PREDICTIVE POWER CONTROL OF GRID-TIED MULTILEVEL INVERTER

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ABSTRACT

The paper presents a power control scheme for grid-tied multilevel cascade inverter with L grid filter and modern predictive current control technique. The reference current for current predictive controller is based on the required active and reactive power supplied to the grid. The reference current is generated using instantaneous power theory (p-q theory). The behaviour of the system is simulated for different values of grid filter inductance and thus different grid current distortions. The quality of proposed control scheme is evaluated as p-q theory was originally designed for three-phase active power compensators and can not be considered as general power theory. The main advantage of proposed control scheme is its simplicity and fast response even with lower switching frequency. Predictive controller enables the control to be designed in stationary reference frame without the need of resonant current controller and PWM modulator.

Keywords: *cascade inverter, p-q theory, predictive control*

1. INTRODUCTION

The power electronics plays an important role in today's renewable energy systems. The electrical energy harvested from a photovoltaic (PV) generator needs to be conditioned in order to by supplied to the electrical grid by a mean of PV inverter.

The modern PV inverter can be considered to by a mature technology. However there are still several problems which need to be addressed. Some of them are higher order harmonics in supplied ac current, common voltage reduction, EMC, output filter size, reliability and lifetime, etc. In order to solve these problem there are several possibilities. One can use modern semiconductor components such as SiC, higher switching frequency, soft-switching technique, new topology of power converter, etc. One of the possibilities is to use multilevel converters. The main advantages of multilevel converters when compared to dual-level converters are staircase output voltage with lower du/dt, lower THD, smaller power transferred by one semiconductor switch, lower switching losses. Some of the abovementioned problems can be addressed by incorporating modern control techniques such as fuzzy logic control, neural networks or predictive control. Traditionally, control technique had to ensure fast dynamics and stability of the systems. Nowadays requirements such as switching losses minimization, lower THD good performance in wide range of operating conditions, considering prohibited switching states, active dumping of oscillations, etc. are taking into account as well. [1][2]

When considering modern power converter with finite number of switching states, nonlinearities and constrains and modern control implementation in discrete time, the predictive control technique comes as natural solution.

Most advantages can be gained by combining modern multilevel converter with modern predictive control strategy. The scope of this paper is to describe predictive control of cascade multilevel converter used for PV inverter with emphasis on instantaneous grip-supplied power control.

2. GRID CONNECTED CASCADE INVERTER

This part describe the multilevel inverter current predictive control which is used as base for power control.

2.1. System Description

The PV generator is connected to the grid by a mean of single-phase cascade H-bridge inverter with output grid filter as shown in Fig. 1. The current control of the inverter is done by predictive control technique which ensures high dynamics. The reference current for predictive controller is generated by power control block which accepts required active and reactive power supplied to the grid as inputs. The control is realized in stationary reference frame.

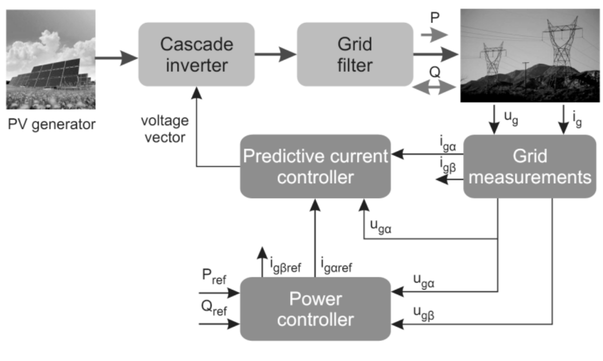

Fig. 1 Proposed control scheme for power control flow of grid connected cascade inverter

2.2. System Model

The main feature of predictive controller is the use of system model to predict the future behavior of controlled variables. The controlled variable in grid connected inverter with current control is the current supplied to the grid. The amplitude and phase shift of grid current with respect to the grid voltage are defined by required active and reactive power supplied to the grid.

The voltage source cascade inverter is connected to the grid through L filter. The system is described in discrete time by (1):

$$i_g\left(k+1\right)=\frac{T_S}{L}\left(u\left(k\right)-u_g\left(k\right)\right)+i_g\left(k\right)\left(1-\frac{RT_S}{L}\right) \tag{1}$$

where:

i_g – is current supplied to the grid,
u – is the output voltage of the inverter,
u_g – is grid voltage,
L – inductance of L filter,
R – resistance of L filter,
T_S – sampling time.

The equation (1) is used in predictive controller to predict the future value of the grid current based on actual grid current and voltage as well as the inverter output voltage (Fig. 2). The proposed asymmetrical H-bridge cascade inverter is capable of creating 15 discrete levels of output voltage.

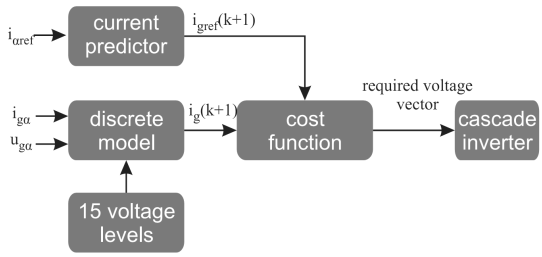

Fig. 2 Predictive current controller of cascade inverter

For predictive control, there is a need to create the cost function which will be evaluated in each sampling time and will define the behavior of the system. The cost function was chosen as difference between desired current i_{gref} and actual current i_g in the next sampling period [8]:

$$z\left(k\right)=\left|i_{gref}\left(k+1\right)-i_g\left(k+1\right)\right| \tag{2}$$

2.3. Grid Measurement

In order to realize a control system of the one-phase cascade inverter in stationary reference frame there is a need to create grid measurements in stationary reference frame αβ. This is normally done by Clarke transformation in three-phase systems. However, Clarke transformation can not be utilized in one-phase system. Thus there is a need to create virtual two-phase generator in order to create stationary reference frame αβ. This virtual two-phase generator needs to be used in grid voltage as well as grid current measurements. In the following, the virtual two-phase generator for voltage measurements in described. The current measurement principle in the stationary reference frame is the same and thus is not mentioned.

The property of the stationary reference frame is that two voltages v_α and v_β are orthogonal. If the grid voltage corresponds to the voltage u_β, than the voltage $u_{g\beta}$ can be created as follows:

$$\begin{bmatrix}u_{g\alpha}\\u_{g\beta}\end{bmatrix}=\begin{bmatrix}u_g\left(\omega t-\pi/2\right)\\u_g\left(\omega t\right)\end{bmatrix}=\begin{bmatrix}U_{gm}\sin\left(\omega t-\pi/2\right)\\U_{gm}\sin\left(\omega t\right)\end{bmatrix}\cong\begin{bmatrix}-U_m\cos\left(\omega t\right)\\U_m\sin\left(\omega t\right)\end{bmatrix} \tag{3}$$

There are several possibilities how to create the 90 degrees phase shift of the grid voltage to produce the $u_{g\beta}$ voltage (e.g. storage elements, filters). One of them is to use second-order low-pass filter [5][6].

When the input voltage u_g passes through the second-order low-pass filter, which damping ratio $\zeta=1/\sqrt{2}$, the undamped natural frequency ω_n has the same value as the grid frequency, a signal with a phase-angle difference of π/2 and amplitude of $U_{gm}/\sqrt{2}$ is obtained [5]:

$$u_{g\alpha}=-\sqrt{2}\frac{U_{gm}}{\sqrt{2}}\sin\left(\omega t-\frac{\pi}{2}\right)=U_{gm}\cos\left(\omega t\right) \tag{4}$$

The second order low-pass filter is realized in discrete form with help of Tustin transformation. The resulting grid measurement block generating voltages and currents in the stationary reference frame is shown in Fig. 3.

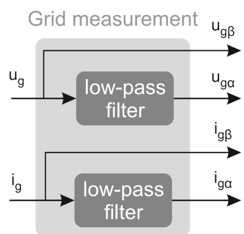

Fig. 3 Inside of grid measurement block

3. POWER CONTROL

The power supplied to the grid by the cascade inverter is defined by grid voltage and grid current. The grid voltage is considered as external variable and can not be changed. Thus the power control is realized solely by current control. By generating the required grid current based on grid voltage and required supplied active and reactive power and ensuring current control technique, the power control is realized as well. One way how to generate the required grid current to met power requirements is to use instantaneous power theory also known as p-q theory presented by Akagi in [4].

The p-q theory was originally developed for active power factor compensators. It is based on the Clarke transformation of grid voltage and current in three-phase system into αβ stationary reference frame. It defines two instantaneous powers named as instantaneous active p and instantaneous imaginary q power (with no physical meaning):

$$\begin{bmatrix}p\\q\end{bmatrix}=\begin{bmatrix}u_{g\alpha}&u_{g\beta}\\-u_{g\beta}&u_{g\alpha}\end{bmatrix}\begin{bmatrix}i_{g\alpha}\\i_{g\beta}\end{bmatrix} \tag{5}$$

The p-q theory can be used for one-phase systems as well. However, the resulting instantaneous active and imaginary powers are doubled with respect to real one-phase powers:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{2} \begin{bmatrix} u_{g\alpha} & u_{g\beta} \\ -u_{g\beta} & u_{g\alpha} \end{bmatrix} \begin{bmatrix} i_{g\alpha} \\ i_{g\beta} \end{bmatrix} \tag{6}$$

In [7] is shown that for sinusoidal balanced three-phase system is the instantaneous reactive power equal to the active power and instantaneous imaginary power is equal to the reactive power:

$$\begin{aligned} p &= P \\ q &= Q \end{aligned} \tag{7}$$

The reference current for predictive current controller can be obtained by combining (6) and (7):

$$\begin{bmatrix} i_{g\alpha ref} \\ i_{g\beta ref} \end{bmatrix} = \frac{1}{u_{g\alpha}^2 + u_{g\beta}^2} \begin{bmatrix} u_{g\alpha} & -u_{g\beta} \\ u_{g\beta} & u_{g\alpha} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \tag{8}$$

Only the current $i_{g\alpha ref}$ is used as reference current for predictive current controller because the grid voltage u_g corresponds to the voltage $u_{g\alpha}$.

4. SIMULATION

4.1. Simulation Setup

The proposed power control technique of single-phase grid-connected cascade inverter with predictive current control was verified by simulation in MATLAB/Simulink. The program realization of control scheme from Fig. 1 is shown in Fig. 4. The asymmetrical 15-level cascade inverter has DC voltage levels of 60, 120 and 240 V. The grid filter has inductance of 10 mH and resistance of 10 mΩ. The grid voltage is ~230V/50Hz and the sampling time T_S was set to 100 μs.

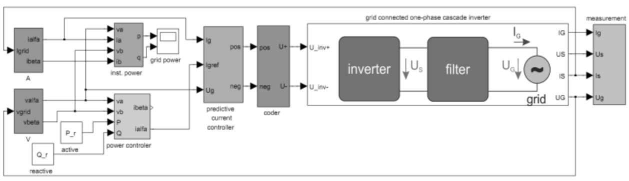

Fig. 4 Simulation scheme in Simulink

4.2. Instantaneous Power

At first, the accuracy of p-q theory when measuring instantaneous power in one-phase system was verified. The reason is that p-q theory is not general power theory [7] and the current supplied to the grid by the cascade inverter has some distortion. The accuracy of the p-q theory under these circumstances could be solved analytically. However, for particular inverter topology and control technique the easiest way is to use simulation.

The simulation results are shown in Fig. 5 and 6. There was a step change in active power on 0.05 and 0.2 s and in reactive power on 0.125 and 0.25 s. The active and reactive power was measured with p-q theory and Active & Reactive Power meter from SimPowerSystems toolbox which measures the power of the first harmonic. The grid filter inductance L was set to 10 and 2 mH to simulate different distortion in grid current.

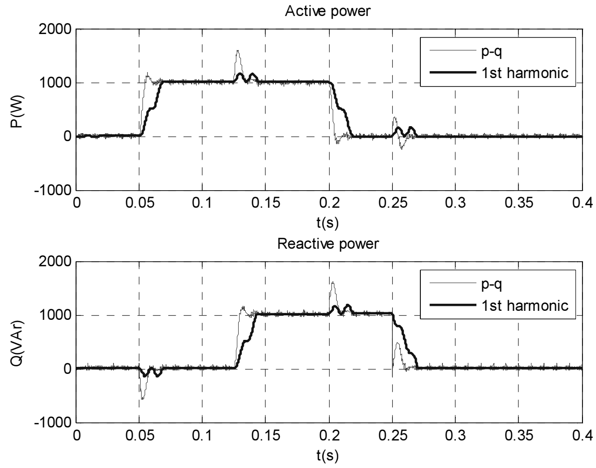

Fig. 5 Comparison of power measurement with p-q theory and first-order harmonic power meter Active & Reactive Power from SimPowerSystems toolbox for L = 10 mH

As can be seen from Fig. 5 and 6 the power measured by p-q theory has high-frequency oscillations but the average value is close to one measured by Active & Reactive Power meter. The advantage of p-q theory is faster response time as there is no need to calculate the rms values of current and voltage. The fast response time is desired for high-dynamic predictive control.

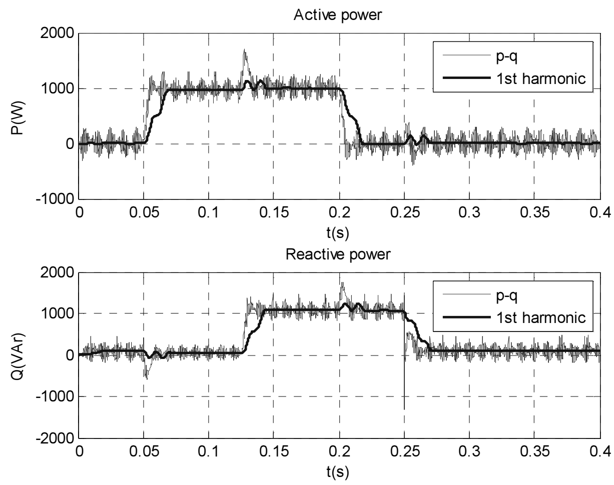

Fig. 6 Comparison of power measurement with p-q theory and first-order harmonic power meter Active & Reactive Power from SimPowerSystems toolbox for L = 2 mH

4.3. Power Control

The power control was realized using (8). The inputs were required active and reactive power and the output was required grid current. The quality of power control was verified for two values of grid filter inductance: 10 and 2 mH. Simulation results are shown in Fig. 7 and 8.

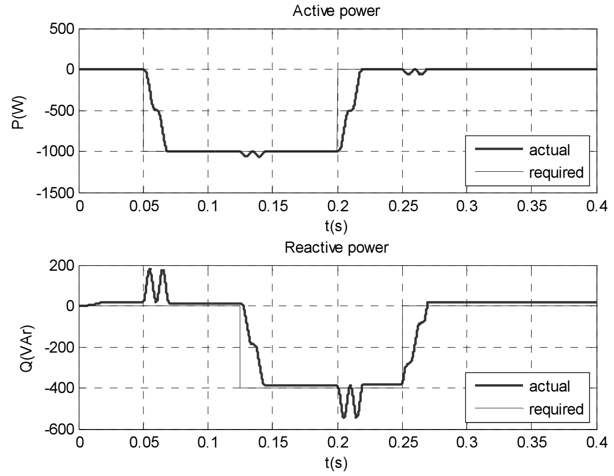

Fig. 7 Comparison of required and actual power measured with Active & Reactive Power from SimPowerSystems toolbox for L = 10 mH

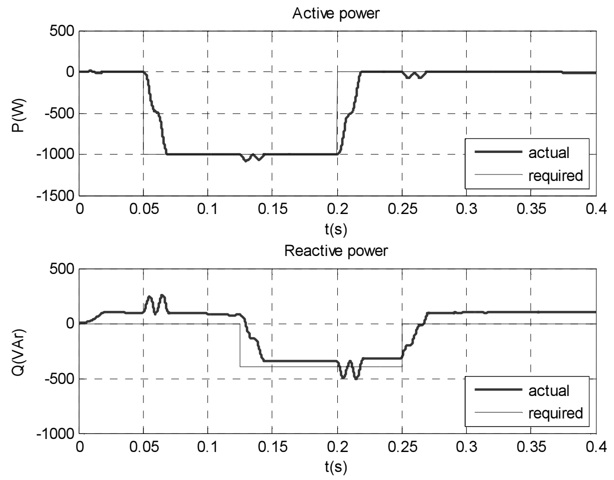

Fig. 8 Comparison of required and actual power measured with Active & Reactive Power from SimPowerSystems toolbox for L = 2 mH

Lower value of grid filter inductance causes higher grid current ripple, as indicates Fig. 10. This higher current ripple generates higher distortion power which results in imbalance between required and desired reactive power. As the value of the inductance is decreased the imbalance between required and actual reactive power is more significant (Fig. 8).

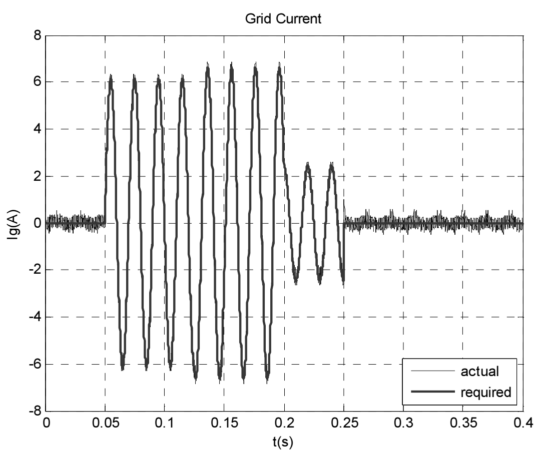

Fig. 9 Comparison of required and actual grid current for L = 10 mH

The current supplied to the grid and reference currents are shown in Fig. 9 and 10.

Due to the fact that the instantaneous active power in p-q theory has real physical meaning (product of the same phase voltage and current) there is no error is steady state between required and actual active power to be supplied to the grid (Fig. 7 and 8). However, the imaginary power in the p-q theory has no real physical meaning (product of different phase current and voltage) and by considering it to be the reactive power the error between required and actual imaginary power is generated. This error is more significant as the grid current distortion is increasing. This is the case especially with lower grid current as the PV inverter is designed to produce the current small distortion (THDi less then 3%) when operating under nominal conditions.

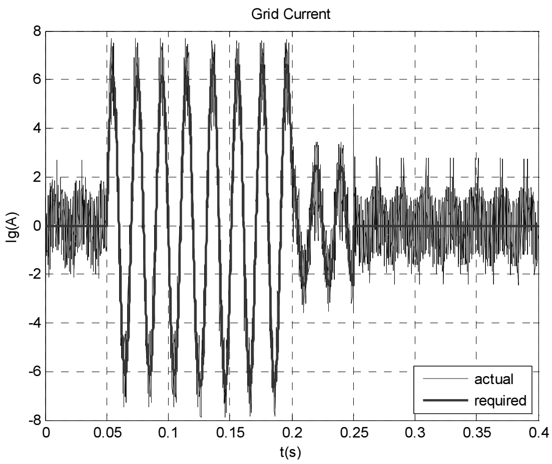

Fig. 10 Comparison of required and actual grid current for L = 2 mH

5. RESULTS

Properties of p-q theory when used as power theory to control the grid-connected inverter are analyzed. The influence of grid current ripple to the accuracy of active and reactive power control is described. The p-q theory is often used for power control of inverters but without any further investigation on the power control accuracy. In the paper it is show that as the grid current distortion is increasing, the accuracy of the reactive power control in decreasing. Thus the p-q theory can not be used as general power theory when controlling grid-connected inverters without further compensation for higher current distortions.

6. CONCLUSIONS

The p-q theory used to power control of grid-connected single-phase inverter is presented. Simulation is used to evaluate the quality of proposed control structure. It is shown that p-q theory can be used for fast power control with acceptable error in reactive power control for small grid current distortion. It is required by grid codes that the current supplied to the grid has small THD. It results in almost sinusoidal grid current. For sinusoidal voltage and current and balanced load the p-q theory can be used as fairly accurate replacement for general power theory. The proposed control structure will be verified by measurement on laboratory model of small grid-tied cascade inverter as simulations show promising results.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0185-10.

REFERENCES

[1] XUE, YAOSUO – DIVYA, K.C. – GRIEPENTROG, G. – LIVIU, M. – SURESH, S. – MANJREKAR, M.: Towards Next Generation Photovoltaic Inverters, Energy Conversion Congress and Exposition (ECCE) IEEE, ISBN 978-1-4577-0542-7, pp. 2467 – 2474, 2011.

[2] National Renewable Energy Laboratory : A Review of PV Inverter Technology Cost and Performance Projections, [Online], p. 100, 2006.

[3] CALAIS ,M. – AGELIDIS, V. G. – MEINHARDT, M: Multilevel Converters for Single-Phase Grid Connected Photovoltaic Systems: An Overview, [Online], Industrial Electronics, 1998. Proceedings. ISIE '98. IEEE International Symposium, ISBN 0-7803-4756-0, pp. 224-229, 1998.

[4] AKAGI, H. – KANZAWA, Y. – NABAE, A.: Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components, IEEE Transactions on Industry Applications, Vol. IA-20, No. 3, ISSN 0093-9994, pp. 625-630, 1984.

[5] CHOI, J. W. – KIM, Y.K. – KIM, H. G.: Digital PLL control for single-phase photovoltaic system, [Online]. Electric Power Applications, IEE Proceedings, ISSN 1350-2352, pp. 40-46, 2006.

[6] MEERSMAN, B. – DE KOONING, J.– VANDOORN, T. – DEGROOTE, L. – RENDERS, B. – VANDEVELDE, L.: Overview of PLL methods for distributed generation units, [Online], Universities Power Engineering Conference (UPEC), ISBN 978-1-4244-7667-1, IEEE, pp. 1-6, 2010.

[7] GUO, J. – XIAO, X. – TAO, S.: Discussion on Instantaneous Reactive Power Theory and Currents' Physical Component Theory, [Online], Harmonics and Quality of Power (ICHQP), IEEE, ISBN 1540-6008, pp. 427-432, 2012.

[8] PERANTZAKIS, G. S. – XEPAPS, F. H. – PAPATHANASSIOU, S. A. – MANIAS, S. N.: A Predictive Current Control Technique for Three-Level NPC Voltage Source Inverter, in Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th, 2005, pp. 1241 – 1246.

[9] TEODORESCU, R. – LISERRE, M. – RODRÍGUEZ, P.: Grid Converters for Photovoltaic and Wind Power Systems, Wiley, ISBN 978-0-470-05751-3, 416 pp., 2011.

[10] RODRÍGUEZ, J. – CORTÉS, P.: Predictive Control of Power Converters and Electrical Drives, Wiley, ISBN 978-1-1199-6398-1, 244 pp., 2012.

[11] KHOMFOI, S. – TOLBERT, L. M.: Multilevel Power Converters, from H.Rashid: Power Electronics Handbook, second release, Elsevier, 2007, ISBN 10: 0-12-088479-8, pp. 451 – 482.

[12] HAQUE, M.T.: Single-phase PQ theory, Power Electronics Specialists Conference, IEEE, ISBN 0-7803-7262-X, pp. 1815 – 1820, 2002.

[13] HAQUE, M.T.: ISE, T.: Implementation of single-phase pq theory, Power Conversion Conference, IEEE, ISBN 0-7803-7156-9, pp. 761 – 765, 2002.

Received July 1, 2013 , accepted September 2, 2013

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Marek Vacek was born in Liptovský Mikuláš (Slovakia) in 1986. He graduated from the Department of Electrical Engineering and Mechatronics at FEI TU of Košice. He now works on getting his PhD at the same department at FEI TU of Košice. His research interests include robotics, artificial intelligence and camera systems.