FEEDBACK LINEARIZING FIELD-ORIENTED CONTROL OF INDUCTION GENERATOR: THEORY AND EXPERIMENTS

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A novel field-oriented vector control for induction generators is presented. Design procedure is based on indirect field orientation concept and exploits output-feedback linearizing technique for voltage controller design. Proposed solution guarantees asymptotic rotor flux and DC-link voltage regulation together with linear nominal dynamics of the DC link voltage error. Decomposition into voltage and current-flux subsystems, based on the two-time scale separation, allows to use a simple controllers tuning procedure. Results of comparative experimental study with standard indirect field-oriented control, having linear PI voltage controller, are presented. It is shown that designed controller, in contrast to standard solutions, provides system performances stabilization when speed is varying. Proposed control algorithm is suitable for standalone and grid connected (via suitable inverter) energy generation systems with variable speed operation.
References 10, figures 8, table 1.
Keywords: induction generator, field-oriented control, energy generation system.

Introduction. During last decades, there has been a growing trend to improve the efficiency of the electromechanical energy conversion process in electrical drives and energy generation systems. Variable speed generation is an attractive solution for many small and medium power energy plants: diesel, hydro and wind power stations [4], [6], aerospace and naval power systems [1]. The main advantage of the variable speed generation is higher achievable energy efficiency of the primary mover and electrical generator.

The most spread configuration of the energy generation systems consists of permanent magnet synchronous generator (PMSG) with AC-DC-AC power converter. Such structure established de facto the industrial standard for modern wind power stations. Nevertheless, the cost of PMSG is significantly higher than induction machine due to the use of rare-earth magnetic materials. The tendency to reduce the use of expensive rare-earth magnets has stimulated a renewed interest for development of advanced control for induction machine based energy generation (IG). The electromechanical systems on the base of vector controlled doubly-fed induction generators is well known solution for the systems with restricted speed variations of the primary mover [8]. The doubly-fed induction generator allows to produce constant-frequency electric power from a prime mover whose speed varies within a slip range, typically 20–30% of the generator synchronous speed. The converter needs only be rated for a fraction of the total output power, which depends on the allowable slip range [8].

Simple and cheap generation systems, based on capacitor self-excited squirrel cage induction machine [7], do not provide required accuracy of the voltage and frequency control. An alternative approach is known as induction generation under field-oriented control (FOC), reported in large number of publications since 1990th [3], [4], Fig. 1. The standard structure of the FOC generation system is simple a copy of the induction motor speed control system with speed PI controller rep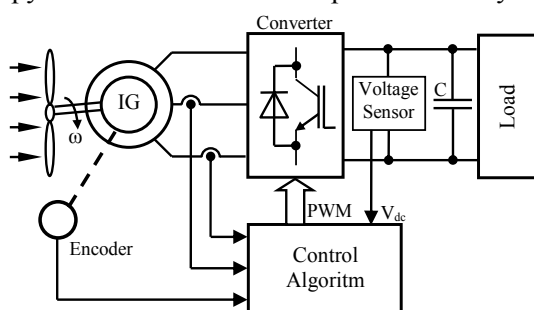laced by the DC-bus PI voltage controller. The similarity of the two system is based on fact that outputs of the both controllers (speed or voltage) form the reference signal for electric machine torque and consequently for torque producing component of the stator current vector. Flux subsystems for motor and generation operation are the same and use the direct or indirect field orientation.

Fig. 1. Generation system structure

The results in [2] – [5] report the basic approaches for DC-bus voltage and flux control of the IG. In [3] speed and flux variations are compensated in torque current computation, a novel nonlinear flux observer with

saturation effect consideration is proposed. More recent publication [2] reports the system analysis based on some sort of linearized model and frequency domain approach. Active losses optimization is considered in [6]. Nevertheless no well-defined and theoretically justified solution of vector controlled IG is still available. The stability properties of the existing systems are not proven theoretically, as result controller tuning for performances specifications cannot be established and typically based on worst-case design consideration. This leads to reduced dynamic performance of the voltage control subsystem, when generator speed and flux are not constant.

The goal of this work is to develop a new IG output-feedback linearizing flux-voltage control algorithm, which in contrast to existing solutions, provides linear nominal DC link voltage error dynamics, and therefore allows specifying the dynamic performances of the voltage control loop.

Some preliminary results of this paper are given in [10], where system dynamic performance has been studied by simulation. In this paper, the results of experimental tests are presented in order to demonstrate the performances of proposed control during different operating conditions. Comparison with a standard solution, having PI voltage controller, is given as well.

This paper is organized as follows. The IG model and control problem formulation are given in Sections II. The flux-voltage controller is designed in Section III. In Section IV, the experimental and simulation results are reported followed by the Conclusions of the study.

II. PROBLEM STATEMENT. The standard two-phase model of the symmetrical induction generator, under the assumptions of linear magnetic circuits and balanced operating conditions, is represented in an arbitrary rotating reference frame (d-q) as [9]

$$
\begin{aligned}
\dot{i}_d &= -\gamma i_d + \omega_0 i_q + \alpha\beta\psi_d + \beta\omega\psi_q + u_d/\sigma, \\
\dot{i}_q &= -\gamma i_q - \omega_0 i_d + \alpha\beta\psi_q - \beta\omega\psi_d + u_q/\sigma, \\
\dot{\psi}_d &= -\alpha\psi_d + \left(\omega_0 - \omega\right)\psi_q + \alpha L_m i_d, \\
\dot{\psi}_q &= -\alpha\psi_q - \left(\omega_0 - \omega\right)\psi_d + \alpha L_m i_q, \\
\dot{\varepsilon}_0 &= \omega_0, \varepsilon_0\left(0\right) = 0, \\
P_s &= -\left(3/2\right)\left(u_d i_d + u_q i_q\right),
\end{aligned}
\tag{1}
$$

where $\mathbf{u} = (u_d, u_q)^T$ is the control vector of stator voltages, $\mathbf{i} = (i_d, i_q)^T$, $\boldsymbol{\psi} = (\psi_d, \psi_q)^T$ denote stator current and rotor flux vectors, ω is the rotor speed. Subscripts d and q stand for vector components in the (d-q) reference frame, ε_0 is the angular position of the (d-q) reference frame with respect to a fixed stator reference frame (a-b), where physical variables are defined; P_s – active power produced by IG.

Positive constants related to the electrical and mechanical parameters of the IM are defined as follows: $\alpha = \dfrac{R_2}{L_2}$, $\sigma = L_1\left(1 - \dfrac{L_m^2}{L_1 L_2}\right)$, $\beta = \dfrac{L_m}{\sigma L_2}$, $\gamma = \dfrac{R_1}{\sigma} + \alpha L_m\beta$, where R_1, R_2, L_1, L_2 are stator/rotor resistances and inductances, respectively, L_m is the magnetizing inductance. One pole pair is assumed without loss of generality.

Transformed variables in (1) are defined according to

$$
\mathbf{x}_{dq} = e^{-\mathbf{J}\varepsilon_0}\mathbf{x}_{ab}, \qquad \mathbf{x}_{ab} = e^{\mathbf{J}\varepsilon_0}\mathbf{x}_{dq}, \tag{2}
$$

where $e^{-\mathbf{J}\varepsilon_0} = \begin{bmatrix} \cos\varepsilon_0 & \sin\varepsilon_0 \\ -\sin\varepsilon_0 & \cos\varepsilon_0 \end{bmatrix}$, $\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $\mathbf{x}_{yz}$ stands for two-dimensional voltage, flux and stator current vectors.

The electrical power P_s, produced by the IG, is transferred to DC-link by IGBT converter. Assuming ideal conversion without losses, the DC-link power P_{dc} is equal to stator-generated power P_s. In this case DC-link voltage V_{dc} dynamics is described by

$$
\dot{V}_{dc} = \left(i_{dc} - i_L\right)/C, \tag{3}
$$

$$
i_{dc} = P_{dc}/V_{dc} = P_s/V_{dc}, \tag{4}
$$

where C – is DC-link capacitance, i_{dc} – DC-link current from converter, i_L – load current.

Consider the IG and DC-link models (1) – (4) and assume that:

A1. The stator currents, rotor speed and load current are available for measurement. Rotor speed $\omega > 0$ is slowly varying. All generator parameters and DC-link capacitance are known and constant.

A2. The DC-link voltage reference $V_{dc}^* > 0$ is constant.

Under these assumptions, the control problem is to design a flux-voltage controller, which guarantees that following control objectives are achieved:

CO1. Asymptotic voltage regulation with all internal signals bounded, i.e.

$$\lim_{t \to \infty} \tilde{V}_{dc} = 0, \qquad (5)$$

where $\tilde{V}_{dc} = V_{dc} - V_{dc}^*$ is voltage regulation error.

CO2. Asymptotic flux regulation:

$$\lim_{t \to \infty} \tilde{\psi} = 0, \qquad (6)$$

where $\tilde{\psi} = \psi - \psi^*$ – is a flux regulation error, ψ – flux vector magnitude, $\psi^* > 0$ – constant flux reference.

CO3. Asymptotic field orientation, i.e.

$$\lim_{t \to \infty} \psi_q = 0. \qquad (7)$$

The following sections report the proposed solution to the formulated control problem.

III. CONTROLLER DESIGN

A. Flux- current field-oriented controller

Let consider the indirect field-oriented control algorithm for system (1) [9], which consist of
- flux controller

$$\dot{\varepsilon}_0 = \omega_0 = \omega + \alpha L_m i_q / \psi^*,$$
$$i_d^* = \left(\alpha \psi^* + \dot{\psi}\right) / \alpha L_m, \qquad (8)$$

- current controllers

$$u_d = \sigma\left(\gamma \dot{i}_d^* - \omega_0 i_q - \alpha \beta \psi^* - k_i \tilde{i}_d + x_d\right),$$
$$\dot{x}_d = -k_{ii} \tilde{i}_d, \qquad (9)$$

$$u_q = \sigma\left(\gamma \dot{i}_q^* + \omega_0 i_d + \beta \omega \psi^* - k_i \tilde{i}_q + x_q\right),$$
$$\dot{x}_q = -k_{ii} \tilde{i}_q, \qquad (10)$$

where $\tilde{i}_d = i_d - i_d^*$ and $\tilde{i}_q = i_q - i_q^*$ are current tracking errors, i_d^*, i_q^* – are references for i_d and i_q currents respectively, x_d, x_q – integral terms of current controllers, $\left(k_i, k_{ii}\right)$ are the current controller's proportional and integral gains.

Assume that i_q^* and i_d^* are slowly varying signal with respect of stator current dynamics, so that $\dot{i}_d^* = \dot{i}_q^* = 0$. Under these conditions, the current-flux error dynamics can be written as

$$\dot{\tilde{i}}_d = -\left(k_i + \gamma\right)\tilde{i}_d - x_d + \alpha \beta \tilde{\psi}_d + \beta \omega \tilde{\psi}_q,$$
$$\dot{x}_d = k_{ii} \tilde{i}_d,$$
$$\dot{\tilde{i}}_q = -\left(k_i + \gamma\right)\tilde{i}_q - x_q + \alpha \beta \tilde{\psi}_q - \beta \omega \tilde{\psi}_d, \qquad (11)$$
$$\dot{x}_q = k_{ii} \tilde{i}_q,$$

$$\dot{\tilde{\psi}}_d = -\alpha \tilde{\psi}_d + \omega_2 \tilde{\psi}_q + \alpha L_m \tilde{i}_d,$$
$$\dot{\tilde{\psi}}_q = -\alpha \tilde{\psi}_q - \omega_2 \tilde{\psi}_d, \qquad (12)$$

where $\tilde{\psi}_d = \psi_d - \psi^*, \tilde{\psi}_q = \psi_q$ – are the flux tracking errors, $\omega_2 = (\omega_0 - \omega)$.

For high enough current controllers gains k_i, k_{ii} we obtain current-fed condition such that

$$\left(\tilde{i}_d, \tilde{i}_q\right) = 0, \tag{13}$$

and as it follows from (12) we have

$$\lim_{t \to \infty}\left(\tilde{\psi}_d, \tilde{\psi}_q\right) = 0. \tag{14}$$

Stability conditions for the system (12) are derived using Lyapunov's method in [9]. From condition (14) we conclude that both rotor flux modulus regulation and asymptotic field orientation (*CO2 and CO3*) are achieved.

B. Feedback linearizing voltage controller

From conditions (13), (14) and $\dot{i}_d^* = \dot{i}_q^* = 0$ it follows that $(x_d, x_q) = 0$, therefore from (9), (10) we obtain

$$\begin{aligned}
u_d &= R_1 i_d^* - \sigma\omega_0 i_q^*, \\
u_q &= R_1 i_q^* + \alpha L_m^2 i_q^* / L_2 + \sigma\omega_0 i_d^* + L_m \omega \psi^* / L_2.
\end{aligned} \tag{15}$$

Using (15) the IG output power is computed as

$$P_s = -\frac{3}{2}\left(R_1\left(i_d^{*2} + i_q^{*2}\right) + R_2 \frac{L_m^2}{L_2^2}i_q^{*2} + \frac{L_m}{L_2}\omega\psi^* i_q^*\right). \tag{16}$$

According to (16) and under conditions (13), (14), $\dot{i}_d^* = \dot{i}_q^* = 0$ the stator output power consist of three components: active loses of the stator circuit (proportional to R_1), active rotor loses (proportional to R_2) and input mechanical power

$$P_m = \frac{3}{2}\frac{L_m}{L_2}\psi^* i_q^* \omega = \frac{3}{2}\frac{L_m}{L_2}\psi\, i_q\omega = T\omega, \tag{17}$$

where T – is electromagnetic torque.

Using equations (3), (4), (15) we can derive

$$\dot{V}_{dc} = -\frac{1}{C}\frac{3}{2V_{dc}}\left(R_1\left[\frac{\psi^{*2}}{L_m^2} + i_q^{*2}\right] + R_2 \frac{L_m^2}{L_2^2}i_q^{*2} + \frac{L_m}{L_2}\omega\psi^* i_q^*\right) - i_L / C, \tag{18}$$

and voltage error regulation dynamics becomes ($V_{dc}^* = const$)

$$\dot{\tilde{V}}_{dc} = -\frac{1}{C}\frac{3}{2V_{dc}}\left(R_1\left[\frac{\psi^{*2}}{L_m^2} + i_q^{*2}\right] + R_2 \frac{L_m^2}{L_2^2}i_q^{*2} + \frac{L_m}{L_2}\omega\psi^* i_q^*\right) - i_L / C. \tag{19}$$

In (19) a torque component of the stator current reference i_q^* is a control input, while i_L is perturbation (measurable signal).

Let us define a desired voltage dynamics as given by the second order linear asymptotically stable system in the following form

$$\begin{aligned}
\dot{\tilde{V}}_{dc} &= -k_v \tilde{V}_{dc} + x_v, \\
\dot{x}_v &= -k_{vi}\tilde{V}_{dc},
\end{aligned} \tag{20}$$

where $(k_v, k_{vi}) > 0$ are the proportional and integral gains of voltage controller.

Feedback linearizing voltage controller from (19) and (20) is given by the solution of nonlinear algebraic equation

$$-\frac{1}{C}\frac{3}{2V_{dc}}\left(R_1\left[\frac{\psi^{*2}}{L_m^2}+i_q^{*2}\right]+R_2\frac{L_m^2}{L_2^2}i_q^{*2}+\frac{L_m}{L_2}\omega\psi^*i_q^*\right)-i_L/C=-k_v\tilde{V}_{dc}+x_v,$$

$$\dot{x}_v=-k_{vi}\tilde{V}_{dc},$$

(21)

as follows

$$i_q^*=\left.\left(-\frac{L_m}{L_2}\omega\psi^*+\sqrt{\left(\frac{L_m}{L_2}\omega\psi^*\right)^2-4\left(\alpha\frac{L_m^2}{L_2}+R_1\right)\rho}\right)\right/2\left(\alpha\frac{L_m^2}{L_2}+R_1\right),$$

$$\rho=R_1\psi^{*2}L_m^{-2}+(2/3)V_{dc}\left(i_L+C\left(-k_v\tilde{V}_{dc}+x_v\right)\right),$$

(22)

$$\dot{x}_v=-k_{vi}\tilde{V}_{dc}.$$

Solution for the voltage controller (22) establishes a physical limitation $\left(L_m\omega\psi^*/L_2\right)^2-4\left(\alpha L_m^2/L_2+R_1\right)\rho>0$ for energy conversion using fully controlled AC-DC converter, which is standard condition for such systems. Since variable ρ is error dependent ($\tilde{V}_{dc},x_v$) this solution is local. If $\psi^*=\text{const}$, $V_{dc}^*=\text{const}$, ω and i_L are slowly varying, ($\tilde{V}_{dc},x_v$) – small enough, voltage controller gains $(k_v,k_{vi})>0$ are small with respect of current controller gains (k_i,k_{ii}), then i_q^* is slowly varying and therefore assumption $\dot{i}_q^*=0$ is valid. From this analysis it follows that according to solutions of (20) $\lim_{t\to\infty}\tilde{V}_{dc}=0$, and therefore asymptotic voltage regulation (*CO1)* is locally achieved. A controller block diagram is shown in Fig. 2.
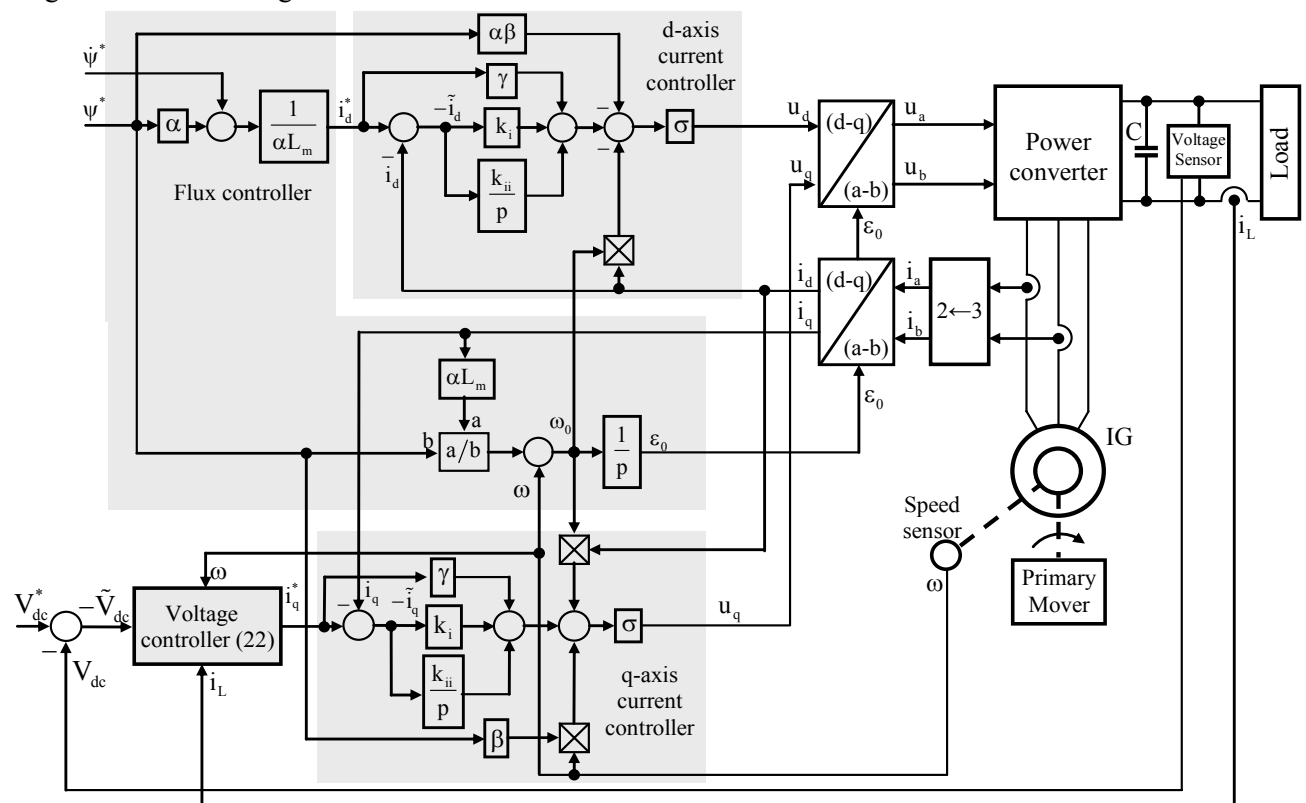

Fig. 2. Block diagram of the voltage control system with feedback linearizing controller

Based on analysis above we conclude that for slowly varying signals in right hand side of (22) the dynamics of the voltage control loop can be designed much slower than current loops dynamics (11) providing the two-time scale separation, needed to justify a common assumption for current fed IG control.

Under these conditions the system error dynamics is given by (20), (11), (12) and allows separated considerations of the two subsystems: voltage control loop (20) and flux-current error dynamics (11), (12).

System tuning is provided by selection of proportional and integral gains for voltage and current controllers as

$$k_{vi} = k_v^2 / 2, \qquad k_{ii} = \left(k_i + \gamma\right)^2 / 2 . \tag{23}$$

Such tuning provides damping factor $\xi = \sqrt{2} / 2$ for each control loop. Natural frequency of undamped oscillations is given by $\omega_{ov}^2 = k_{vi}$ for voltage controller and $\omega_{0i}^2 = k_{ii}$ for current controllers. The two-time scale separation between voltage and current loops is satisfied for condition $\omega_{0i} > \left(3 - 4\right)\omega_{ov}$.

From this stability analysis it follows that $\lim_{t \to \infty} \left(\tilde{\psi}_d, \tilde{\psi}_q, \tilde{i}_d, \tilde{i}_q\right) = 0$, $\lim_{t \to \infty} \tilde{V}_{dc} = 0$, and therefore control objectives CO1-CO3 are locally achieved if $\left(L_m \omega \psi^* / L_2\right)^2 - 4\left(\alpha L_m^2 / L_2 + R_1\right)\rho > 0$.

Remark. For $i_L = \text{const}$ a compensation term i_L may be removed from feedback linearizing controller (22) leaving i_L compensation for the integral action of the voltage controller.

IV. EXPERIMENTAL STUDIES. The experiments are carried out using the Rapid Prototyping Station, which includes (Fig. 3): (1) induction generator (see rated data in Table 1) coupled with DC- motor used as primary mover; (2) three-phase PWM controlled converter, operated at 5 kHz switching frequency; (3) commutated load resistance R_L; (4) DSP TMS320F28335 controller which performs data acquisition, implements control algorithms with programmable tracing of selected variables; (5) personal computer for processing, programming, interactive oscilloscope, data acquisition, etc. The motor speed is measured by a 2500 pulse/revolution optical encoder. The sampling time is set at 200 μs. DC-link capacitance is equal to 1000 μF.
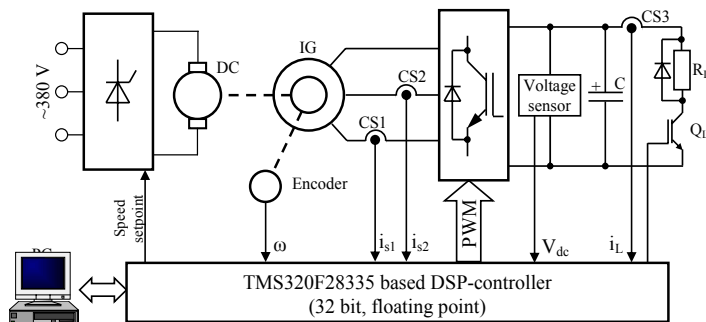
During all experiments, rotor speed is controlled by industrial closed loop DC-drive. In order to compare proposed solution with the standard PI controller, described in [10], we eliminate compensation of the load current i_L in (22) at the first stage of experiments.

Tuning parameters of the controller are set to: current controller (9), (10) $k_i = 600$, $k_{ii} = \left(k_i + \gamma\right)^2 / 2$; voltage controller (22) $k_v = 125$, $k_{vi} = k_v^2 / 2$; standard PI controller [10] $k_v = 0.15$, $k_{vi} = 15$. Standard and developed controllers are tuned to provide the same performances when system operates at speed 140 rad/s.

Fig. 3. Experimental set-up of induction generator electromechanical system

Table 1. IG parameters

Rated mechanical power	5.5 kW	Stator resistance	1.04 Ohm
Rated phase voltage, rms	220 V	Rotor resistance	0.7 Ohm
Rated phase current, rms	11 A	Stator inductance	0.124 H
Rated frequency	50 Hz	Rotor inductance	0.124 H
Number of pole pairs	2	Magnetizing inductance	0.118 H

All tests are performed using the following operating sequences (Fig. 4):

- at initial time the DC-link voltage is charged to 290 V, rotor speed is stabilized by the primary mover at ω = 140 rad/s;

- initial time interval 0…0.3 s is used to excite the generator by applying flux reference trajectory, reported in Fig. 4, with $\psi^*\left(0\right) = 0.02$ Wb and reached the value of 0.5 Wb (low flux level is used in order to prevent converter voltage saturation during system start-up with low level of V_{dc});

- starting at t=0.5 s, the voltage reference increases to 540 V with first time derivative equals to 500 V/s;

- starting at t=1.5 s, the flux reference increases to ψ^*=0.96 Wb in order to achieve IG operation with rated flux;

- at time t=2 s the load current equal to 6.7 A (correspond to 3.6 kW of power, 80% of rated value) is applied and at t=5.5 s is removed;

- under load condition a speed variations are applied: starting from t=2.5 s speed increased to 150 rad/s and from t=3.5 s is decreased to 130 rad/s.
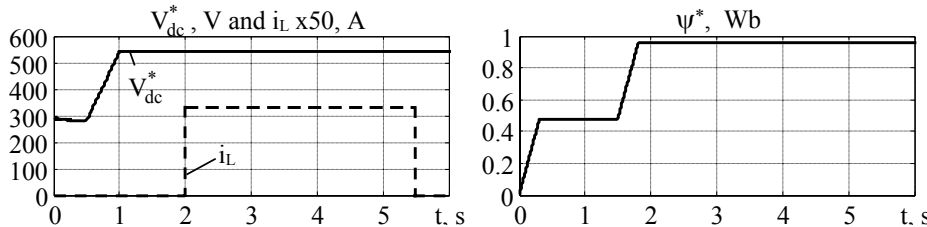

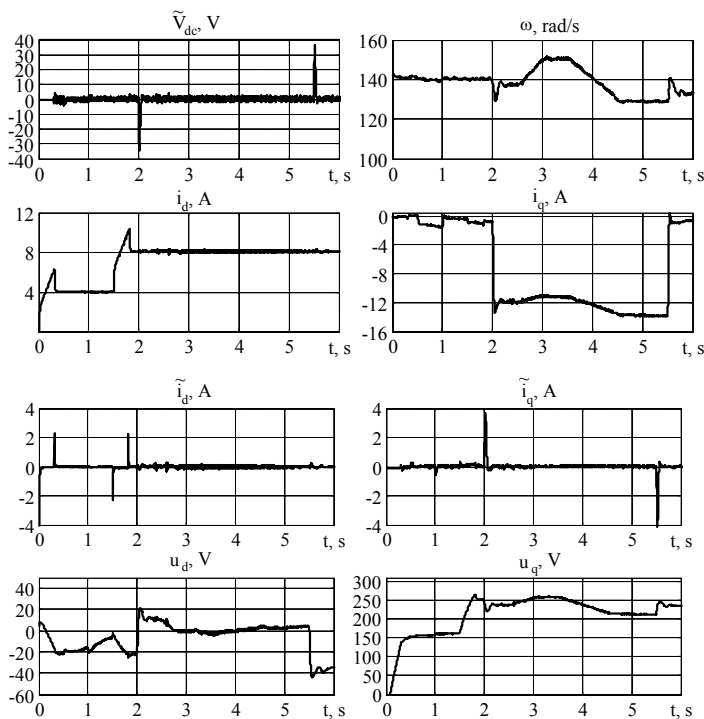**Fig. 4.** Flux, voltage reference trajectories and load current profile

Fig. 5. Transients during flux-voltage regulation: experimental results
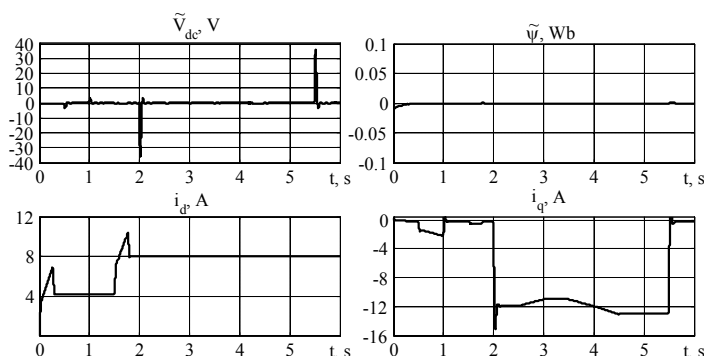

Fig. 6. Transients during flux-voltage regulation: simulation results

Experimental results for proposed voltage control algorithm (8)−(10), (22) are shown in Fig. 5. Flux and voltage tracking errors as well as currents i_d and i_q during simulation are depicted in Fig. 6. As it follows from the transients in Fig. 5 and Fig. 6 the proposed control algorithm provides asymptotic flux-voltage regulation under speed variation condition. Experimental transients are close to results of simulation.

Transients with i_L compensation in control algorithm (22) are shown in Fig. 7. Due to presence of i_L compensation a dynamical voltage error at t = 2 s and t = 5.5 s is reduced to negligible level.

In order to compare dynamic behavior of the standard PI and developed feedback linearizing voltage controllers for different constant speeds ω=140 rad/s and ω=75 rad/s we perform the additional experimental test. During this tests the load current (33% of rated value) is applied at t = = 0.2 s and removed at t = 0.6 s. Transients for both controllers are depicted in Fig. 8.

From voltage error evolutions reported in Fig. 8 it follows that both controllers provides the same dynamic behavior when system operates at speed 140 rad/s. Performances of the proposed controller are independent from generator speed. At the same time dynamics of standard controller deteriorates when ω=75 rad/s with almost twice increasing of the dynamical voltage error.

Note that systems under experimental comparison demonstrates similar to [10] dynamic behavior, which has been obtained by simulations with 2.2 kW generator.
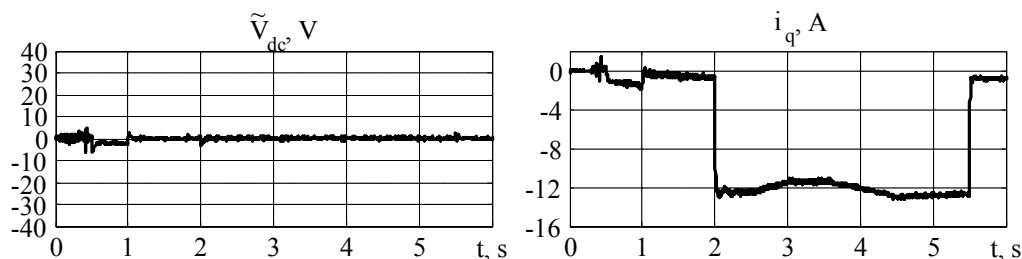
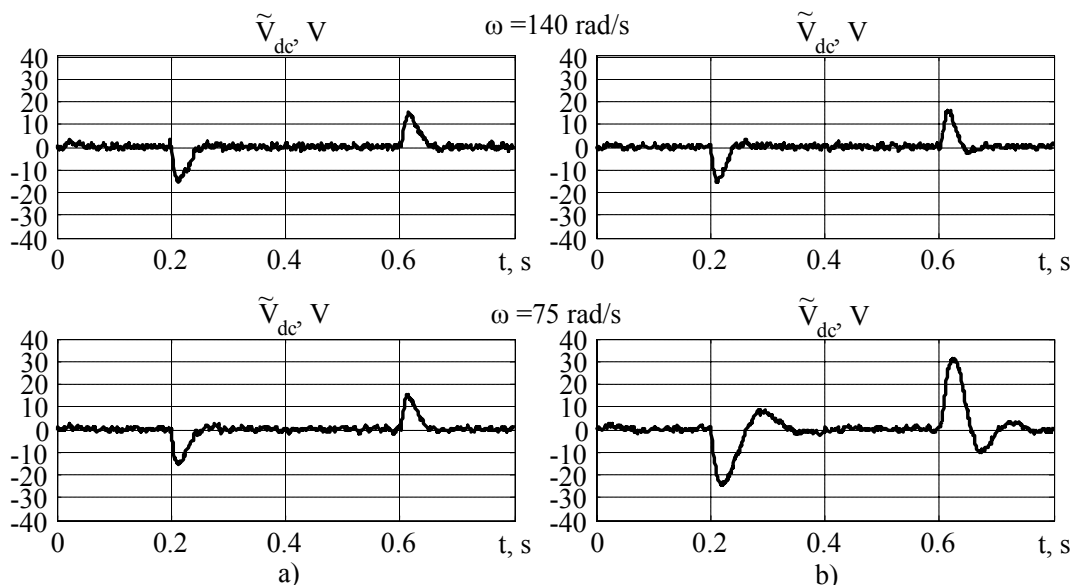**Fig. 7.** Transients with i_L compensation

Fig. 8. DC-link voltage regulation at speed 140 rad/s and 75 rad/s. Experimental results:
a) proposed controller (8)-(10), (22); b) standard PI voltage controller

V. CONCLUSIONS. In this paper, a novel indirect field-oriented controller for induction generator based on output-feedback linearizing technique has been designed and experimentally verified. The nonlinear control algorithm guarantees local asymptotic voltage-flux regulation under variable speed conditions. The proposed design approach provides simple and substantiated controller tuning procedure. An intensive experimental study of the proposed solution and comparison with standard PI voltage controller has proved that, in contrast to existing solutions, feedback-linearizing controller provides system performances stabilization when speed and flux are varying. Experimental transients are close to simulation results. Designed controller is suitable for standalone and grid connected (via suitable inverter) energy generation systems with variable speed operation.

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ПОЛЕОРІЄНТОВАНЕ ЛІНЕАРИЗУЮЧЕ КЕРУВАННЯ АСИНХРОННИМ ГЕНЕРАТОРОМ: ТЕОРІЯ ТА ЕКСПЕРИМЕНТИ

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Представлено нову систему векторного керування асинхронними генераторами. Процедура проектування базується на концепції непрямої орієнтації за вектором потокозчеплення ротора і використовує метод лінеаризації зворотнім зв'язком для проектування регулятора напруги. Запропоноване рішення гарантує асимптотичне регулювання потокозчеплення ротора і напруги в ланці постійного струму, забезпечуючи лінійну динаміку похибки регулювання напруги. Завдяки розділенню контурів регулювання в часі досягається декомпозиція на підсистему напруги і підсистему струму-потокозчеплення, що дозволяє використовувати просту процедуру налаштування регуляторів. У роботі представлені результати порівняльного експериментального дослідження запропонованого алгоритму і стандартного, який базується на алгоритмі з непрямою орієнтацією за потокозчепленням ротора і використовує лінійний ПІ регулятор напруги. Показано, що розроблений контролер, на відміну від стандартних рішень, забезпечує стабілізацію показників якості системи при зміні кутової швидкості ротора генератора. Запропонований алгоритм керування може застосовуватися в системах генерування зі змінною робочою швидкістю, які працюють в автономному режимі чи підключені до мережі через відповідний інвертор. Бібл. 10, рис. 8, табл. 1.
Ключові слова: асинхронний генератор, полеорієнтоване керування, система генерування енергії.

ПОЛЕОРИЕНТИРОВАННОЕ ЛИНЕАРИЗИРУЮЩЕЕ УПРАВЛЕНИЕ АСИНХРОННЫМ ГЕНЕРАТОРОМ: ТЕОРИЯ И ЭКСПЕРИМЕНТЫ

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Представлена новая система векторного управления асинхронными генераторами. Процедура проектирования базируется на концепции косвенной ориентации по вектору потокосцепления ротора и использует метод линеаризации обратной связью для проектирования регулятора напряжения. Предложенное решение гарантирует асимптотическое регулирование потокосцепления ротора и напряжения в звене постоянного тока, обеспечивая линейную динамику ошибки регулирования напряжения. Благодаря разделению контуров регулирования во времени достигается декомпозиция на подсистему напряжения и подсистему тока-потокосцепления, что позволяет использовать простую процедуру настройки регуляторов. В работе представлены результаты сравнительного экспериментального исследования предложенного алгоритма и стандартного, который основан на алгоритме с косвенной ориентацией по потокосцеплению ротора и использует линейный ПИ регулятор напряжения. Показано, что разработанный контроллер, в отличие от стандартных решений, обеспечивает стабилизацию показателей качества системы при изменении угловой скорости ротора генератора. Предложенный алгоритм управления может применяться в системах генерирования с переменной рабочей скоростью, которые работают в автономном режиме или подключены к сети через соответствующий инвертор. Библ. 10, рис. 8, табл. 1.
Ключевые слова: асинхронный генератор, полеориентированное управление, система генерирования энергии.