INTEGRAL STATE FEEDBACK CONTROL OF GRID POWER INVERTER

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REZUMAT. În această lucrare se prezintă topologia unui invertor de rețea şi performanțele controlului cu reacție dupa stare cu acțiune integrală. Beneficiul major adus de aceasta topologie este utilizarea unui invertor comun care injectează puterea generată de la surse regenerabile în rețea. Structura de control a invertorului de putere este de tip vectorial, în sistem de referință sincron şi foloseşte conceptul de echilibru de putere. Structura de control a prototipului a fost implementată cu ajutorul procesorului digital de semnal dSMC 101 . Soluția propusă în această lucrare introduce avantaje suplimentare față de sistemul de putere cu control convențional doar cu reacție după stare: filtrul proiectat pe intrarea buclei de curent asigură eroare staționară zero şi prin adăugarea unei componente adecvate, sistemul de control conduce la o rejectare dinamică adevata a perturbației de sarcină. Deoarece foloseste componenta integrală, structura de control are capabilități robuste pentru la acțiuni perturbatoare.

Cuvinte cheie: Energii regenerabile, conditionarea puterii, conectare la retea, control cu reactie dupa stare integral.

ABSTRACT. This paper shows the topology of grid-connected green power system and the performances of the front-end three-phase power inverter by applying integral state feedback control. The proposed topology benefits of the one common DC-AC inverter which injects the generated power into the grid. The control structure of the DC-AC power inverter is vector control type, in synchronous reference frame, and it uses the power balance concept. The control of the DC-AC converter prototype has been implemented based on the dSMC 101 digital signal processors-DSP. The proposed solution adds supplementary benefits to power system besides to the conventional state feedback control: the designed input filter of the current loop assures zero steady state error and an adequate component is added for dynamic rejection of the load disturbance. Because it uses the integral component, the control structure has robust capabilities to load disturbance actions.

Keywords: Renewable energy, power conditioning, grid-connected, integral state feedback control, Matlab

1. INTRODUCTION

The fossil energy sources (oil, natural gas, coal) are finite and generate pollution. The alternative (renewable) energy relates to issues of sustainability, renewability and pollution reduction [1], [2] [3]. In order to convert the type of energy (AC to DC, or vice versa), the high performance power converters are used. The use of the force-commutated [1] PWM source converters is related to attaining of the bi-directional power flow and unity power factor, respectively.

This paper presents the performances of the grid connected power inverter, which works properly based on integral state feedback current controllers. The integral state feedback current controllers assure fast disturbance rejection resulting in low dc-link ripple voltage, zero steady state error and a stable power system. By maintaining a constant dc link voltage the dc link current follows the load levels requirements.

2. THE STRUCTURE OF THE POWER SYSTEM

The proposed topology assures a constant DC link voltage, integration of the renewable energy into the grid, the power quality issues, active and reactive decoupled power control, and grid synchronization. The power stage of the three-phase voltage DC-AC power converter system is exhibited in the Fig.1. It contains one three-phase IGBT power module, the three-phase boost inductor, and the DC capacitor. IGBT gate drive board is Semikron type and it is directly mounted around IGBT modules. The control diagram of the DC-AC power inverter is shown in the Fig.1. On the basis of a DC voltage reference V^{*}_{dc}, dc voltage feedback signal (V_{dc}), ac input voltages (E_{ab} and E_{bc}), current feedback signals (I_a, I_b for grid power inverter), and load power signal, the DSP software operates the DC-AC control (voltage and current) system and generates the firing gate signals to the PWM modulator.

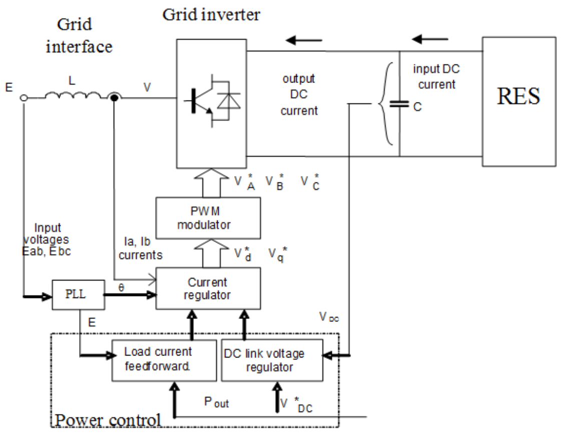

Fig. 1 Control block diagram of the grid power inverter.

The input boost inductor is designed from the THD factor point of view. Therefore, the input current THD factor is constrained to be less than 5% at the full load. The boost inductor limits the peak switching currents to an acceptable value and smoothing the line current. The DC link capacitor provides a decoupling function between the grid side and load side, respectively. Thus, the DC capacitor provides a reduced value for the ripple current generated by both converters and maintains a controllable dc link voltage. The phase-locked loop (PLL) is necessary for the proper current controllers decoupling, and for *d-q* axes synchronization with the grid reference voltage, respectively. The PLL tracks the grid frequency. Because of the system stability limit [4], [5] the proportional feedback gain of the PI dc voltage controller must be small according to [6]. In order to obtain a sinusoidal AC current shape, the DC link voltage is regulated at a higher level than the peak of the AC line such that the IGBTs can control the current.

Assumptions considerations for system modelling: the ac source voltages are balanced and distortion free, the converter switches are ideal, the DC voltage reference is constant.

The current model in the *q-d* reference frame is represented by the following first-order differential equations:

$$\frac{dI_D}{dt} + \omega \cdot I_Q = -\frac{1}{L} \cdot V_D + \frac{1}{L} \cdot E_D$$
$$\frac{dI_Q}{dt} - \omega \cdot I_D = -\frac{1}{L} \cdot V_Q + \frac{1}{L} \cdot E_Q \qquad (1)$$

$$C \cdot \frac{dV_{dc}}{dt} = I_{inDC} - I_{outDC} \qquad (2)$$

where:

- the inverter voltage components are denoted by V_d and V_q, respectively;
- the grid voltage components by E_d and E_q, respectively;
- the line current components by i_d and i_q, respectively;
- the dc-link voltage by V_{dc};
- the fuel cell output current by $I_{RES}=I_{inDC}$.
- V_{dc} is the instantaneous dc capacitor voltage [V];
- I_{RES} is the instantaneous current from Renewable Energy Source (RES) [A];

Taking into account the energy balance equation [7], the DC link capacitor voltage (2) becomes:

$$\frac{dV_{dc}}{dt} = \frac{I_{RES}}{C} - \frac{3}{2} \cdot \frac{V_d \cdot I_d + V_q \cdot I_q}{C \cdot V_{dc}} \qquad (3)$$

Thus, it is possible to independently control the ac converter currents I_d and I_q by acting upon V_d and V_q, respectively.

By aligning the *d-q* synchronous reference frame with the input voltage vector, through PLL circuit, the E_d supply voltage *d*-component becomes zero. Therefore, the following equations are available:

$$E_d = 0, \quad E_q = E \qquad (4)$$

where E is the maximum value of the grid phase voltage.

3. GRID INVERTER CONTROL

In order to improve the performances of the conventional state feedback control [8], a new state has been introduced:

$$\dot{\mathbf{z}} = y^* - y = y^* - \mathbf{C} \cdot \mathbf{x} \qquad (5)$$

Taking into account (5) eq. and the mathematical model of the state feedback control [9], the new standard state space model of the grid power inverter becomes:

$$\begin{cases} \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{z}} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & 0 \\ -\mathbf{C} & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x} \\ \mathbf{z} \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} \cdot \mathbf{u} + \begin{bmatrix} \mathbf{F} \\ 0 \end{bmatrix} \cdot \mathbf{e} + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \cdot y^* \\ y = \begin{bmatrix} \mathbf{C} & 0 \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x} \\ \mathbf{z} \end{bmatrix} \end{cases} \qquad (6)$$

The control action consists mainly of three components: the state feedback, the pre-filter placed on the reference channel, and the direct compensation of the disturbances [8],[9]:

$$\mathbf{u} = \mathbf{G}\mathrm{x} + \mathbf{K}\mathbf{z} + \mathbf{R}\mathrm{e} = \widetilde{\mathbf{G}}\widetilde{\mathrm{x}} + \mathbf{R}\mathrm{e} \tag{7}$$

where, $\mathbf{G} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$, $\mathbf{K} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix}$, $\mathbf{R} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} = -\mathbf{B}^{-1}\mathbf{F}$ are the adequate matrices, $\widetilde{\mathbf{x}} = \begin{bmatrix} \mathbf{x} \\ \mathbf{z} \end{bmatrix}$ is the new state and $\widetilde{\mathbf{G}} = [\mathbf{G} \quad \mathbf{K}]$ is the new state feedback control matrix.

The structure of the integral state-feedback control system is depicted in Figure 2.

Since $R_{12}=R_{21}=0$ (due to the structure of the system under control), these gains have not been reported in Figure 2.

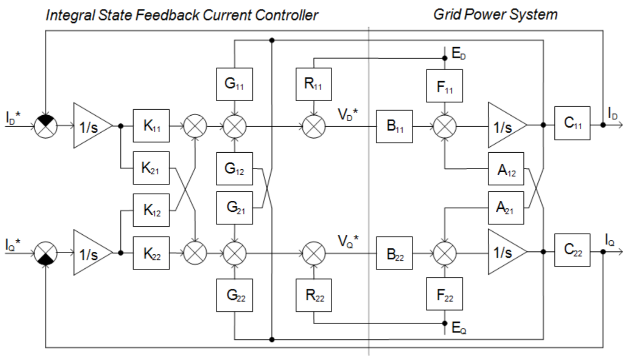

Fig. 2 Integral state feedback current control of the grid power inverter

The designed input filter of the current loop assures zero steady state error and an adequate component is added for dynamic rejection of the load disturbance. Because it uses the integral component, the control structure has robust capabilities to load disturbance actions.

By imposing the zero steady state error, the pre-filter gain value, **K**, on the input reference is provided:

$$\mathbf{K} = -\mathbf{B}^{-1} \cdot (\mathbf{A} + \mathbf{B} \cdot \mathbf{G}) \cdot \mathbf{C}^{-1} \tag{8}$$

By using the pole placement method, the final value of the **G** gain is determined.

The closed loop eigenvalues are assigned by imposing an adequate time response T_R and a damping factor d, which yields:

$$\lambda_{1,2} = -d \cdot \omega_0 \pm \omega_0 \cdot \sqrt{1-d^2}\, i \tag{9}$$

where

$$\omega_0 = \frac{1}{d \cdot T_R} \cdot \left(3 - \frac{1}{2}\ln\left(1-d^2\right)\right) \tag{10}$$

The feedforward current component was added to the reference (Fig.1). Its value is provided from the power balance equation, i.e. the power converter must meet the load power requirements. Therefore,

$$I^*_{q2} = \frac{2}{3E} \cdot P_{out} \;. \tag{11}$$

Through the feedforward component, since E is constant, the active power flow is controlled indirectly by the reference current. The output power, P_{out} (Fig.1), is estimated from the load terminals.

A unity power factor is necessary in AC drive. This implies a proper orientation of the reference frame and a zero *d*-axis current reference value:

$$I^*_d = 0 \;. \tag{12}$$

By linearizing (3) through the small perturbation method around the equilibrium point, the parameters of the dc-voltage controller are derived. The method of *symmetrical optimum* in Kessler variant [10] (the amplitude and the phase plot are symmetrical given the crossover frequency), was used in order to synthesize the voltage controller parameters by using open-loop transfer function. The main task of the voltage controller is to maintain the dc link voltage to a certain value. Another task is to control the voltage converter power flow.

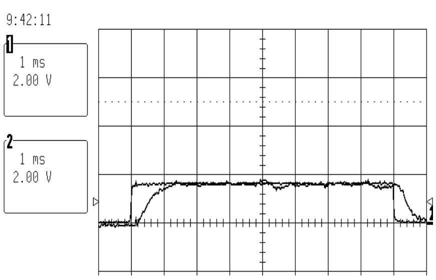

Fig. 3 The input and the output signals of the *d* axis current loop: Ch.1: the *d* axis current reference 50A/div. Ch.2: the actual *d* axis current.

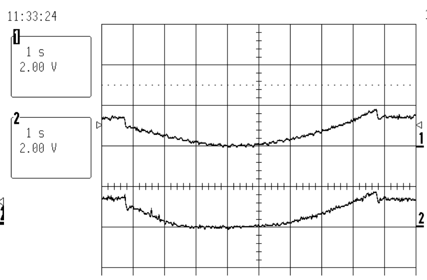

Fig. 4 The input and the output signals of the *q* axis current loop: Top trace (Ch.1): the *q* axis current reference, I^*_q 50A/div. Bottom trace (Ch.2): the actual *q* axis current, I_q.

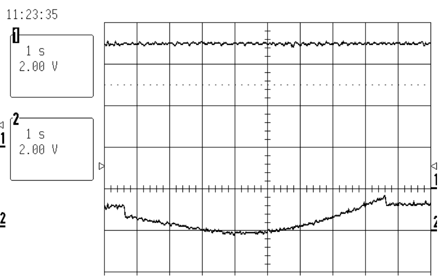

Fig. 5 Ch1 – The dc link voltage, V_{dc}190V/div, Ch2- the actual load current of the supply converter, I_q 50 A/div.

4.THE EXPERIMENTAL RESULTS

The particular inverter parameters are given as follows: line inductance 0.5(mH), and DC bus capacitor 1000(μF), DC link reference voltage 690(V), switching frequency 8(kHz), supply voltage (line-to-line) 400(V), main frequency 50(Hz), and ambient temperature 40(^{o}C).

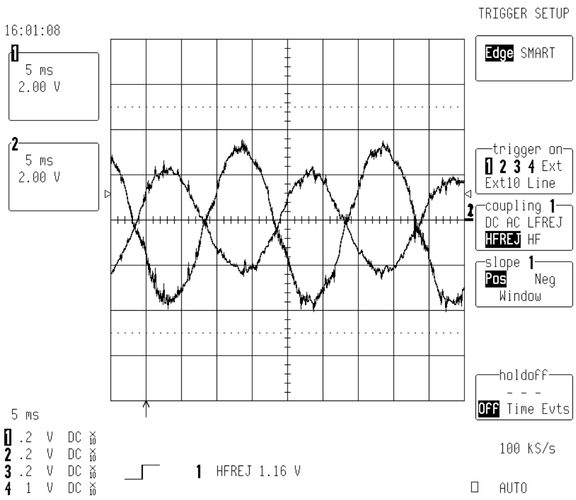

Fig. 6 Waveforms showing unity power factor in inverter operation mode. Ch.1: *A* phase source voltage (E_PHASE_A)- 190V/div. Ch.2: Input line current, I_A – 50A/div.

The basic values of the current controller parameters are as follows: by choosing the response time T_r = 0.7e-3 and the damping coefficient d = 0.707, the following desired poles of the closed loop system are obtained **P**=[l1 l2 l3 l4], where l1=l3=-4.7667e+003 +4.8630e+003i and l2=l4= -4.7667e+003 - 4.8630e+003i. Knowing the output inductance, based on the above mentioned design expressions; the integral state-feedback controller has been designed by using the Matlab software. Thus, the following matrices: **G**= [3.8133 -0.1257; 0.1257 3.8133]; **K**= [-1.8548e+004 1.7323e-012; 7.4925e-012 -1.8548e+004] and **R**= [1 0; 0 1; 0 0; 0 0] are obtained.

From the power conditioning system design stage the capacitor bank has two parallel connected 500(μF) film capacitors with 900(V) dc rating voltage. The power semiconductor switches are operated with a switching time T_s=125(μs).

The performances of the grid - power inverter current controllers are presented by the Fig. 5, for *q*-axis (load) current component. A test current generator was used in order to obtain the *d*-axis current reference waveforms (Fig.3). The reference of the source load current (Fig.4) has ripples in transients to regulate the dc-link voltage and the power matching control. The actual load current, I_q, accurately follows its reference I^{*}_{q} (Fig.4).

Additionally, the Figs. 3-6 show the performances of the grid current controller and of the dc-link voltage controller. Power matching control is proved by no DC voltage variation to the change of the rated load in normal (Fig.5) operation mode. The trace of the *A* phase of the grid current is in phase with *A* phase of the grid voltage, which clearly demonstrates the unity power factor operation (Fig. 6).

5. CONCLUSIONS

✓ The stationary and transient performances are presented in (Figs.3-7) in order to show the effectiveness of the proposed control strategy for the grid inverter. Less than 5% current THD factor (under rated power level) and a unity power factor operation have been obtained.

✓ This paper presents the performances of the grid connected power inverter, which works properly based on integral state feedback current controllers. The integral state feedback current controllers assure fast disturbance rejection resulting in low dc-link ripple voltage, zero steady state error and a stable power system. By maintaining a constant dc link voltage the dc link current follows the load levels requirements.

✓ The resulted grid connected inverter has following advantages: reduction of the lower order harmonics in the ac line current, constant dc-link voltage, nearly unity efficiency, zero displacement between voltage and current fundamental component, power reversibility capabilities as well as the good power matching control, disturbance compensation capability, fast control response and high quality balanced three-phase output voltages, small (up to 5%) ripple in the dc-link voltage in any operating conditions.

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