



CURRENT CONTROLLER PARAMETER INFLUENCES ON THD FOR GRID CONNECTED CONVERTER

Bane Popadić, Vladimir Katić, Boris Dumnić, Dragan Milićević, Zoltan Čorba

University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Trg Dositeja Obradovića 6

Tel: 021/ 485 2503, e-mail: banep@uns.ac.rs

Abstract: Number of the grid connected converter topologies is raising steadily in the recent years. With the increase in the number of grid connected converters, their influence on the power quality of the system became noticeable. This paper is investigating the influence of the current controller parameter variation on the total harmonic distortion of the current injected to the grid. It also looks to compare the influence of different controller topologies, where PI and PR controller are compared. Simulation results were experimentally verified using advanced laboratory setup developed on the Faculty of Technical Sciences.

Key Words: Grid Connected Converter, Current Controller, Total Harmonic Distortion (THD), PI controller, PR controller, Power Quality

1. INTRODUCTION

Ever since first marketed, power electronics has been a rapidly growing field. Today it is hard to imagine a device without integrated power electronics. Even so, special attention has deservedly always been given to grid connected converters. With expansion of modern technologies, grid connected converters firmly established their role in the power system. Whilst the influence of a single low power grid connected converter can freely be neglected, high power grid connected converters and their increasing number lead to significant influence on the power quality in the system.

Renewable energy sources, in the wake of several energy crises as well as the impact of conventional energy sources on the environment, expanded significantly. This has particularly been the case for solar energy. Grid connected converter claimed its place in transformation of energy to fulfill the requirements of the grid, i.e. Grid Code. For the wind energy grid connected converter is not necessary a part of the system, but with decrease in component prices a back to back converter topology for wind energy conversion system is no longer a rarity [1]. Apart from the renewable energy sector, there are two more exceptionally attractive areas for grid connected converter utilization. Development of electrical vehicles and automotive industry around EV's

opened up new possibilities for grid connected converter. As a coupling element between electrical vehicle and an open energy market, grid connected converter will take a pivotal role in energy trading. On the other hand it has to be fully capable of achieving satisfactory power quality of generated energy. As storing of electrical energy is the main issue in the rise of electrical vehicle, accompanying the rise in that field will be energy storage devices, i.e. batteries. Electrical storage is the way of also solving renewable energy intermittency issues. This represents another prospect for grid connected converters. General structure for a grid connected converter applications is shown in figure 1.

Total harmonic distortion (THD) is most commonly used as an indicator of power quality. For the grid connected converter where grid dictates and grid connected converter has little or no influence on the voltage, output current THD is a power quality indicator.

This paper will look to show the influence of current controller parameter variation on THD of the injected current. Also different control topologies are shown to have different influence on current THD [2]. In that regard, a comparative analysis will be shown depicting the influence of Proportional-Integral (PI) and Proportional-Resonant (PR) controllers.

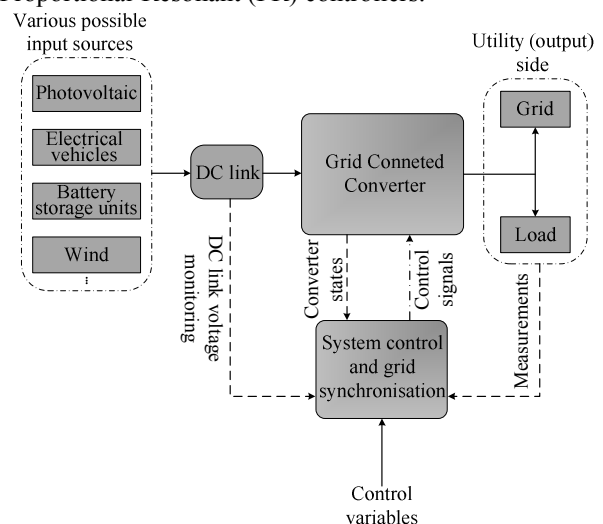


Fig. 1. Grid connected converter applications

2. CURRENT CONTROLLER TOPOLOGIES

Usually the control of grid connected converter consists of two cascaded loops. Inner loop controls the output current and outer loop is used to control the DC link voltage. Current controllers have primarily always been chosen for their dynamic response characteristics. Based on the knowledge of the process and its variables different dynamics could be allowed, sometimes even preferred. The dynamic response characteristics differ due to parameter variation of the controller. In addition the type of the controller will also influence the control dynamics. Different current controller types have been suggested in the literature for the grid connected converter [2]-[4]. Some of them are:

- PI controller,
- PR controller,
- Fuzzy-logic current controller,
- Hysteresis controller,
- Fuzzy-Hysteresis controller,
- Predictive controller etc.

While any of the previously mentioned controller has certain advantages over the others main selection criteria, still to this day, remains the simplicity of implementation while maintaining acceptable response characteristics.

Most commonly used controllers are PI and PR controller [2], and they will be analyzed in this paper as well. They do not require high computational times, are easy to implement and have very good dynamic responses.

2.1. PI controller

Synchronous reference frame (dq) for a grid connected converter greatly simplifies the control by transforming the voltage and current waveforms and thus the control variables to dc values. That also allows for a decoupled control of active and reactive power injected to the grid. For the control in the dq reference frame PI controller has a well established position. It has highly satisfactory dynamic responses while regulating dc values. Control structure for the PI controller is given in figure 2. The transfer function of the PI controller is given by equation (1).

$$PI = K_p \cdot \left(1 + \frac{1}{T_i s}\right) = K_p \frac{1 + T_i s}{T_i s} \quad (1)$$

Simple PI controller can have a several implementation forms. Incremental form of the PI controller, sometimes used for grid connected converters will be investigated in the paper as well. This controller has slightly modified structure to the conventional PI controller, but also provides very good dynamic response.

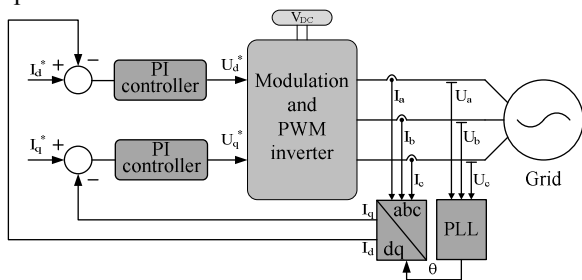


Fig. 2. Control structure block diagram of a PI controller

2.2. PR controller

Grid current control can be done in a stationary reference frame. Due to sinusoidal variables in the stationary reference frame PI controller would not suffice for this control scheme. In that regard, a new current controller has to be implemented.

Proportional Resonant (PR) controller has gained a great popularity in the last decade, especially for the control of grid connected converters. In addition to being able to control sinusoidal values and remove the steady state error, it can also have better response characteristics. The transfer function of the PR controller is given by equation (2).

$$PR = K_p + \frac{K_i s}{s^2 + \omega^2} \quad (2)$$

It can be seen that this controller has a very high gain around the resonant frequency, which eliminates the steady state error. The width of the frequency band around the resonant frequency is determined by integral gain. Figure 3 shows the control structure for the PR controller.

3. DESIGN OF CURRENT CONTROLLER

The parameters of the current controller can be determined using several methods proposed in the literature [5]-[8]. As recognized in [9], current controller for the grid connected converter has specific requirements. A fast dynamic response of at least 10 ms for a frequency of 50 Hz is necessary, so that the grid connected converter is able to deal with different disturbances in the grid. Another valuable characteristic for this particular implementation might be little or no overshoot response. High overshoot can cause power oscillation between the grid and the converter leading to system instability. To avoid haphazard approach to selecting current controller parameters two methods from the [5]-[8] were chosen. Those are modulus optimum and Ziegler-Nichols method.

3.1. Modulus optimum

Optimization is a powerful tool for designing of PI controller. With a simple concept modulus and symmetrical optimum are two of the most known PI controller optimization methods. It is based on optimizing the transfer function of the complete system so that desired output is achieved. For this particular implementation modulus optimum is chosen due to its lesser overshoot of only 4.3 %.

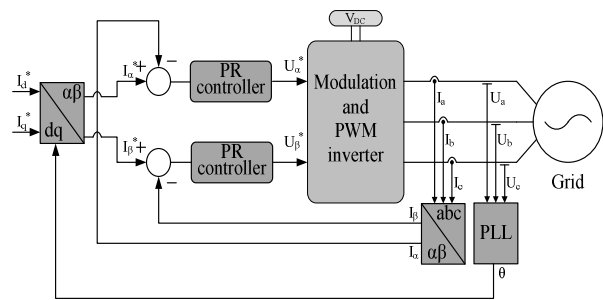


Fig. 3. Control structure block diagram of a PR controller

PI controller parameters using modulus optimum are calculated as follows:

$$K_p = \frac{T_d}{2K_d T_\delta}, \quad K_i = \frac{K_p}{T_d} \quad (3)$$

Dominant time constant designated T_d is equal to the grid equivalent time constant $\tau_i = L_s/R_s$. The time constant T_δ equals current loop sampling time T_i . The direct path gain in the control loop value is $K_d = 1/R_s$. When parameters are calculated as in (3) the rise time of the response should be equal to $T_r = 4.7 \cdot T_\delta$ and the settling time to $T_s = 8.4 \cdot T_\delta$.

3.2. Ziegler-Nichols method

Ziegler – Nichols method for tuning the current PI controller was applied to the simplified current loop. This simplified loop includes key components of the current control, thus forming a valid model for the parameter calculation. Ziegler – Nichols method is applied by reducing the PI controller to only proportional part ($T_i \rightarrow \infty, T_i = \text{inf}, K_i = \frac{K_p}{T_i}$), while K_p was set to low value resulting in stable response to step excitation. Proportional gain was then increased until it reached the critical gain $K_{p_{cr}}$. Critical gain can be recognized by observing the output signal oscillations. The gain at which the signal achieved marginal stability is called the critical gain. Critical oscillation period of the response T_{cr} is determined. According to the Table 1 given by Ziegler and Nichols, PI controller parameters can be determined [8]. The same exact values calculated according to the table are used for d and q axis controller.

Table 1. Ziegler – Nichols PI controller tuning

PI controller	K_p	T_i	T_d
P	$0.55 \cdot K_{p_{cr}}$		
PI	$0.35 \cdot K_{p_{cr}}$	$1.25 \cdot T_{cr}$	
PID	$0.6 \cdot K_{p_{cr}}$	$0.80 \cdot T_{cr}$	$0.2 \cdot T_{cr}$

4. MATHEMATICAL MODEL OF THE GRID CONNECTED CONVERTER

In order to implement the current control for grid connected converter first mathematical model of the process is developed. Mathematical model of a grid connected converter was then implemented using Matlab/Simulink. The performance of the current control loop, and the controllers within was observed.

Mathematical representation of the inverter is given with the equation (4). The parameter $T_{a,b,c}$ represents duty cycle for a particular inverter leg (phases a, b and c). For this application inverter switching model was used.

$$U_x = (2 \cdot T_x - T_y - T_z) \cdot \frac{V_{dc}}{3}, \quad x, y, z \in \{a, b, c\} \quad (4)$$

Duty cycles fed to the inverter are calculated using space vector pulse width modulation technique (SVPWM). Voltage drops on the components are neglected (ideal switches were approximated). Grid has been modeled by Thevenin equivalent circuit. The current controllers have been implemented according to (1) and (2).

Current control is located in the task that is executed 2 times slower than PWM period, while PWM switching frequency is set at 8 kHz. Built in Matlab/Simulink tools for fast Fourier transformation (FFT) is used to monitor the current THD.

4.1. Simulation results

Control structure models from fig. 2 and fig. 3 have been implemented in Matlab/Simulink and were used for simulation. Simulation results will show the influence of the current control parameters calculated as in 3.1. and 3.2., as well as the influence of the control structures described in 2. Figures 4 and 5 show the PI and PR controllers responses for d-axis reference step change from 0 A to 2 A for parameters calculated with Modulus optimum (a) and Ziegler-Nichols method (b). Responses for the incremental PI are similar to the PI responses.

It can be safely concluded that both PI and PR topologies satisfy the basic dynamic response criteria. In addition, parameter calculation method leads to slight differences in response features. These differences are still well within the margins of acceptable dynamic behavior for a current control loop. After careful consideration it can be seen that all settling times are lower than 5 ms. The overshoot exists for some variation and its value is around 10 %, which can be accepted even for the grid connected converter current loop.

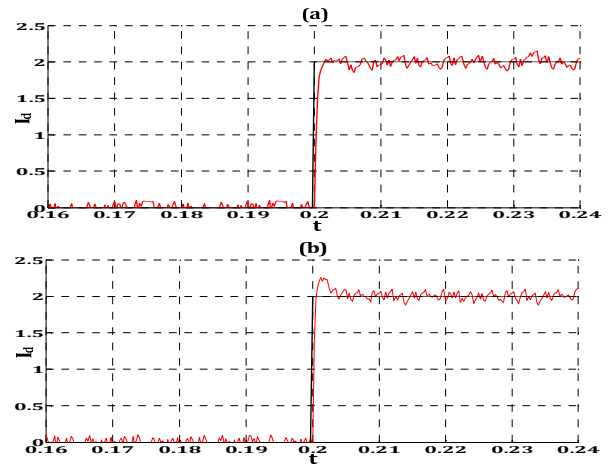


Fig. 4. PI controller response for Modulus optimum (a) and Ziegler-Nichols method (b)

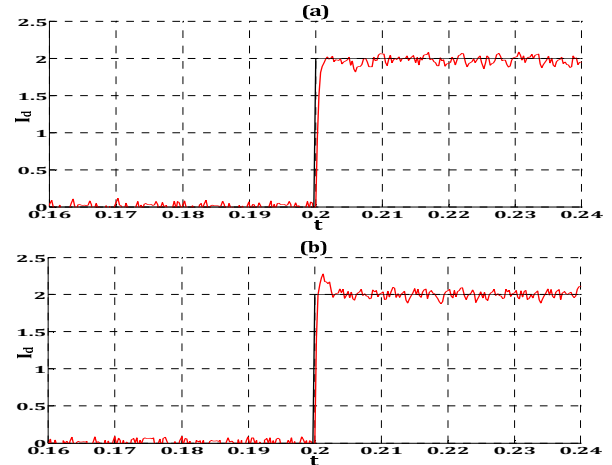


Fig. 5. PR controller response for Modulus optimum (a) and Ziegler-Nichols method (b)

As different parameters and topologies still lead to acceptable response features, any of the mentioned combination can be used. However, these topologies may have different impact on other current characteristics. The current THD will be given in table 2. From the table 2 it can be observed that all topologies have slightly different influence on THD with different parameters. Whilst that influence is lower for the standard PI controller, it is highly noticeable for the PR controller

The best performance was achieved using PR controller with parameters calculated by Ziegler-Nichols method. More parameter variation and slight manual adjustment can lead to even better results regarding harmonic distortion. On the other hand, special attention must be paid on the dynamic features, especially the overshoot.

Table 2. Current THD for different topologies and parameters (simulation)

Current THD	Modulus optimum	Ziegler-Nichols
PI	2.82 %	2.83 %
Incremental PI	3.04 %	2.93 %
PR	3.34 %	2.29 %

5. EXPERIMENTAL RESULTS

Results gained by the simulation model are experimentally verified for PI and incremental PI controller. Similar parameter variations are made, and the response characteristics and THD are compared. The experimental validation is performed using advanced laboratory setup developed on the Faculty of Technical Sciences, Group of Power Electronic and Drives [10]. Basis of the hardware is highly modular dSPACE system with modified industrial converters. Laboratory setup is shown in figure 6. Software implementation is done using Total Development Environment (TDE).

5.1. Experimental results

These results will show the behavior of the current control loop, for the same parameter variation, on the actual grid connected system. Figures 7 and 8 shows the PI controllers responses for d-axis reference step change from 1 A to 2 A for parameters calculated with Modulus optimum (a) and Ziegler-Nichols method (b). Actual waveforms of injected current can be seen in figure 9.

It can be seen that responses on an actual system are slower than on the simulation. The differences in experimental and simulation results came from the fact that simulation does not include every single element of the actual system. Some simplifications to the simulation process are made. Furthermore, some processes can't be represented with the simulation. On the other hand, some differences may arise as a result of the real time control, where processes like data acquisition and conversion were not part of the simulation process. This leads to the conclusion that certain manual corrections of the parameters are often needed for the particular system. Since the main objective to show is current control parameters influences, these response times are accepted, with no manual parameter adjustment. As proposed by the simulation, different topologies and parameter variations will lead to different THD.



Fig. 6. Advanced laboratory setup

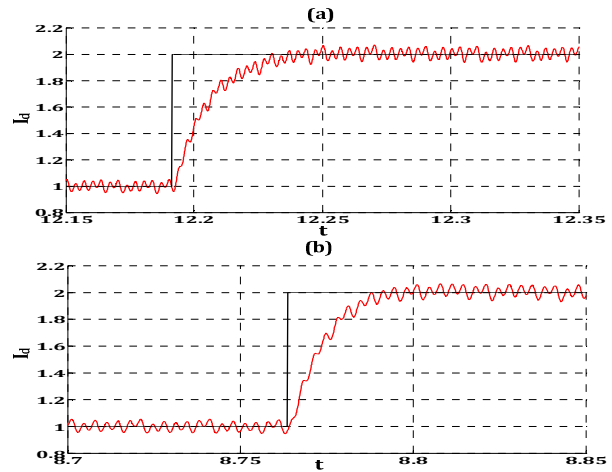


Fig. 7. Experimental PI controller response for Modulus optimum (a) and Ziegler-Nichols method (b)

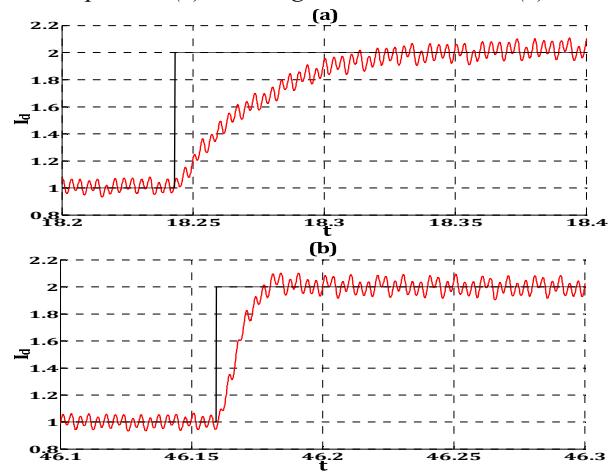


Fig. 8. Experimental PI incremental controller response for Modulus optimum (a) and Ziegler-Nichols method (b)

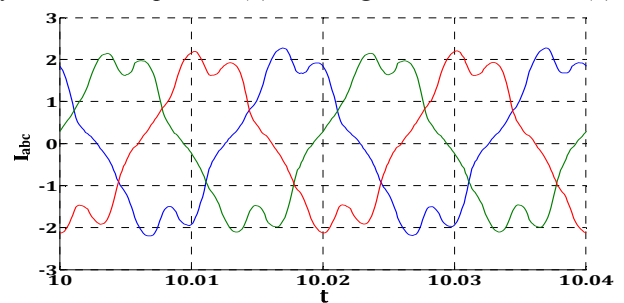


Fig. 9. Waveforms of injected grid currents

The reason for the high THD factor is the fact that the actual voltages are not ideal. The PLL emphasize the voltage distortion which results with a high 5th current harmonic [11]. That influence can be seen in figure 9. This can be lessened by using controller structures with harmonic compensation. Even so, as it can be seen in Table 3, different parameters can decrease the THD, thus influencing 5th current harmonic also. In addition, it can be observed that both simulation and the experiment showed that PI controller has lesser THD then incremental PI. Moreover, it is shown that PI controller favors Modulus optimum, whereas incremental form favors Ziegler-Nichols method. The influence of the parameters for both PI and incremental PI controller are higher on the actual system then in the simulation. Manual parameter variation could lead to even better results, as there still exists margin between actual and optimal system response.

Table 3. Current THD for different topologies and parameters (experiment)

Current THD	Modulus optimum	Ziegler-Nichols
PI	11.18 %	11.63 %
Incremental PI	18.63 %	17.77 %

6. CONCLUSION

As power electronic technology rises, so does the numbers of installed power electronic devices. For its influence on the power system, grid connected converter takes a key role. With the increase in numbers, power quality of the inverter becomes an important issue.

This paper investigated the influence of the current control topology and parameters on current THD. Due to the fact that satisfactory dynamic responses can be achieved with multiple control structures, and different parameter variation within the same structure, this paper showed how the choice of the two can lead to different THD for the grid currents. It can be seen that different parameters, obtained by the two proposed methods, can lead to noticeable influence on current THD. Also with manual parameter variation, this influence can be even higher. Different current control loops can have noticeable differences in current distortion as well, as shown in the experiment.

To conclude, the power quality can somewhat be influenced by adequately optimizing current control loop of the system. With the choice of optimal current controller and its parameters, sometimes even significant improvements on the current THD can be made. That can be done while maintaining the desired dynamic response characteristic.

7. ACKNOWLEDGEMENT

This paper is a result of the scientific project No. III 042004 of Integrated and Interdisciplinary Research entitled "Smart Electricity Distribution Grids Based on Distribution Management System and Distributed Generation", funded by Republic of Serbia, Ministry of Education and Science.

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