CAN THE SYNTHESIS OF DC MOTOR CASACADE CONTROL PARAMETERS BE THE SAME AS FOR THE FIELD-ORIENTED CONTROLLED INDUCTION MOTOR

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Abstract: In induction motors, the spatial angle between the stator and rotor flux changes with the load, which creates more complex relations between currents, voltages and fluxes in the machine, as well as oscillatory dynamic responses. Controlling this space angle can ideally be carried out by converting the input stator current into direct i_{1d} - component, responsible for the excitation flux and quadrature component i_{1q}, responsible for the developed electromagnetic torque. This can be achieved by a vector control method that allows for a relatively simple solution to the problem of "coupling" between axes *d* and *q*, thus bringing the dynamic IM model closer to the separately-excited DC motor model.

Key words: induction motor, coupling, decoupling, synthesis, control circuit

1. INTRODUCTION

For a field-oriented vector control (FOC) of an electromotive drive with IM, it is necessary to consider all space vectors $\vec{i}_1$, $\vec{i}_2$, $\vec{u}_1$, $\vec{u}_2$, $\vec{\psi}_1$, $\vec{\psi}_2$ describing the dynamic IM model as one rotating coordinate system oriented on machine's field, i.e., to the rotor flux space vector $\vec{\psi}_2$. In this concept of field-oriented vector control in the machine, the $\vec{i}_1 - \vec{\psi}_2$ IM model is used because, as it will be shown later in this paper, overall control is based on the space vectors of the stator current $\vec{i}_1$ and the rotor flux $\vec{\psi}_2$.

The choice of the *d–q* coordinate system which rotates at angular velocity ω_2 and is tied to the rotor flux space vector $\vec{\psi}_2$, is made based on the machine model to

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provide the best possible dynamics, control accuracy and relatively high degree of simplicity. In this vector control concept, the impact of the inverter switching mode, i.e., its discrete dynamic model is not taken into account in the analysis. Different model based observers for the estimation of the stator flux, rotor flux, and rotor speed in a direct field-oriented controlled IM are developed [1],[2],[3]. Some of them are based on a novel integrator scheme with a closed-loop dc offset compensation algorithm which enables accurate and stable operation, including the critical low stator frequency range [2].

This approach to IM vector control, rotor flux space vector $\vec{\psi}_2$-oriented, enables the control circuits themselves to define the waveform of the 3-phase time-varying stator voltages, which later on by means of an external PWM- modulator (e.g. sinusoidal or enhanced sinusoidal PWM-modulator) are transformed into the required switch-on/off inverter pulses. This external PWM modulator enables the production of adequate modulated synchronous pulses which can be optimized in terms of the high-order harmonic components [3] of the current and voltage space vectors.

2. CONTROL STRUCTURE

The concept of field-oriented vector control (FOC) is considered in a rotating frame of reference aligned with the rotor flux vector. Structural scheme of the control circuits is given in Figure 1.

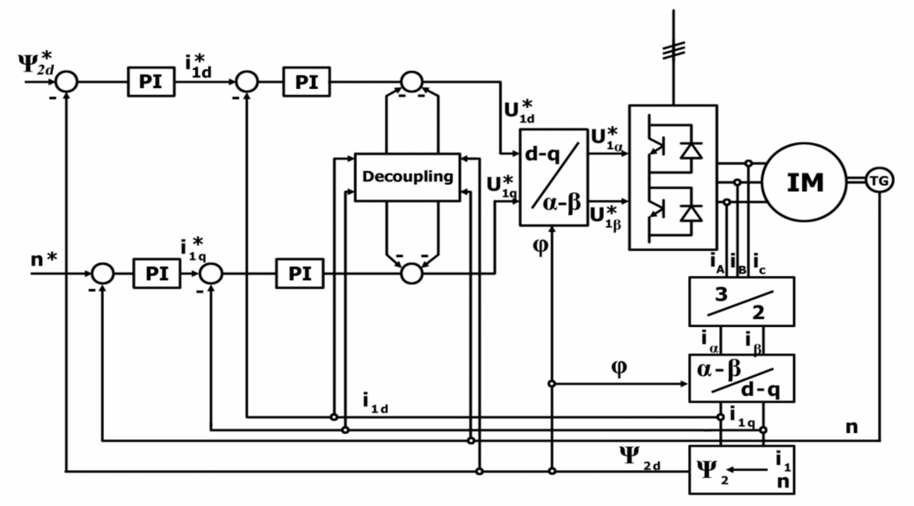

Figure 1. Functional block scheme of speed control

The concept of IM speed control is based on converting the stator current vector $\vec{i}_1$ into the d-axis i_{1d} component, which creates flux in the machine, and into the q-axis i_{1q} component, which is responsible for the machine's developed torque. By means of these two current components, the torque and flux in the machine can be controlled similarly to the armature and excitation current in a separately-excited DC machine. By converting the stator current $\vec{i}_1$ in two components: one direct i_{1d} - component aligned with the rotor flux space vector $\vec{\psi}_2$, and the other, quadrature component i_{1q}, perpendicular to it, the following is valid:

$$\left|\vec{\psi}_2\right| \approx i_{1d} \tag{1}$$

$$M \approx i_{1q} \tag{2}$$

The orientation of the current relative to the rotor flux space vector gives advantages for simple current-, flux- and speed control circuit synthesis. Only synthesis of controller parameter in the rotating frame of reference aligned to the rotor flux space vector $\vec{\psi}_2$ gives the complete analogy of IM with a compensated separately-excited DC motor. Figure 1 shows that the assigned speed references and the amplitude of the rotor flux vector, after PI controller, result in the reference of the current component which creates the torque and the reference of the current component which creates the flux in the machine. The IM armature current is measured and, by transforming the coordinates, is turned into real value of the component generating the flux and the component generating the machine torque. After comparing reference values to real values of both components of the stator current vector $\vec{i}_1$, by means of two proportionally integral controllers (torque controller and flux controller) and by a decoupling circuit, the required references of the stator voltage space vector U_{1d}^* and U_{1q}^* are obtained. Following the transformation of these components in an α-β coordinate system and corresponding modulation, the required switch on/off pulses of the inverter supplying the IM is obtained.

3. CONTROL CIRCUIT SYNTHESIS

For the purpose of analyzing and synthesizing the control circuits of the current, flux and speed/torque, this section will briefly reiterate the $\vec{i}_1 - \vec{\psi}_2$ IM model in the *d–q* coordinate system tied to the rotor flux space vector.

Through the angular velocity rated value ω_2 of the rotor flux space vector $\vec{\psi}_2$ with $n_k = \omega_2$, $\psi_{2d} = 0$, $\frac{d\psi_{2d}}{dt} = 0$, the following is obtained:

$$u_{1d} = R_1 \cdot i_{1d} + \frac{d\psi_{1d}}{dt} - \omega_2 \cdot \psi_{1q} \tag{3}$$

$$u_{1q} = R_1 \cdot i_{1q} + \frac{d\psi_{1q}}{dt} + \omega_2 \cdot \psi_{1d} \tag{4}$$

$$0 = R_2 \cdot i_{2d} + \frac{d\psi_{2d}}{dt} \tag{5}$$

$$0 = R_2 \cdot i_{2q} + (\omega_2 - n) \cdot \psi_{2d} \tag{6}$$

$$\psi_{1d} = X_1 \cdot i_{1d} + X_m \cdot i_{2d} \tag{7}$$

$$\psi_{1q} = X_1 \cdot i_{1q} + X_m \cdot i_{2q} \tag{8}$$

$$\psi_{2d} = X_2 \cdot i_{2d} + X_m \cdot i_{1d} \tag{9}$$

$$\psi_{2q} = 0 = X_2 \cdot i_{2q} + X_m \cdot i_{1q} \tag{10}$$

By substituting (9) and (10) in the rotor voltage equations (5) and (6) it follows that:

$$\frac{d\psi_{2d}}{dt} + \frac{R_2}{X_2} \cdot \psi_{2d} = \frac{R_2}{X_2} \cdot X_m \cdot i_{1d} \tag{11}$$

$$(\omega_2 - n) \cdot \psi_{2d} = \frac{R_2}{X_2} \cdot X_m \cdot i_{1q} \tag{12}$$

Now the developed electromagnetic torque, by means of equations (7) to (10), can be transformed into:

$$M = \frac{X_m}{X_2} \cdot \psi_{2d} \cdot i_{1q} \cdot \tag{13}$$

The equations (11) to (13) represent the $\vec{i}_1 - \vec{\psi}_2$ IM model in *d–q* rotating coordinate system. Figure 2 shows the control structure. The rotor flux space vector results in the reference signal of direct axis current component i_{1d}^*, while the speed controller output represents the required machine torque, which in turn is transformed into the required current reference i_{1q}^*. The outputs of decoupling blocs A, B, A_1, B_1 give the references of the voltage space vector U_{1d}^* - and U_{1q}^* - components. Then, by blocks 30–32 a three-phase system of reference voltages U_a^*, U_b^*, U_c^* is obtained, which after modulation are carried to the inverter input (blocks 1–13).

The IM model in *d–q* coordinate system is described by blocks 48–55, while the angular velocity estimation of the rotor flux space vector is carried out by means of blocks 200–208.

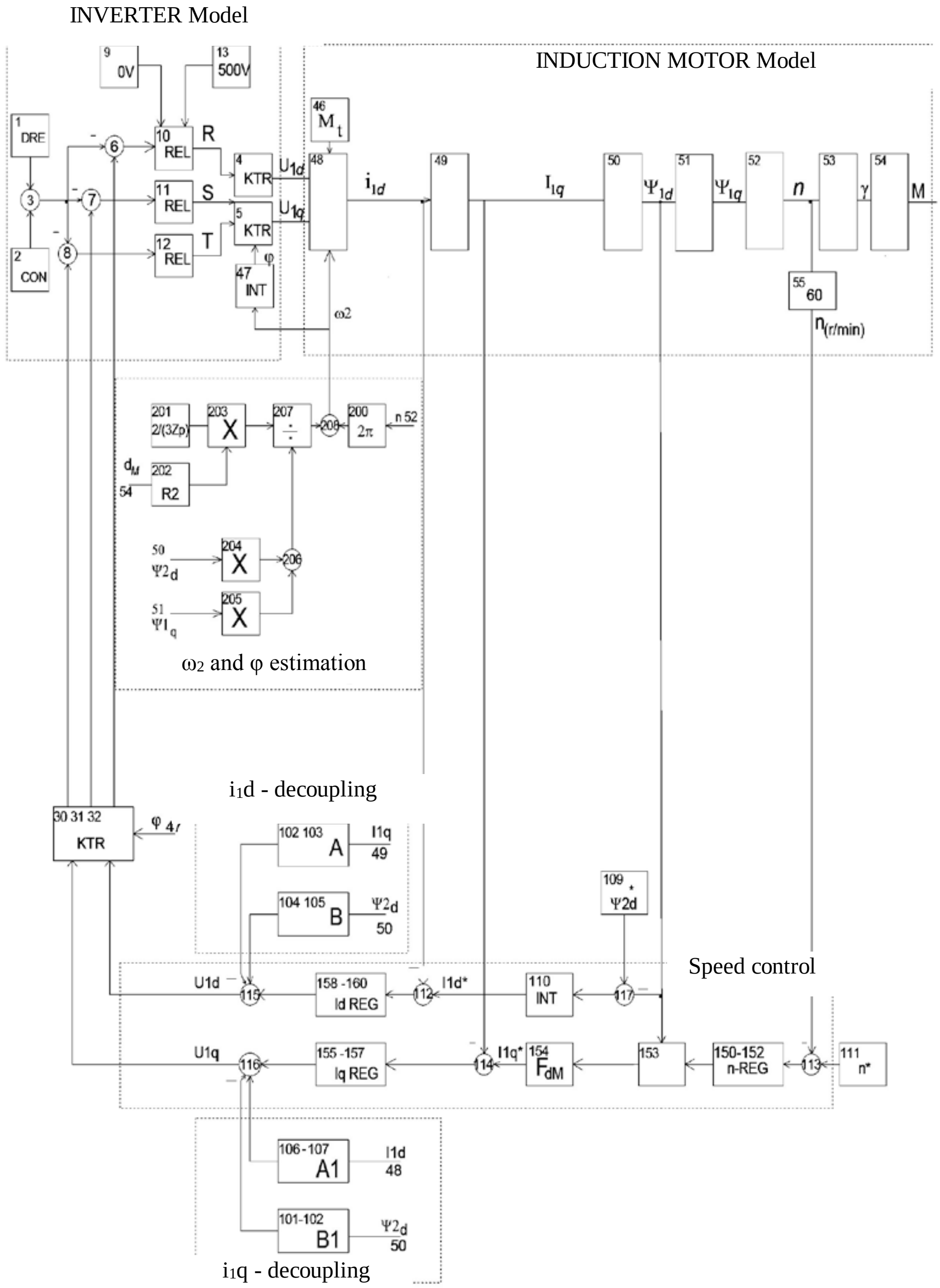

Figure 2. Vector control of IM speed with cascading control circuits i_{1d} and i_{1q}

3.1. Current and decoupling control loop

To compensate the coupling effect, between the i_{1d} and i_{1q} components of the stator current space vector, it is necessary to design a mathematical model of the decoupling device. This model is a key element for the synthesis of the current control circuit. To achieve this, it is necessary to obtain the dependence of the current component i_{1d} in function of the corresponding components of the voltage U_{1d}, the flux ψ_{2d} and the current i_{1q}, i.e., of the i_{1q} component in function of $U_{1q}, \psi_{2d}, i_{1d}$.

$$i_{1d} = f(U_{1d},\ \psi_{2d},\ i_{1q}) \quad (14)$$

$$i_{1q} = f(U_{1q},\ \psi_{2d},\ i_{1d}) \quad (15)$$

1) Current i_{1d} and decoupling control circuit

From the stator equation (3), by means of equations (5) to (10), the following is obtained:

$$i_{1d} = \frac{1}{R_1 \cdot (1 + pT)} \cdot \left[U_{1d} - p \cdot B \cdot \psi_{2d} + A \cdot i_{1q}\right] \quad (16)$$

with

$$T = \frac{X_1}{R_1} - \frac{X_m^2}{X_2 R_1},\ B = \frac{X_m}{X_2},\ A = \omega_2 \left(X_1 - \frac{X_m^2}{X_2} \right) \quad (17)$$

Equations (15) and (16) are rated (per unit system), while the IM model is simulated in frequency time-domain. To obtain compatibility in the overall control structure, it is necessary to decouple equations (16) and (17), which results in:

$$i_{1d} = \frac{1}{R_1 \cdot (1 + pT)} \cdot \left[U_{1d} - p \cdot b \cdot \psi_{2d} + a \cdot i_{1q}\right] \quad (16a)$$

with:

$$T = \frac{L_1}{R_1} - \frac{L_m^2}{L_2 R_1},\ b = \frac{L_m}{L_2},\ a = \omega_2 \left(L_1 - \frac{L_m^2}{L_2} \right). \quad (17a)$$

The block structure of the current component i_{1d} control circuit which creates the flux in the machine and the accompanying decoupling model are shown in Fig.3.

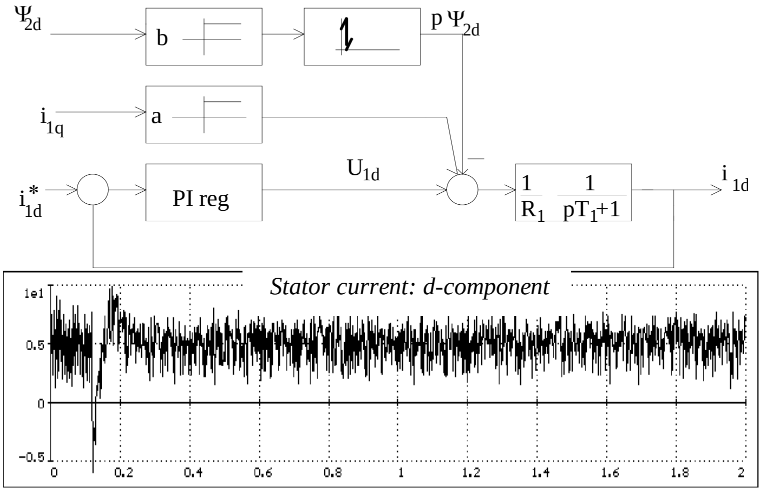

Figure3. Decoupling control circuit and time response of current component i_{1d}

2) Current i_{1q} and decoupling control circuit

As with the current component generating the machine flux, the following is obtained for the i_{1q} component of the stator current space vector, which is responsible for the torque developed in the machine, via stator equation (3), by means of equations (5) to (10):

$$i_{1q} = \frac{1}{R_1 \cdot (1 + pT)} \cdot \left[U_{1q} - \cdot B \cdot \psi_{2d} + A \cdot i_{1d} \right] \quad (18)$$

with:

$$T = \frac{X_1}{R_1} - \frac{X_m^2}{X_2 R_1}, \; B_1 = \frac{X_m}{X_2} \cdot \omega_2, \; A_1 = \omega_2 \cdot \left(\frac{X_m^2}{X_2} - X_1 \right). \quad (19)$$

After decoupling the following is obtained:

$$i_{1q} = \frac{1}{R_1 \cdot (1 + pT)} \cdot \left[U_{1q} - b_1 \cdot \psi_{2d} + a_1 \cdot i_{1d} \right] \quad (18a)$$

with

$$T = \frac{L_1}{R_1} - \frac{L_m^2}{L_2 R_1}, \; b_1 = \frac{L_m}{L_2} \cdot \omega_2, \; a_1 = \omega_2 \cdot \left(\frac{L_m^2}{L_2} - L_1 \right). \quad (19a)$$

In line with equation (18a), Figure 4 shows the block structure of the current component control circuit, responsible for the machine's developed torque together with the accompanying decoupling element.

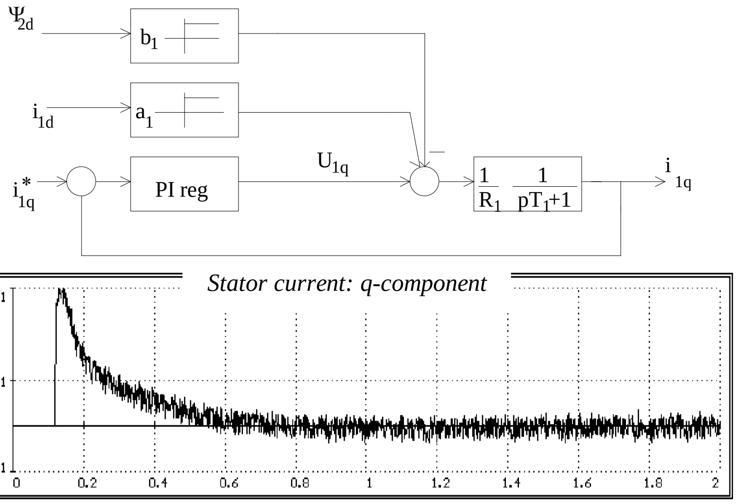

Figure 4. Decoupling control circuit and time response of current component i_{1q}

Oscilograms (Fig. 3 and Fig.4.) show time responses of the stator current space vector i_{1d}, i_{1q} -components, and the space vector $\vec{i}_1$ itself, i.e., its phase component (Fig. 5) at one time period. It is obvious that both stator current space vector components have the same control path transfer function. Hence, having in mind the inverter transfer function, i.e., the delay time T_i, the block structural scheme given in Fig. 5 is obtained for the current control circuit.

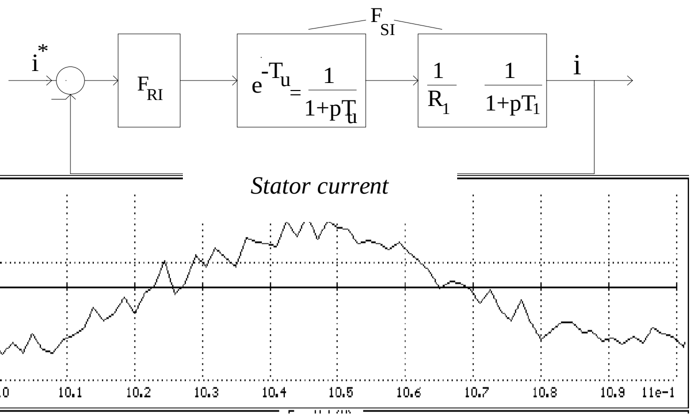

***Figure 5** Closed current control loop of the stator current*

The transfer function of the open current control loop is:

$$F_{OI} = F_{RI} \cdot \frac{1}{R_1} \cdot \frac{1}{1+p\cdot T} \cdot \frac{1}{1+p\cdot T_i}. \tag{20}$$

The current controller synthesis is carried out by applying module optimization which, yields an increase relative to the reference signal by only 4.3%. Consequently, the transfer function of the open current control loop, according to module optimization method shall be:

$$F_{OI} = \frac{1}{2 + p \cdot T_i} \cdot \frac{1}{1 + p \cdot T_i}. \tag{21}$$

By comparing the transfer functions given by equations (20) and (21) the value of the proportionally integrated PI current controller is obtained:

$$F_{RI} = \frac{R_1 \cdot T}{2 \cdot T_i} \cdot \frac{(1 + p \cdot T)}{p \cdot T}. \tag{22}$$

3.2. Rotor flux control circuit

Equation (11) and the transfer function of the closed current control loop given by equation (23) completely define the flux control circuit whose structural block scheme is given in Figure 6. Analysis is made in frame of reference rotating with rotor flux vector.

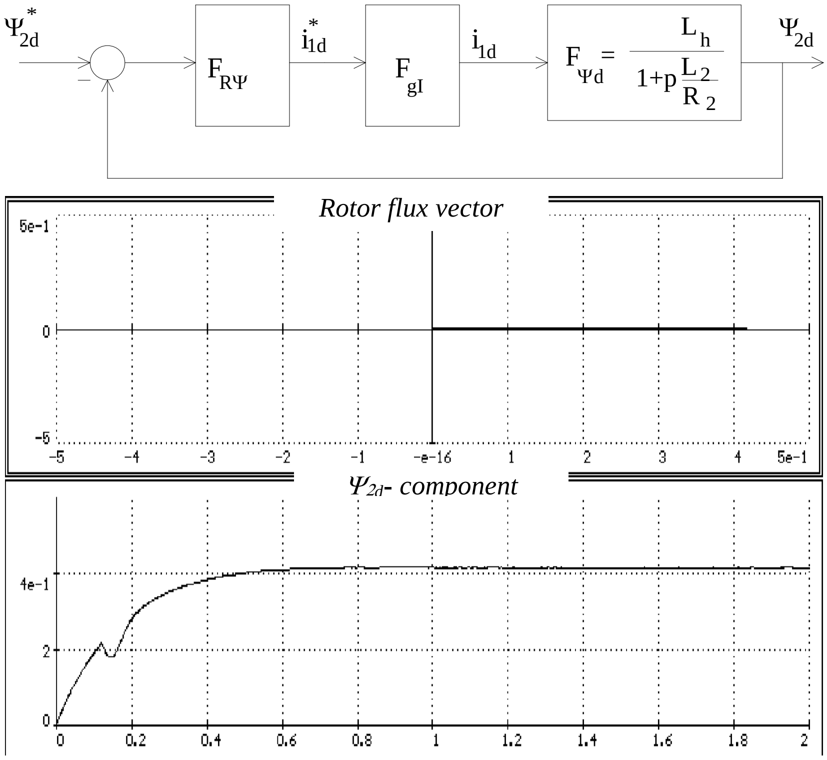

Figure 6. Closed control loop of rotor flux

Knowing the transfer function of the open current control loop F_{OI}, the following is obtained for the closed control loop F_{ZI}:

$$F_{ZI} = \frac{F_{OI}}{1+F_{OI}} = \frac{1}{1+\frac{1}{F_{OI}}} = \frac{1}{1+2\cdot p\cdot T_i(1+p\cdot T_i)} \cong \frac{1}{1+2\cdot p\cdot T_i} = \frac{1}{1+p\cdot T_i^*} \quad (23)$$

with

$$T_i^* = 2\cdot T_i . \quad (24)$$

According to Figure 6, the transfer function of the open flux control loop amounts to:

$$F_{O\Psi} = F_{R\Psi}\cdot F_{ZI}\cdot F_{\Psi} = F_{R\Psi}\cdot\frac{1}{p\cdot T_i^*}\cdot\frac{K_{\Psi}}{1+p\cdot T_{\Psi}}, \quad (25)$$

where the F_{Ψ} transfer function, given by

$$F_{\Psi} = \frac{L_m}{1+p\cdot\frac{L_2}{R_2}} = \frac{K_{\Psi}}{1+p\cdot T_{\Psi}}, \quad (26)$$

is determined by equation (11) of the $\vec{i}_1 - \vec{\psi}_2$ IM model and T_{Ψ} represents the rotor time constant. In line with module optimization, for the transfer function of the open flux control loop it holds that:

$$F_{O\Psi} = \frac{1}{2\cdot p\cdot T_i^*(1+pT_i^*)}. \quad (27)$$

By comparing the transfer functions given by equations (25) and (27), the transfer function of the proportionally integrated (PI) flux controller is determined:

$$F_{R\Psi} = \frac{T_{\Psi}}{K_{\Psi}\cdot 2\cdot T_i^*}\cdot\left(\frac{1+p\cdot T_i}{p\cdot T_{\Psi}}\right). \quad (28)$$

3.3. Speed control circuit

The dynamic equation of the machine's torques balance is given by:

$$M - M_t = 2\cdot\pi\cdot J\cdot\frac{dn}{dt}, \quad (29)$$

where J is the machine's inertia.

Equations (13) and (29) completely define the structural block scheme (fig.7) of the speed control circuit. As well fig.7 shows the speed response n, torque M and the rotor axis angle $\gamma = 2\cdot\pi\cdot\int ndt$.

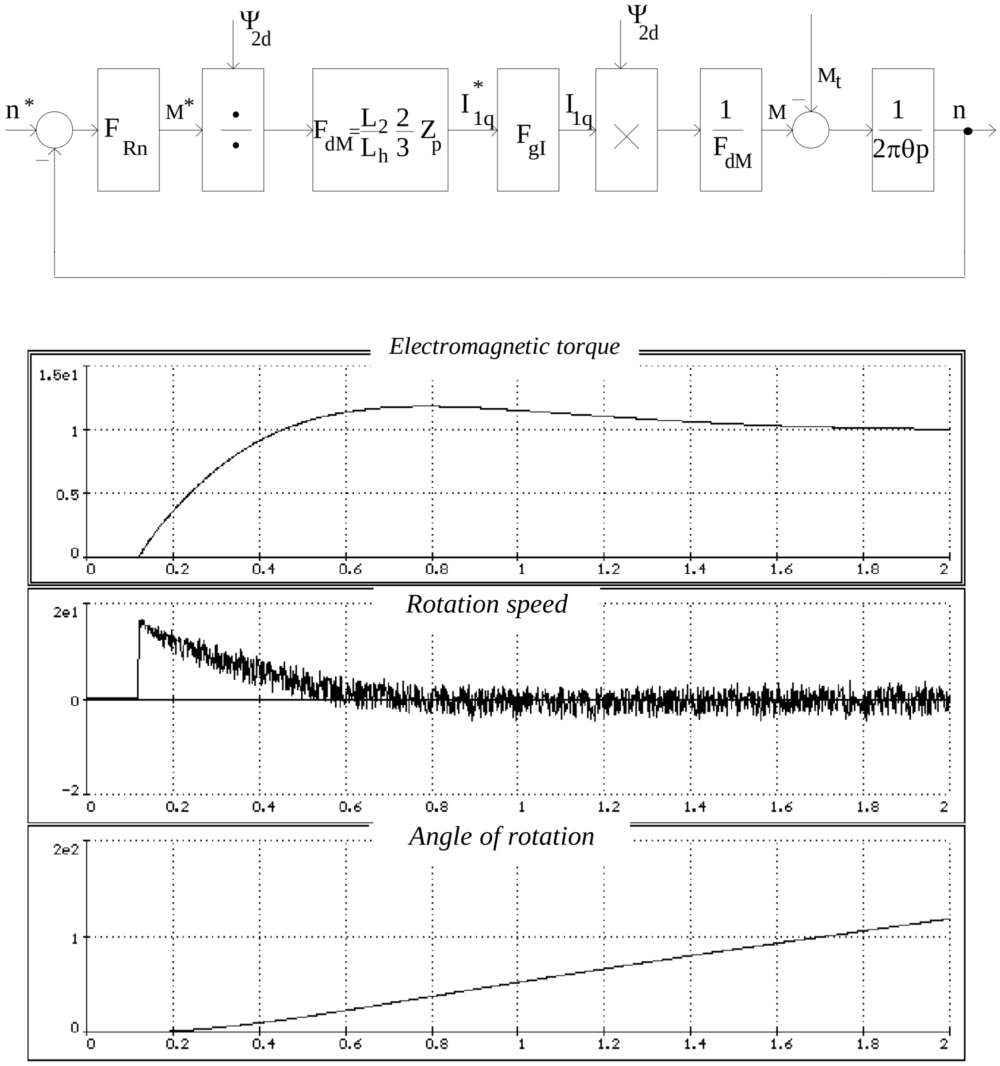

Figure 7. Structural block scheme of closed speed control loop

In accordance with Fig. 7, the transfer function of the open speed control loop results in:

$$F_{On} = F_{Rn} \cdot \frac{1}{1 + p \cdot T_i^*} \cdot \frac{1}{2 \cdot \pi \cdot J} \cdot \frac{1}{p}. \qquad (30)$$

The speed control circuit synthesis in this case will be carried out by applying symmetrical optimization which yields to faster response by approximately 50% compared to module optimization.

The maximum increase in symmetrical optimization, however, amounts to 43% above the reference signal and is 10 times the corresponding increase in module optimization. As per symmetrical optimization, the transfer function of the open speed control loop will be:

$$F_{On} = \frac{1 + p \cdot 4 \cdot T_i^*}{p^2 \cdot 8 \cdot T_i^{*2} \cdot \left(1 + p \cdot T_i^*\right)}. \tag{31}$$

By comparing equations (30) and (31) the transfer function of the proportionally integrated speed controller is obtained:

$$F_{Rn} = \frac{\pi \cdot J}{T_i^*} \cdot \left(\frac{1 + p \cdot 4 \cdot T_i^*}{p \cdot 4 \cdot T_i^*} \right). \tag{32}$$

To determine numerically the d- and q- components of the rotor flux space vector (Fig. 7), equations (33) and (34) are used, which are obtained by eliminating the i_{2d} and i_{2q} components of the rotor current space vector $\vec{i_2}$ from equations (7) to (10). Stator flux vector as obtained as integral from stator voltage. And stator voltage can be measured or estimated (even predicted) by switching mode of the voltage source inverter (VSI) [3].

$$\psi_{1d} = i_{1d} \cdot \left(X_1 - \frac{X_m^2}{X_2} \right) + \psi_{2d} \cdot \frac{X_m}{X_2} \tag{33}$$

$$\psi_{1q} = i_{1q} \cdot \left(X_1 - \frac{X_m^2}{X_2} \right) + \psi_{2q} \cdot \frac{X_m}{X_2} \tag{34}$$

4. CONCLUSION

Induction motor behavior under field oriented control is similar to that of dc motor. Control system design is also similar and similar optimization methods can be used taking into account the impact of decoupling effect. In this paper relatively simple approach for synthesis of speed torque and rotor flux circuits is presented. All data processing for the simulations have been carried in per unit system form assuming the following base quantities:

$$voltage\ u_{p.u.}=\frac{u}{U_n\sqrt{2}};\quad current\quad i_{p.u.}=\frac{i}{I_n\sqrt{2}};\ power\ P_{p.u.}=\frac{p}{3\cdot U_n\cdot I_n};$$

$$torque\quad m_{p.u.}=\frac{m\cdot 2\cdot \pi\cdot f_n}{3\cdot U_n\cdot I_n\cdot z_p}\ flux\quad \psi_{p.u.}=\frac{\psi\cdot 2\cdot \pi\cdot f_n}{U_n\cdot\sqrt{2}};\ frequency\ f_{p.u.}=\frac{f}{f_n};$$

$$angular\ frequency\ \omega_{p.u.}=\frac{\omega}{2\cdot \pi\cdot f_n}$$

Where the *n* and *p.u.* indices are referred to the rated value and per unit (base) quantities respectively. The induction motor considered in the simulation and measurement is the three phase, squirrel cage motor. The main motor parameters are: rated power 7.5 (kW); rated frequency 50(Hz); rated voltage: 380(V); stator inductance 0.087 (H); rated current 16 (A); rotor inductance 0.087 (H); pole pairs 2; magnetizing inductance: 0.083 (H); stator resistance 0.42(Ω); inertia 0.098 ($kg\cdot m^2$); rotor resistance 0.53 (Ω); dc link voltage 500(V).

Using symmetrical and technical optimization method for current and speed control loops respectively an optimum transient response is obtained. Furthermore by means of simulation the validity of proposed concept for parameter estimation of the decoupling device is proved.

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