***Peresada S.M.*** ***Ukraine***
***Dynnik T.V.*** ***Kiev***

*National Technical University of Ukraine "Kiev polytechnic institute"*

## VECTOR CONTROL OF DOUBLY-FED INDUCTION MACHINE: ROBUSTNESS WITH RESPECT TO PARAMETERS VARIATION

INTODUCTION

Electromechanical systems on the base of Doubly-Fed Induction Machine (DFIM) is an attractive solution for high performance, restricted speed range drives and energy generation applications [1]. For limited speed variations around the synchronous speed of the induction machine, the power handed by the converter at rotor side is a small fraction (depending on slip) of the overall converted power.

In variable speed drives during motor operating condition, the rotor slip power is regenerated to line grid by the rotor power supply, resulting in efficient energy conversion. Variable speed energy generation allows to produce constant-frequency electric power from a prime mover whose speed varies within a slip range (sub and super) of the DFIM synchronous speed, maximizing the efficiency of electromechanical energy conversion. [2].

The concept of indirect stator flux orientation has been introduced in [3],[4] similarly to indirect rotor flux orientation in squirrel cage induction motor control. The torque tracking, stator-side unity power factor control problem is considered. Asymptotic torque tracking together with unity power factor stabilization are achieved when all DFIM and line parameters are known and constant.

Nevertheless line voltage amplitude and angular frequency, used in controller as constant parameters, have some variations due to line perturbation as well as stator resistance varies as result of machine heating. Parameter perturbations cause torque and flux errors. The aim of this paper is to study the robustness of the indirect field-oriented controller with respect line and machine parameters variations in order to define the most critical of them.

1. DFIM MODEL AND VECTOR CONTROL ALGORITHM

The DFIM model presented in line voltage oriented reference frame is given by [3]

$$\begin{aligned}
&T=\mu\left(\Psi_{1q}\cdot i_{2d}-\Psi_{1d}\cdot i_{2q}\right)\\
&\dot{\Psi}_{1d}=-\alpha\Psi_{1d}+\omega_1\Psi_{1q}+\alpha L_M i_{2d}+U_1\\
&\dot{\Psi}_{1q}=-\alpha\Psi_{1q}-\omega_1\Psi_{1d}+\alpha L_M i_{2q}\\
&\dot{i}_{2d}=-\gamma i_{2d}+(\omega_1-\omega p)i_{2q}+\alpha\beta\Psi_{1d}-\beta\omega\Psi_{1q}p-\beta U_1+\frac{1}{\sigma}u_{2d}\\
&\dot{i}_{2q}=-\gamma i_{2q}-(\omega_1-\omega p)i_{2d}+\alpha\beta\Psi_{1q}+\beta\omega\Psi_{1d}p+\frac{1}{\sigma}u_{2q}
\end{aligned}\quad, \tag{1}$$

where T – is electromagnetic torque, $\Psi_{1d}$, $\Psi_{1q}$, $i_{2d}$, $i_{2q}$ – components of the stator flux linkage and rotor current vectors, ω – is rotor speed, $U_1$ and $\omega_1$ are the (constant) amplitude and angular frequency of the line voltage vector, p is number of pole pairs. Positive constants in (1) are defined as:

$$\sigma=L_2\left(1-\frac{L_m}{L_1L_2}\right)\quad \alpha=\frac{R_1}{L_1}\quad \beta=\frac{L_m}{L_1\sigma}\quad \gamma=\frac{R_2}{\sigma}+\alpha\beta L_M\quad \mu=\frac{3}{2}\cdot\frac{pL_m}{L_1}. \tag{2}$$

Indirect stator flux field- oriented torque-reactive power controller includes[ 3]: torque and flux controllers

$$i_{2d}{}^*=\frac{T^*}{\mu\Psi^*},\ i_{2q}{}^*=\frac{1}{\alpha L_m}\left[\alpha\Psi^*+\dot{\Psi}^*\right],\ \Psi^*=\frac{-U_1-\sqrt{U_1^2-\left(8T^*R_1\omega_1\right)/(3p)}}{2\omega_1}; \tag{3}$$

two-dimensional current controller

$$\begin{pmatrix}u_{2d}\\ u_{2q}\end{pmatrix}=\sigma\begin{pmatrix}\gamma i_{2d}{}^*-(\omega_1-\omega p)i_{2q}{}^*+\beta\omega\Psi^*p+\beta U_{1M}+\dot{i}_{2d}{}^*-k_i\cdot\tilde{i}_{2d}-z_d\\ \gamma i_{2q}{}^*+(\omega_1-\omega p)i_{2d}{}^*-\alpha\beta\Psi^*+\dot{i}_{2q}{}^*-k_i\cdot\tilde{i}_{2q}-z_q\end{pmatrix},\quad \begin{matrix}\dot{z}_d=k_{ii}\cdot\tilde{i}_{2d}\\ \dot{z}_q=k_{ii}\cdot\tilde{i}_{2q}\end{matrix}, \tag{4}$$

where T* and Ψ* are torque and flux references, current regulation errors are defined as $\tilde{i}_{2d}=i_{2d}-i_{2d}{}^*$, $\tilde{i}_{2q}=i_{2q}-i_{2q}{}^*$, $k_i$, $k_{ii}$ – current controller proportional and integral gains.

Under condition of current-fed rotor control when current controller gains are sufficiently large the current regulation errors are $\tilde{i}_{2d}=0$, $\tilde{i}_{2q}=0$ and reduced order error dynamics is

$$
\begin{aligned}
&\tilde{T} = \mu\left(\tilde{\Psi}_{1q}\cdot i_{2d}^{*} - \tilde{\Psi}_{1d}\cdot i_{2q}^{*}\right)\\
&\dot{\tilde{\Psi}}_{1d} = -\alpha\tilde{\Psi}_{1d} + \omega_1\tilde{\Psi}_{1q}\\
&\dot{\tilde{\Psi}}_{1q} = -\omega_1\tilde{\Psi}_{1d} - \alpha\tilde{\Psi}_{1q}
\end{aligned}
\tag{5}
$$

where $\tilde{\Psi}_{1d} = \Psi_{1d}$, $\tilde{\Psi}_{1q} = \Psi_{1q} - \Psi^{*}$, $\tilde{T} = T - T^{*}$ – flux and torque errors.

When torque references are bounded the linear system (5) with nonlinear output is globally asymptotically stable, i.e.

$$
\lim_{t\to\infty}\left(\tilde{T}, \tilde{\Psi}_{1d}, \tilde{\Psi}_{1q}\right)^{T} = 0 \quad \text{and} \quad \mathbf{u}_1^{T}\,\mathbf{Щ}_1 = U_1\tilde{\Psi}_{1d}\,. \tag{6}
$$

If $\dot{T}^{*} = 0$ than in steady state $\lim_{t\to\infty}\Psi_{1q} = \Psi^{*} = L_M i_{2q}$, and condition $\lim_{t\to\infty} i_{1q} = 0$ is guaranteed. As result DFIM operates with zero stator side reactive power.

## 2.PARAMETER SENSETIVITY STUDY

Correct knowledge of the three parameters of the controller (3),(4) defines an ideal indirect stator flux field orientation. Stator resistance $R_1$ varies due to motor heading, line voltage parameters $U_1$ and $\omega_1$ may have some variations $\Delta U_1$ and $\Delta\omega_1$ as result of power system perturbations. Under these parameter perturbations asymptotic properties of the field oriented controller are not guaranteed unless some compensation for parameter perturbations is applied.

Stator resistance variation. Let us consider the influence of stator resistance deviation on static torque with $\dot{T}^{*} = 0$, defining resistance value in control algorithm as sum of real value $R_{1N}$ and resistance deviation $\Delta R_1$:

$$
R_1 = R_{1N} + \Delta R_1\,,\ \alpha = \alpha_N + \Delta\alpha\,. \tag{7}
$$

Using definition (7) equations (5) may be rewritten as

$$
\begin{aligned}
&\dot{\tilde{\Psi}}_{1d} = -\alpha_N\tilde{\Psi}_{1d} + \omega_1\tilde{\Psi}_{1q} - \Delta\alpha L_m\frac{T^{*}}{\mu\Psi^{*}}\,.\\
&\dot{\tilde{\Psi}}_{1q} = -\alpha_N\tilde{\Psi}_{1q} - \omega_1\tilde{\Psi}_{1d}
\end{aligned}
\tag{8}
$$

Steady state solutions of (8) are

$$
\tilde{\Psi}_{1d} = -\frac{\alpha_N\Delta\alpha L_m}{\alpha_N{}^2 + \omega_1{}^2}\frac{T^{*}}{\mu\Psi^{*}},\quad \tilde{\Psi}_{1q} = \frac{\omega_1\Delta\alpha L_m}{\alpha_N{}^2 + \omega_1{}^2}\frac{T^{*}}{\mu\Psi^{*}}\,. \tag{9}
$$

From (5) and (9) torque error is

$$
\begin{aligned}
&\tilde{T} = \frac{\Delta\alpha}{\alpha_N{}^2 + \omega_1{}^2}\left[\frac{2\omega_1{}^3 L_m}{\mu U_1^2 + \mu\lambda_\Delta U_1 - 2\omega_1 L_m(\alpha_N + \Delta\alpha)T^{*}}T^{*2} + \alpha_N T^{*}\right].\\
&\lambda_\Delta = \sqrt{U_1^2 - 4\omega_1(\alpha_N + \Delta\alpha)L_m\frac{T^{*}}{\mu}}
\end{aligned}
\tag{10}
$$

*Line voltage amplitude*. Defining $U_1 = U_{1N} + \Delta U_1$ in controller (3 - 4) we obtain the following steady state solutions for flux and torque errors

$$
\begin{aligned}
&\tilde{\Psi}_{1d} = \frac{-\alpha}{\alpha^2 + \omega_1{}^2}\Delta U_1,\quad \tilde{\Psi}_{1q} = \frac{\omega_1}{\alpha^2 + \omega_1{}^2}\Delta U_1\\
&\tilde{T} = -\frac{\Delta U_1}{\alpha^2 + \omega_1{}^2}\left[\frac{2\omega_1{}^2 T^{*}}{\lambda_\Delta} + \frac{\mu\alpha\lambda_\Delta}{2\omega_1 L_m}\right],\ \lambda_\Delta = \left(U_{1N} + \Delta U_1\right) + \sqrt{\left(U_{1N} + \Delta U_1\right)^2 - 4\omega_1\alpha L_m\frac{T^{*}}{\mu}}
\end{aligned}
\tag{11}
$$

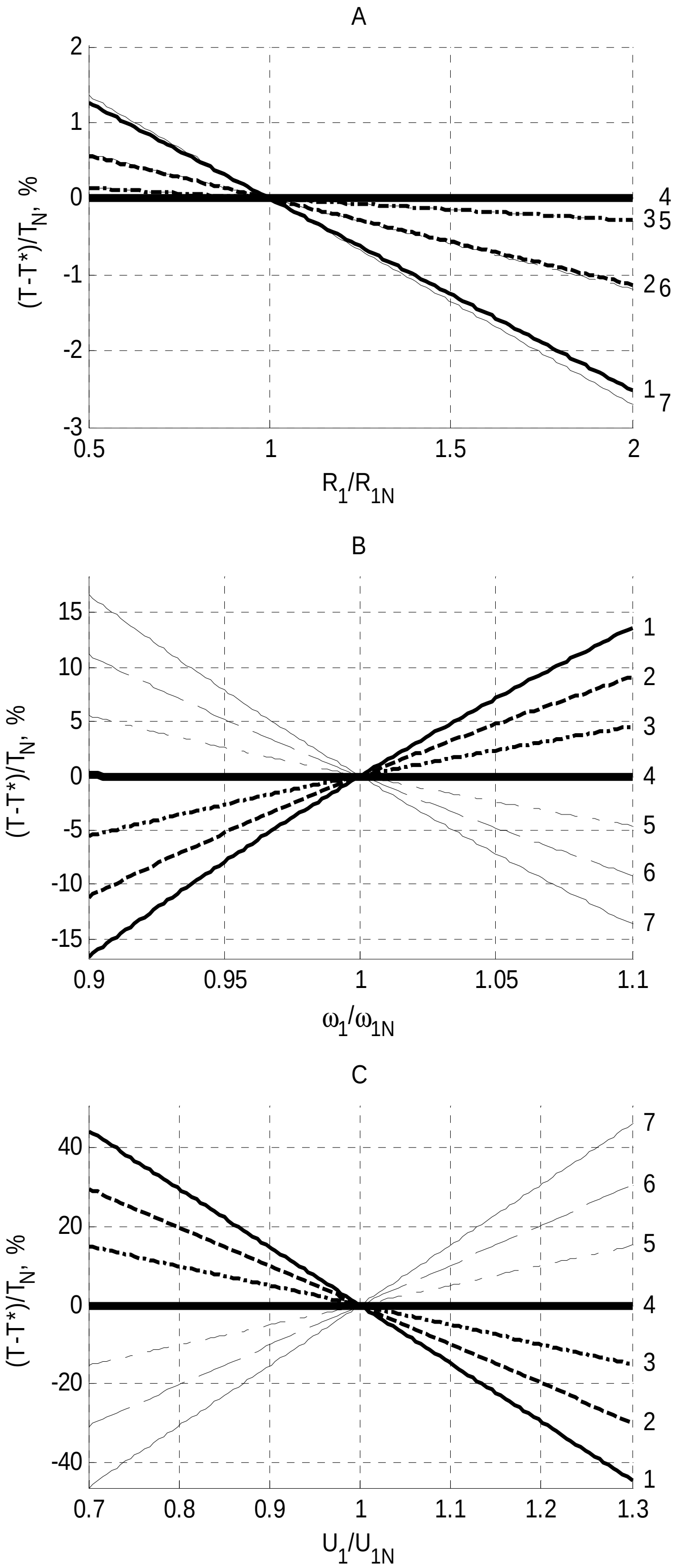
*Line voltage frequency*. Defining $\omega_1 = \omega_{1N} + \Delta\omega_1$ steady state solutions for flux and torque errors are computed as

$$
\tilde{\Psi}_{1d} = -\frac{\alpha\Psi^{*}}{\omega_{1N}^2 + \alpha^2}\Delta\omega_1,\quad \tilde{\Psi}_{1q} = \frac{\omega_{1N}\Psi^{*}}{\omega_{1N}^2 + \alpha^2}\Delta\omega_1,\quad \tilde{T} = \frac{\Delta\omega_1}{\omega_{1N}^2 + \alpha^2}\left[\omega_{1N}T^{*} + \frac{\mu\alpha}{L_M}\Psi^{*2}\right], \tag{12}
$$

where $\Psi^{*} = \dfrac{-U_1 - \lambda_\Delta}{2(\omega_{1N} + \Delta\omega_1)}$ $\quad \lambda_\Delta = \sqrt{U_1^2 - \dfrac{8T^{*}R_1(\omega_{1N} + \Delta\omega_1)}{3p}}$ .

## SIMULATION RESULTS

DFIM control system was simulated using two motors with different rated power. Smaller DFIM (1.25kW) has following rated data: $\omega_N$ =105 rad/s, $U_1$ = 180 V, $T_N$ = 12 N·m, $R_1$ = 2.68 Ohm, $R_2$ = 2.645 Ohm, $L_m$ = 0.14 H, $L_1$ = 0.15Hн, $L_2$ = 0.15Hн, J = 0.2 kg·m$^2$, bigger one's (400kW) rated values are: $\omega_N$ =150 rad/s, $U_1$ = 466.7 V, $T_N$ = 2800




N·m, $R_1$ = 0.0086 Ohm, $R_2$ = 0.016 Ohm, $L_m$ = 0.0107 H, $L_1$ = 0.0127 H, $L_2$ = 0.0127 H, J = 0.6 kg·m$^2$. Each DFIM was driven by prime mover and should produce specified torque according to torque reference. Static torque errors and stator side power factor were studied as functions of parameter deviation.

For simulation tests we set the following parameters variations relative to rated values: stator resistance -50% -+200%; frequency of stator supply voltage -10% -+ 10% (according to possible deviations in industrial networks); magnitude of stator supply voltage $U_1$ +70% -+130% .

Torque error behavior as function of different parameter deviations is shown on figure 1 for 400 kW DFIM (as function of stator resistance – A, supply voltage frequency – B, supply voltage magnitude – C ) under condition of different torque references (1 – -1.5$T_N$, 2 – -$T_N$, 3 – -0.5$T_N$, 4 – 0, 5 – 0.5$T_N$, 6 – $T_N$, 7 – 1.5$T_N$). Simulation results correspond to computations using expressions (10-12).

From torque errors behavior in Fig.1 we conclude that for high power machines with small stator resistance no significant influence of this parameter variations is present. At the same time under condition of rated torque reference a torque error of 8.5% is occurred for 1.25kW DFIM. Voltage frequency deviation under condition of rated torque reference produces a torque errors of 11.5% for 1.25kW DFIM, and 11.1% for 400kW DFIM and about 34% for 1.25kW DFIM, and 30% for if voltage varies. Reduction of stator side power factor for 400kW DFIM is negligibly small (less than 0.004) for all three considered perturbations.

CONCLUSIONS

Our robustness study allows using the analytical expressions to analyze sensitivity of indirect field-oriented control systems of the DFIM. The obtained results show, that the most significant influence upon torque error has deviation of stator supply voltage magnitude and frequency. These result proofs that line voltage amplitude and frequency should be updated during motor operation.. Torque error depends also on stator resistance, but only in small machines. Since DFIMs application sphere specifies usage of high power machines, the two critical parameters of supply network – magnitude and frequency should be measured or observed by the control system.

REFERENCES

[1] W. Leonhard, *Control of Electric Drives*, Springer-Verlag, Berlin, 2002.

[2] R. Pena, J.C. Clare, G.M. Asher, "Doubly Fed Induction Generator using Back-to-Back PWM Converters and Its Applications to Variable-Speed Wind-Energy Generation", *IEE Proceedings of Electric Power Applications*, vol.143, no.3, May 1996, pp.231-241.

[3] S. Peresada, A. Tilli, A. Tonielli, “Robust Active-Reactive Control of a Doubly-Fed Induction Machine”, *Proc. of IEEE - IECON'98*, Aachen, Germany, Sept. 1998, pp.1621-1625.

[4] Peresada S., Tilli A. and Tonielli A. Indirect stator flux-oriented output feedback control of the doubly fed induction machine // IEEE Trans. on Control Systems Technology. – November 2003. –Vol. 11, No. 6. –P. 875–888.