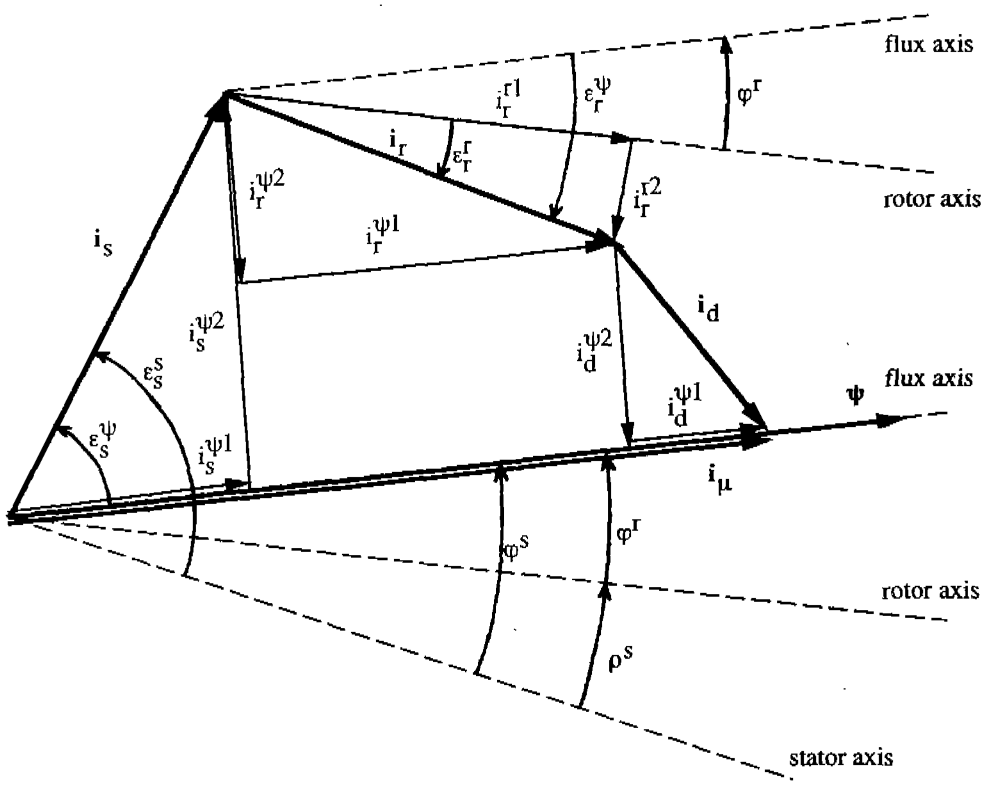


Fig. 1: Current vectors in the (damper winding) flux reference coordinate system

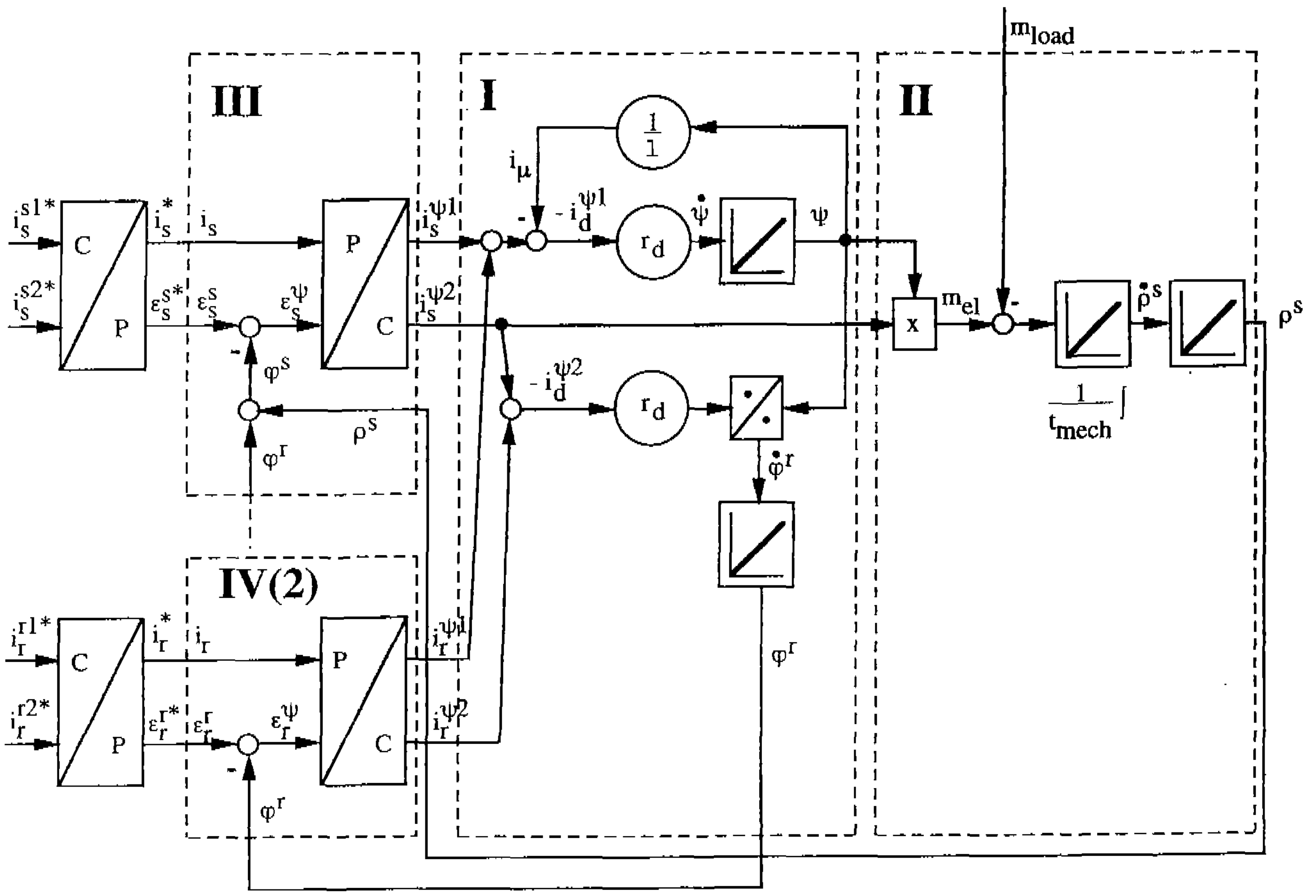


Fig. 2: Block diagram of the IS(2), representing the equations (1) to (22)

ever, in a stationary operating condition a vector triangle originates, as the damper winding current vector $\mathbf{i}_d$ is zero.

2.FIELD-ORIENTED CONTROL

The field orientation of the IS(2) requires the angles φ^s and φ^r, as can be seen from Fig. 3. Then the four command values $i_s^{\psi1*}$, $i_s^{\psi2*}$, $i_r^{\psi1*}$ and $i_r^{\psi2*}$ can be supplied ideally to the machine.

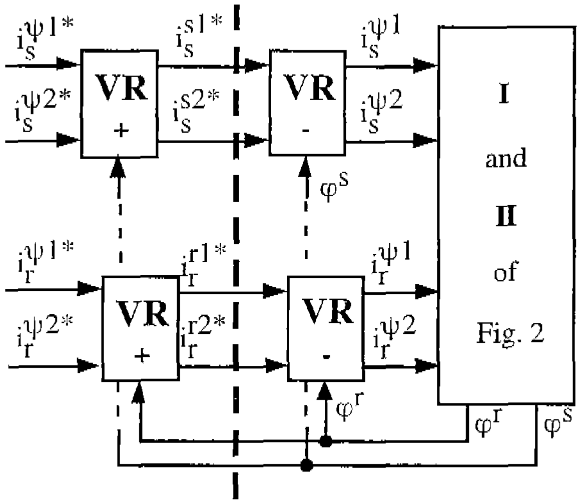


Fig.3: Field orientation of the IS(2)

Considering the state of the art of the field orientation technique three methods exist to get these two angles.

In the first method one gets $\hat{\varphi}^s$ from a $\mathbf{u}_s/\mathbf{i}_s$-model and ρ^s from a rotor position sensor. The angle $\hat{\varphi}^r$ is

$$\hat{\varphi}^r = \hat{\varphi}^s - \rho^s \tag{23}$$

In the second method one also yields $\hat{\varphi}^s$ from a $\mathbf{u}_s/\mathbf{i}_s$-model and $\hat{\varphi}^r$ from a $\mathbf{i}_s/\rho^s$-model. Finally, the third method consists of getting ρ^s from a rotor position sensor and $\hat{\varphi}^r$ from a $\mathbf{i}_s/\rho^s$-model. The angle $\hat{\varphi}^s$ is

$$\hat{\varphi}^s = \rho^s + \hat{\varphi}^r \tag{24}$$

When using a $\mathbf{u}_s/\mathbf{i}_s$-model a permanent influence of the stator resistance will disturb the field orientation at least in the low frequency region. Therefore, method 1 and 2 are excluded.

The field-oriented control circuit of method 3, using the angles $\hat{\varphi}^s = \rho^s + \hat{\varphi}^r$ and $\hat{\varphi}^r$ is shown in the left part of Fig. 4. The $\mathbf{i}_s/\rho^s$-model is a copy of block **I** of the IS(2).

Besides the main inductance $\hat{l}$ it contains the rotor damper resistance $\hat{r}_d$ as parameter. When detuning occurs, i.e. $\hat{r}_d \neq r_d$, it follows that $\hat{\mathbf{I}} \neq \mathbf{I}$ and $\hat{\varphi}^r \neq \varphi^r$. It is extremely important to notice that in a synchronous machine this detuning effect does only result in a transitory error, as it will be proved in section 3.

The four command values $i_s^{\psi1*}$, $i_s^{\psi2*}$, $i_r^{\psi1*}$ and $i_r^{\psi2*}$ of the IS(2) are only determined in the sense that the components $i_s^{\psi1*}$ and $i_r^{\psi1*}$, parallel with $\boldsymbol{\psi}$, are taking care of the magnetisation and the components $i_s^{\psi2*}$ and $i_r^{\psi2*}$, perpendicular to $\boldsymbol{\psi}$, are producing the torque. The value of the separate coordinates in each group is arbitrary.

3.FIELD ORIENTATION OF THE IS(1)

In the conventional current-fed rotating field synchronous machine with a damper winding system and one rotor winding, the so-called IS(1), only one rotor current i_r^{r1} exists (see Fig. 5). It is also assumed here that the total magnetizing current $i^{\psi1*}$ is commanded through $i_r^{\psi1*}$, in other words, the stator doesn't take part in the magnetisation process. The rotor current component i_r^{r2} is set to zero by commanding $i_r^{\psi2*}$ as follows

$$i_r^{\psi2*} = - i_r^{\psi1*} \tan \hat{\varphi}^r \tag{25}$$

Consequently, the current vector $\mathbf{i}_r^{\psi*}$ has the angle $-\hat{\varphi}^r$, which will be compensated by the angle $\hat{\varphi}^r$ of the vector rotator **VR**, resulting in a current vector $\mathbf{i}_r^{r*}$ with angle zero.

When the model $\hat{\mathbf{I}}$ is exactly tuned, $\hat{\varphi}^r$ equals φ^r stationary and dynamically, and the command values $i_s^{\psi1*}$, $i_s^{\psi2*}$, $i_r^{\psi1*}$ and $i_r^{\psi2*}$ are transferred into the machine without any error, as shown in Fig. 6a.

When the model $\hat{\mathbf{I}}$ is detuned, $\hat{\varphi}^r$ still equals φ^r in stationary operating conditions. In the model the stationary condition is given by

$$\left[\hat{i}_d^{\psi2}\right]_0 = 0 \tag{26}$$

It means that the vector $-\hat{\mathbf{i}}_d^{\psi}$ is parallel with the estimated $\hat{\psi}$-axis. In this case

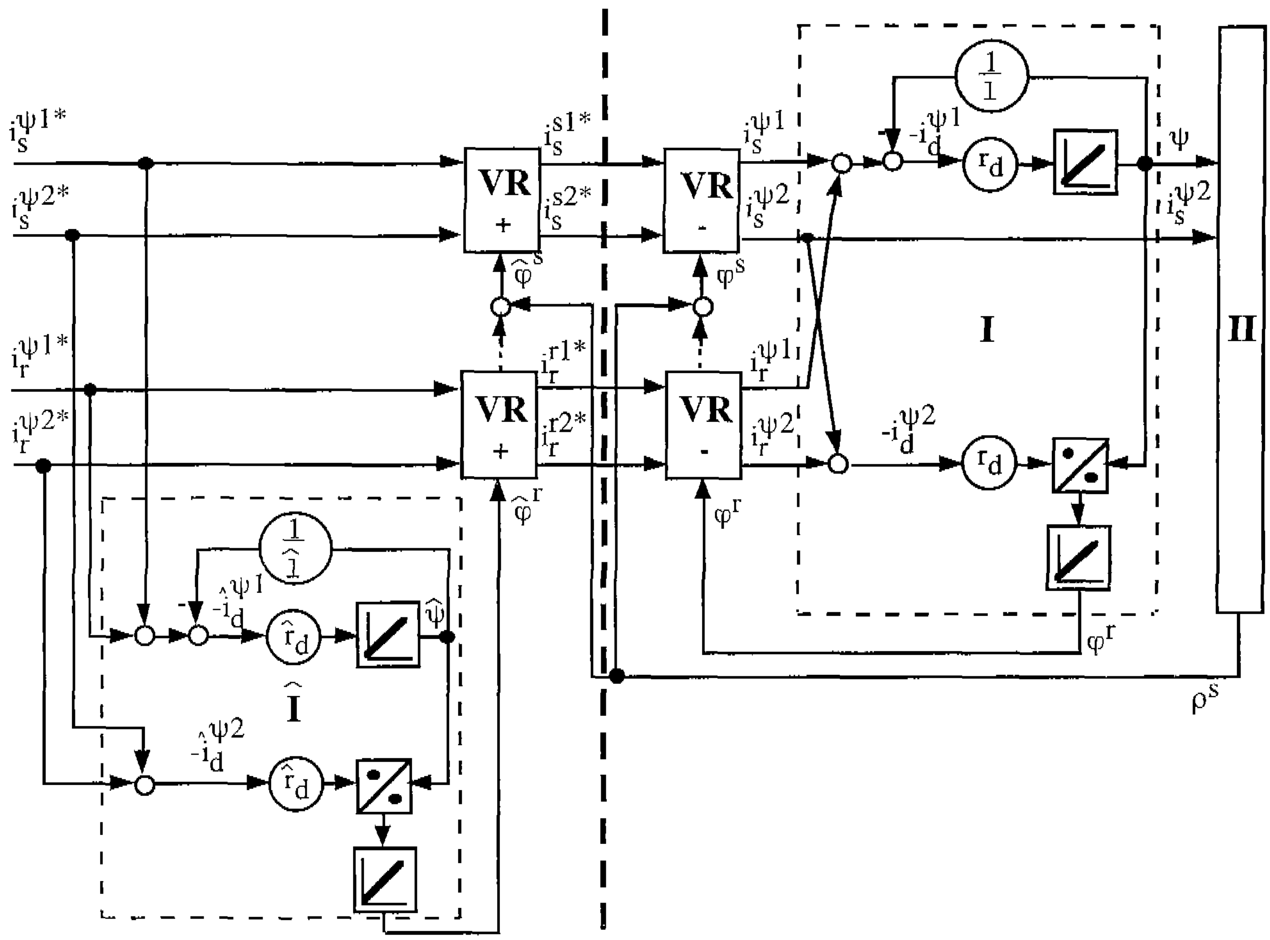


Fig. 4: Field-oriented IS(2)

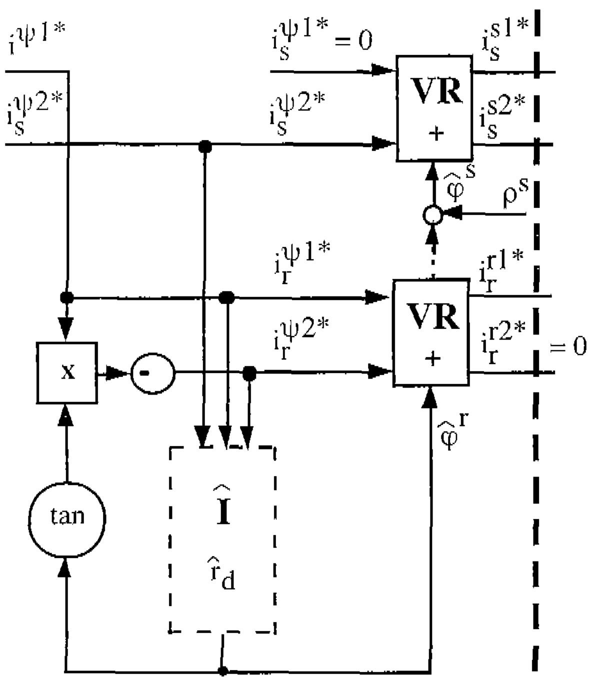


Fig. 5: Field-oriented control structure of the IS(1)

$$\left[-i_r^{\psi 2*}\right]_0 = \left[i_s^{\psi 2*}\right]_0 \tag{27}$$

From (27) one yields

$$\left[\tan \hat{\varphi}^r\right]_0 = \left[i_s^{\psi 2*}/i_r^{\psi 1*}\right]_0 \tag{28}$$

On the other hand the stationary condition is the machine is given by

$$\left[i_d^{\psi 2}\right]_0 = 0 \tag{29}$$

This also means that the vector $-\mathbf{i}_d^{\psi}$ is parallel with the real ψ-axis. This transfer phenomenon is only possible if

$$\left[\varphi^r\right]_0 = \left[\hat{\varphi}^r\right]_0 \tag{30}$$

since only then the simultaneous transfers from $\mathbf{i}_s^{\psi*}$ and $\mathbf{i}_r^{\psi*}$ to $\mathbf{i}_s^{\psi}$ and $\mathbf{i}_r^{\psi}$ occur in an identical way.

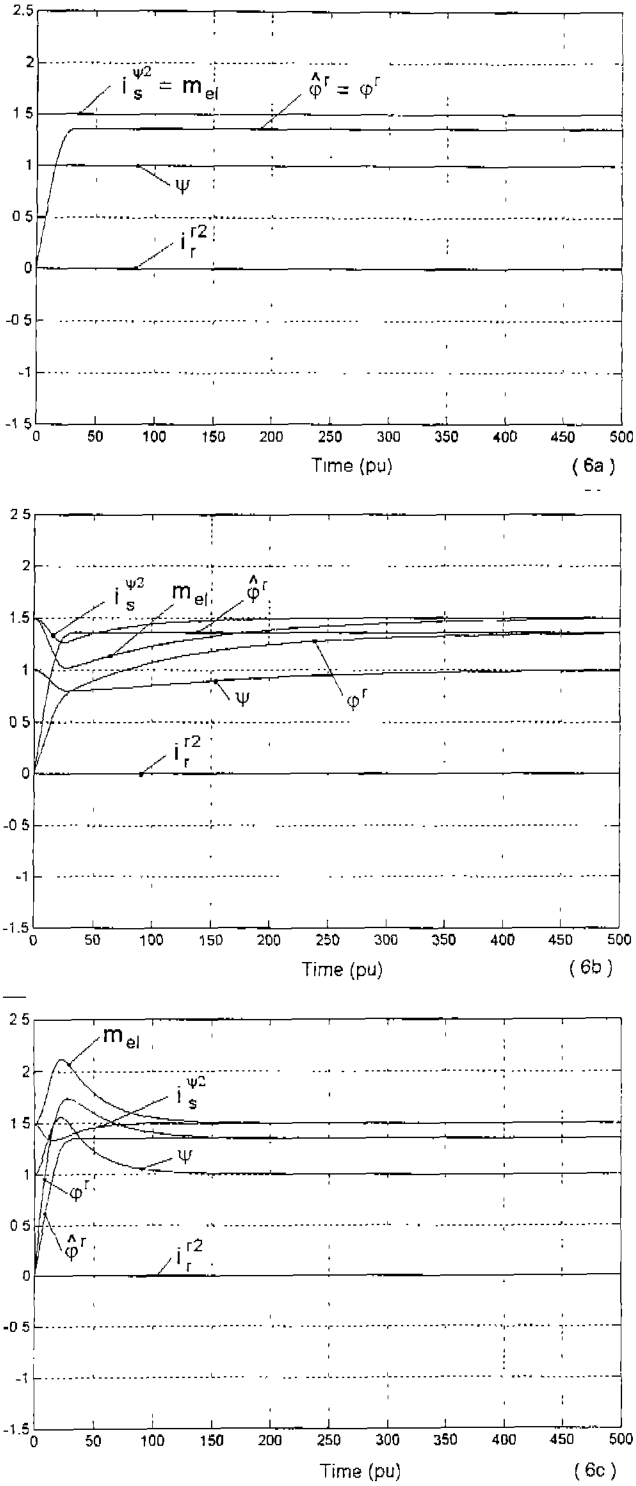


Fig. 6: Behaviour of the field-oriented IS(1) after a step increase of the torque producing stator current component $i_s^{\psi 2*}$ of 1.5 pu $(l = \hat{l} = 3, \hat{r}_d = 0.05)$ a) $r_d = 0.05$ b) $r_d = 0.025$ c) $r_d = 0.1$

During transient operating conditions, however, with a detuned model an angle inequality

$$\varphi^r \neq \widetilde{\varphi}^r \tag{31}$$

will exist due to the fact that with $\hat{r}_d \neq r_d$ the inputs of the integrators are different and therefore unequal movements arise. The flux and torque values diverge transitory from the commanded ones, which is demonstrated in Fig. 6b, c.

4.FIELD ORIENTATION OF THE IS(2) WITH FULL PARAMETER INDEPENDENCE

Using an IS(2) it is possible to neglect the requirement $i_r^{r2} = 0$. On the contrary, one is able to prescribe freely the rotor current component $i_r^{\psi 2*}$. Instead of (25) this current component is commanded as follows (see Fig. 7)

$$i_r^{\psi 2*} = - i_r^{\psi 1*} \tan \widetilde{\varphi}^r - K\, i_s^{\psi 2*} \tag{32}$$

In contrast with (28) the stationary condition of the model is now given by

$$\left[\tan \widetilde{\varphi}^r\right]_0 = \left[i_s^{\psi 2*} (1 - K) / i_r^{\psi 1*}\right]_0 \tag{33}$$

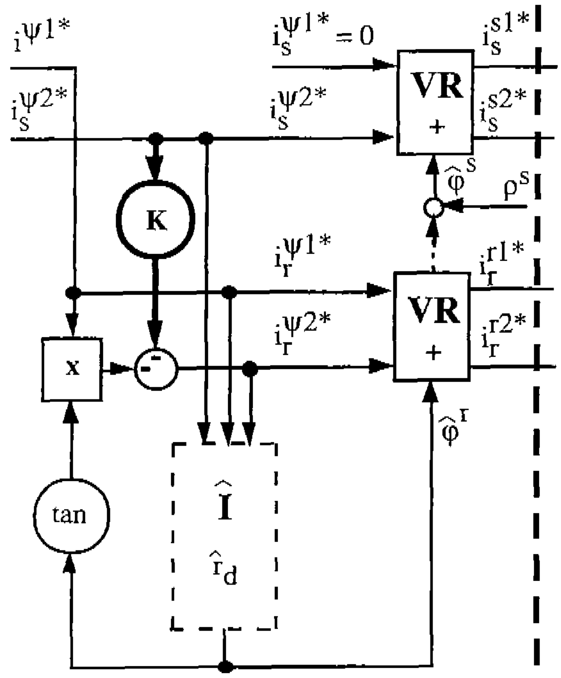
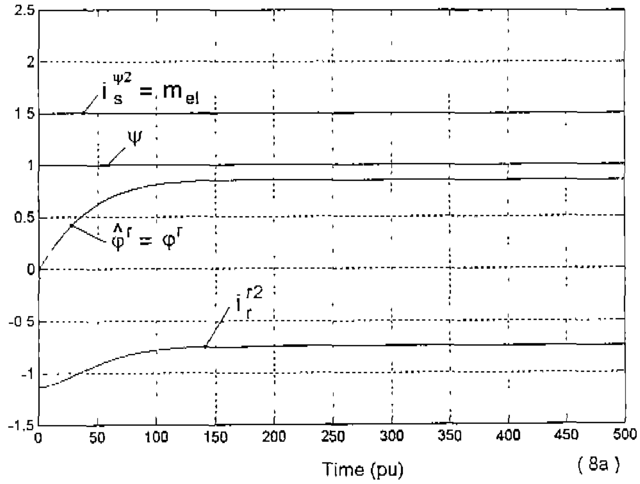
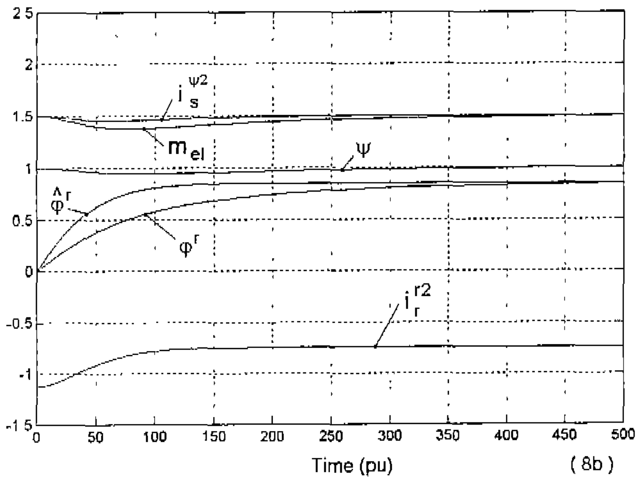
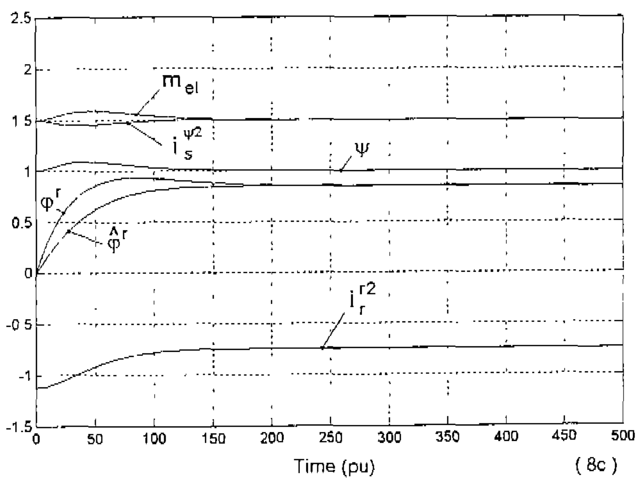


Fig. 7: Field-oriented control circuit of the IS(2) with full parameter independence.

By varying K from 0 to 1 the value of $\left[\tan \widetilde{\varphi}^r\right]_0$ is reduced from that of (28) to zero. This is equivalent with reducing the effects of the detuned model in transient operating conditions. These effects totally vanish when K = 1. Fig. 8 clearly demonstrates the behaviour of the field-oriented IS(2). The trajectory of the machine torque resembles more that of the commanded one, namely a step function, when the value of K approaches 1. It can also be demonstrated that the deviations from the ideal trajectory almost vanish when K is in the vicinity of 1; therefore, the proposed method is very robust. The behaviour will still be satisfactory when the value of i_r^{r2} can not be increased to that of $i_s^{\psi 2*}$ due to, for instance, possible overloading of the field winding system.







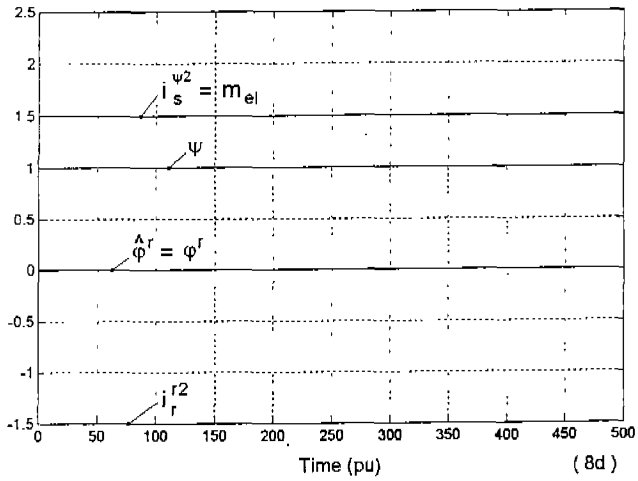


Fig. 8: Behaviour of the field-oriented IS(2) after a step increase of the torque producing stator current component $i_s^{\psi 2*}$ of 1.5 pu $\left(l = \hat{l} = 3, \hat{r}_d = 0.05\right)$

a) K = 0.75, $r_d = 0.05$
b) K = 0.75, $r_d = 0.025$
c) K = 0.75, $r_d = 0.1$
d) K = 1, $r_d = 0.025$, 0.05 , 0.1

Finally, it should be mentioned that these very positive results are only valid in constant flux operation, since the inequality of the command flux value and the real flux value can not be prevented when the model is detuned.

5.CONCLUSIONS

For constant flux operation the current-fed synchronous machine with two perpendicular excitation windings and provided with the field-oriented control circuit of Fig. 7 is fully parameter independent when K = 1, i.e. when $i_r^{\psi 2} = -i_s^{\psi 2}$ or $\varphi^r = 0$ at any instant. The disturbing damper winding current $\mathbf{i}_d$ is completely suppressed. The "resulting" structure of such a field-oriented IS(2) equals that of a separately excited dc machine provided with a compensating winding.

6.REFERENCES

[1] F. Blaschke, Das Verfahren der Feldorientierung zur Regelung der Drehfeldmaschine, Ph. D. thesis, TU Braunschweig, 1974.

[2] F. Blaschke and A. Vandenput, Control of ac machines, Vol.1 Text, Vol.2 Figures (in Dutch), Eindhoven University of Technology Report 96-E-296, 1996.