SINUSOIDAL ACTIVE FRONT END UNDER THE CONDITION OF SUPPLY DISTORTION

Milijana Odavic MSc.EE. [1)], Sasa Sladic B.Sc. [2)], Zeljko Jakopovic Ph.D. [3)]
[1,3)] Department of Electric Machines, Drives and Automation
University of Zagreb
Unska 3, 10000 Zagreb, Croatia
[2)] Technical Faculty Rijeka
University of Rijeka
Vukovarska 58, 51000 Rijeka
[1)] Phone (+385) 16219783, Fax (+385) 16129705, E-Mail: milijana.odavic@fer.hr www.fer.hr
[2)] Phone (+385) 51651440, Fax (+385) 51675818, E-Mail: sladics@riteh.hr, www.riteh.hr
[3)] Phone (+385) 16219804, Fax (+385) 16129705, E-Mail: zeljko.jakopovic@fer.hr www.fer.hr

Abstract. Sinusoidal active front end is used to achieve the controllable dc voltage at the output with the sinusoidal input current at unity power factor. In the real system supply voltage always contains lower harmonics, most commonly the 5th and the 7th harmonic. Therefore an analysis of the sinusoidal active front end under the power supply distortion here is presented. At the core of this paper is the performance of the synchronous PI current controller both during transients and in steady state operation. Simulation model of the sinusoidal active front end was made in SIMULINK environment and its accuracy was verified comparing the simulation and experimental results. The control algorithm was implemented on the experimental rig; Dspace board was used.

Keywords. Sinusoidal active front end, converter control, power factor correction, power quality.

1. INTRODUCTION

An increased number of power electronic equipments (typical non-linear loads) connected to the grid cause the decrease of power quality of the grid. Reduction of harmonic content in the input current of electrical consumers connected to the grid is maintained through IEC 555 standard in Europe [3]. Therefore, the electronic equipment with a small influence to the grid is getting more and more attention.

The aim of this paper is an analysis of the impact of the sinusoidal active front end to the grid. Vector control of the sinusoidal active front end was implemented. It can be considered as a dual problem to the vector control of induction machines so experiences from induction machine field can be used in power electronic field.

It was developed an appropriate simulation model based on the existing laboratory model. The validation of the simulation model was made through comparison of simulation and experimental system responses in dynamic as well as in steady state operating conditions. The comparison of simulation and experimental results was given in our previous work [2]. As can be seen from this comparison the developed simulation model can be used in further analyses and improvements of the analysed system.

Behaviour of the sinusoidal active front end connected to the grid and its influence to power quality were compared with diode front end connected to the grid via the same input inductors in the same operating conditions. The results of this comparison show an improvement of the sinusoidal active front end input current harmonic spectrum against the diode front end input current harmonic spectrum.
The experiment was made under the supply voltage distortion; measured supply voltage total harmonic distortion was 4,3%. In such conditions input current waveform of the tested sinusoidal active front end isn't sinusoidal. The waveform of the sinusoidal active front end input current is very close to the supply voltage waveform so total power factor is high.

In this paper simulation model is used to analyse the impact of the supply voltage distortion on the vector control of the sinusoidal active front end. Simulation results with the sinusoidal supply voltage were compared with the results when in the supply voltage 5th and 7th harmonic were injected.

2. MATHEMATICAL MODEL

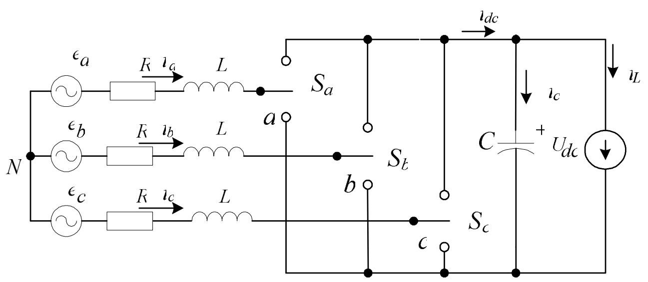

Fig. 1. Sinusoidal active front end topology

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The circuit of the sinusoidal front end (Fig.1.) consists of six fully controlled switches with anti-parallel diodes and three line inductors. Controlling the voltage across the line inductor controls the line current. The voltage across the line inductor can be controlled by measuring line voltage and by proper control of six switches to achieve desired voltage at the ac side of converter. To get unity power factor line current need to be in phase with line voltage so voltage across the line inductance need to lead line voltage by 90°.

Mathematical model of the sinusoidal front end (Fig. 1) can be written as:

$$\boldsymbol{u}(t)=\boldsymbol{e}(t)-L\cdot\frac{\mathrm{d}\boldsymbol{i}(t)}{\mathrm{d}t}-R\cdot\boldsymbol{i}(t) \tag{1}$$

$$i_{dc}(t)=C\cdot\frac{\mathrm{d}u_{dc}(t)}{\mathrm{d}t}+i_L(t) \tag{2}$$

, where $\boldsymbol{e}(t)=\begin{bmatrix}e_a(t) & e_b(t) & e_c(t)\end{bmatrix}^{\mathrm{T}}$ (3)

$$\boldsymbol{i}(t)=\begin{bmatrix}i_a(t) & i_b(t) & i_c(t)\end{bmatrix}^{\mathrm{T}} \tag{4}$$

In d-q reference frame (Fig. 2) rotating synchronously with the fundamental supply voltage frequency, equations (1) and (2) are:

$$\frac{\mathrm{d}i_d(t)}{\mathrm{d}t}-\omega\cdot i_q(t)=\frac{1}{L}\cdot\begin{bmatrix}-R\cdot i_d(t)+e_d(t)- \\ \frac{1}{2}\cdot d_d(t)\cdot u_{dc}(t)\end{bmatrix} \tag{5}$$

$$\frac{\mathrm{d}i_q(t)}{\mathrm{d}t}+\omega\cdot i_d(t)=\frac{1}{L}\cdot\begin{bmatrix}-R\cdot i_q(t)+e_q(t) \\ -\frac{1}{2}\cdot d_q(t)\cdot u_{dc}(t)\end{bmatrix} \tag{6}$$

According to the equations (5) and (6) a model of the line current plant in s-domain can be written as:

$$G(s)=\frac{i_d}{u_{Ld}}=\frac{i_q}{u_{Lq}}=-\frac{1/R}{1+s\cdot T} \tag{7}$$

, where u_{Ld} and u_{Lq} are d and q components of the voltage drop on the inductance L. Time constant of the plant is $T=L/R$

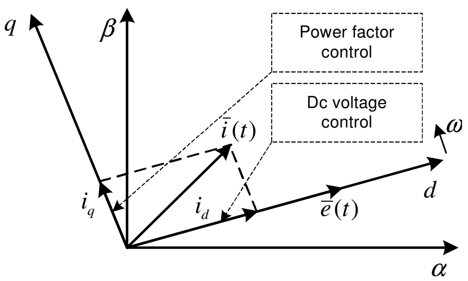


Fig. 2. Rotating d-q reference frame

Analysis of the voltage control loop is under the scope of this paper; analysis is made under the assumption that the voltage on the dc side of converter is constant. Equivalent circuit for voltage control loop is given in [1].

3. CURRENT CONTROL LOOP

Many different control strategies of the sinusoidal active front end have bee developed [1]. Here is used vector control in cascaded structure; current control as inner and voltage control as outer control loop. System dynamic performance is dependent of the inner line current control loop. The output of dc voltage PI controller is the d component of line current reference.

In current control loop PI controller is used, the optimization of PI parameters is made to achieve fast response for step change in current reference. For current control loop d-q reference frame rotating synchronously with fundamental supply voltage frequency is used. The line currents (i_a, i_b, i_c) are measured and transformed to d-q reference frame. To get the information about the position of line voltage vector PLL (phase locked loop) is implemented. PI controllers for d and q components of line current are identical; ωL terms are included to eliminate the coupling effect among the d and q components (equations 5 and 6). The outputs of line current PI controllers present d and q components of voltage across the line inductance. Subtracting this voltage from supply voltage gives the converter voltage from ac side that is used as modulation signal for proper switching of six switching devices. In d-q reference frame rotating synchronously with supply voltage the vector of fundamental harmonic has constant d and q components while the vectors of higher harmonics have pulsating d and q components.

The main task of the sinusoidal front end is to operate with sinusoidal line current; so d and q components of line current reference are dc values. Using this approach of control it is possible to control the output voltage of converter as well as the power factor of converter in the same time.

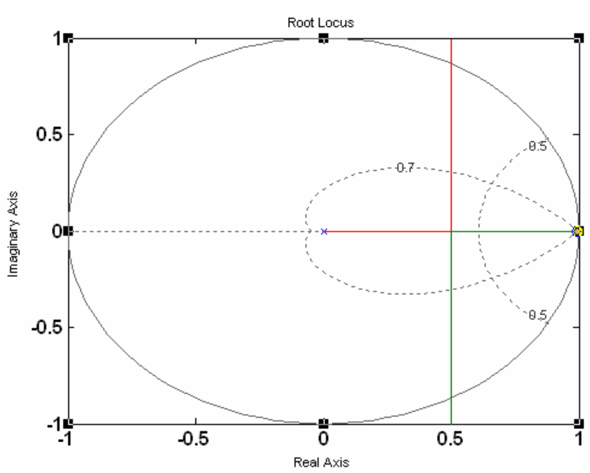


Fig. 3. Root locus of current control loop

To achieve unity power factor the reference of *q* current component need to be set on zero. So if synchronous PI controller is used controllable variables are dc values so static error can be eliminated.

Implemented controllers are discrete-time systems, while the controlled plant is analogue. Therefore the plant is connected to the controller by A/D and D/A converters. Two basic ways can be used for controller design. The first strategy is based on the analogue system model; the controller design is carried out in the continuous domain including a delay caused by A/D conversion [1]. The second approach uses discrete system model and design procedure is done on the discrete time domain. Plant model converted to the discrete-time domain contains a delay of half of sampling time caused by ZOH method of discretization.

The transfer function (equation 7) of line current plant in z – domain using ZOH method is:

$$G(z) = \frac{0.02}{z - 0.994} \tag{8}$$

with sampling time T_s= 200µs.

PI controller of the line current is chosen so to eliminate dominant pole of the plant. The transfer function of PI controller of line current is:

$$C(z) = \frac{z - 0.994}{z - 1} \tag{9}$$

The gain of the line current controller is determined using root locus technique. Root locus of the closed current loop with included one processing delay is presented on the figure 3. The gain of PI current controller is chosen to achieve damping ξ=0.7 (Fig. 4. and Fig. 5).

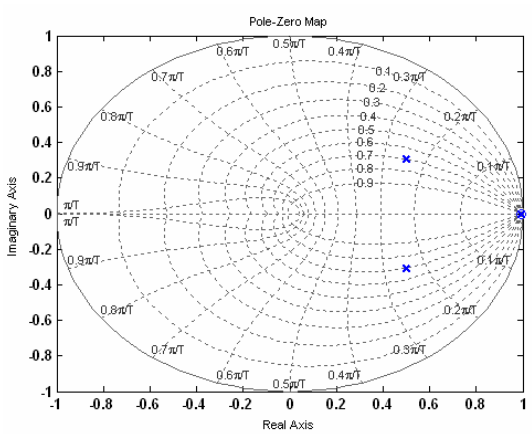


Fig. 4. Pole-zero placement of closed current control loop

The achieved bandwidth of the line current control loop is 638 Hz (Fig.6). The design procedure of line current controller for sinusoidal front end can be easily adjusted for shunt active filter applications. The only difference is in current reference generation. In d-q reference frame shunt active filter references are sinusoidal varying waveforms. The most common injected harmonics in the point of connecting are 5th and 7th harmonics. These harmonics in d-q reference frame appears as sinusoidal waveforms with the frequency of 300 Hz. Therefore for the applications of active filtering the demand for high bandwidth of current control loop is more critical.

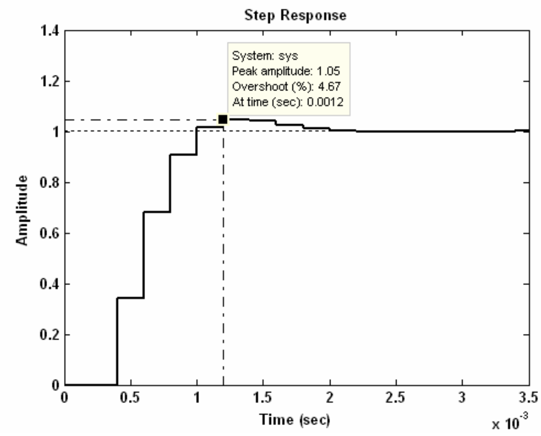


Fig.5. Step response of closed current control loop

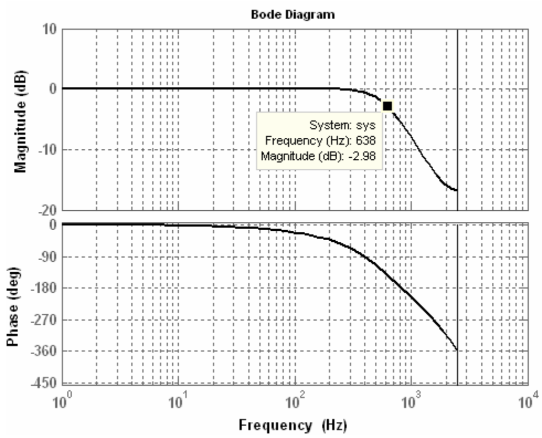


Fig. 6. Bode diagram of closed current control loop

4. SINUSOIDAL SUPPLY VOLTAGE

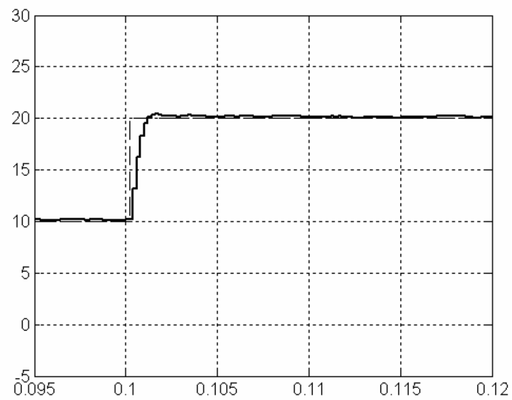


Fig. 7. Step response of d component of line current with sinusoidal supply voltage

Simulation model is used for testing the vector control algorithm of the sinusoidal front end with sinusoidal supply voltage. From the simulation results (Fig.7 and Fig.8) it can be seen that current control loop itself doesn't introduce any harmonics.

The control of active power is achieved by controlling the *d* component of line current; in conditions of sinusoidal supply voltage this is the dc value and by adopting PI controller steady state error can easily be eliminated. Reactive component of power is controlled by the *q* component of line current; to achieve unity power factor *q* component of line current need to be set to zero.

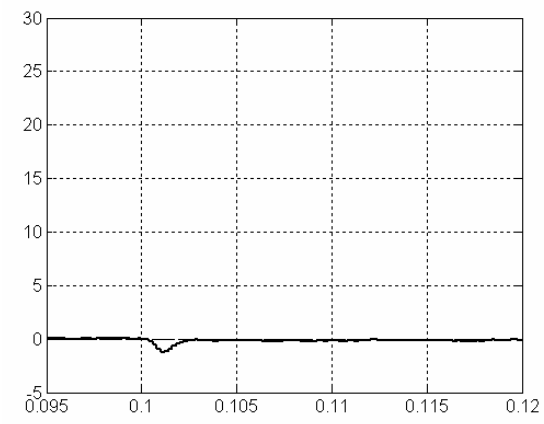


Fig. 8. Step response of q component of line current with sinusoidal supply voltage

5. SUPPLY VOLTAGE DISTORTION

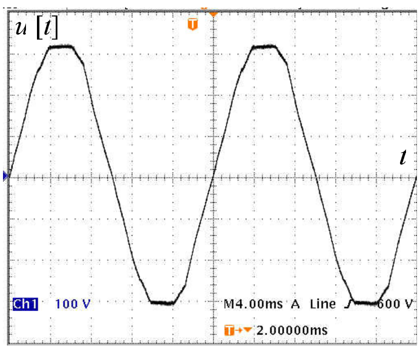


Fig. 9. Supply voltage

Harmonic analysis of the supply voltage at the point of converter connection was made (Fig 9.). It was measured 3.37% of fifth and 1.37% of seventh harmonic. This supply voltage distortion introduces large fifth and seventh harmonic currents; the magnitude of this distortion is determined by the magnitude of the fifth and seventh harmonic voltage of the supply, the impendance of the line inductors and the bandwidth of the current control loop.
The influence of supply distortion on the applied vector control of sinusoidal front end can be seen on the figures 10 and 11. It can be seen from these waveforms that *d* and *q* components of line current contain 6th harmonic due to 5th and 7th harmonics in supply voltage. It should be noted that distortion of line current caused by the supply distortion is independent of the magnitude of current drawn by the converter. Therefore this current distortion will be more noticeable at lower power. Decrease of THD (total harmonic distortion) of line current caused by supply distortion can be improved by adopting the feed forward term in current control loop [4].

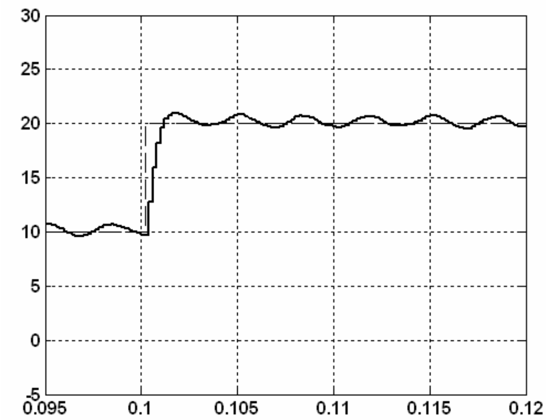


Fig. 10. Step response of *d* component of line current with supply voltage distortion

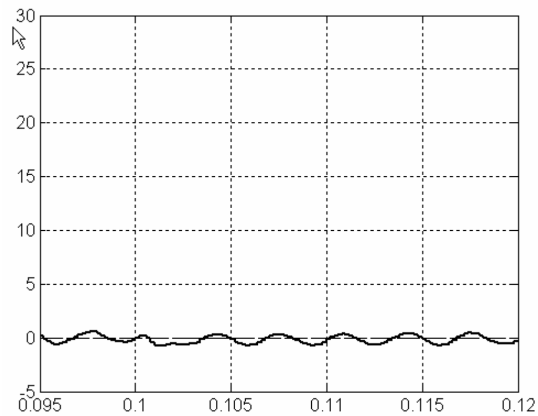


Fig. 11. Step response of *q* component of line current with supply voltage distortion

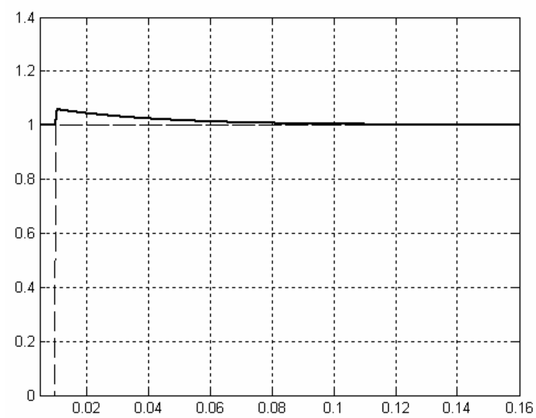
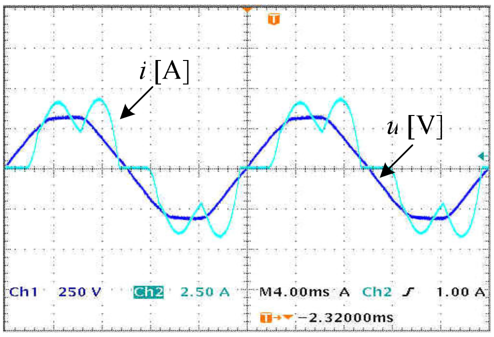


Fig. 12. Current control loop response for a step disturbance

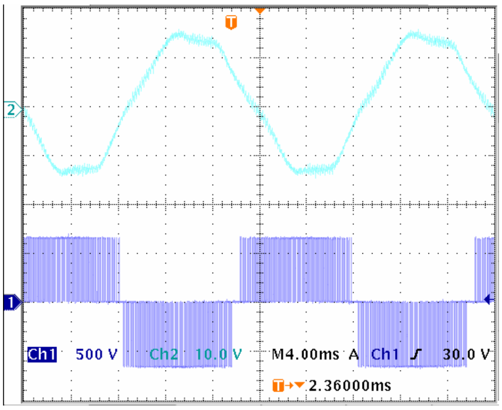
The current controller has been optimised to follow the reference current as fast as possible. This makes it easily affected by disturbances. Figure 12 presents the behaviour of the designed current control loop when the disturbance is introduces into the loop before the plant mode.

6. EXPERIMENTAL RESULATS

The experimental rig consists of the universal IGBT converter (20 kVA, 800 V) connected to the grid (220V, 50Hz) via input inductors (10mH). Sampling frequency is the same as switching frequency (5 kHz). In order to get control signals for six IGBT switches, Dspace controller board was used. The advantage of used controller board is the possibility of control algorithm developing in SIMULINK environment.



a)



b)

Fig. 13. Experimental waveforms a) input current (light blue) and line voltage (dark blue) of diode front end with input inductor b) input current (light blue) and input voltage of sinusoidal active front end

Comparing the results of diode front end line current and sinusoidal active front end line current, THD (total harmonic distortion) was improved from 30% to 10%. The transient responses of tested sinusoidal front end for the step changes in reference and disturbances are given in our previous work [2]. The measured line current (Fig. 13b) contains the 5^{th} and the 7^{th} harmonics that also present dominant lower harmonics in the supply voltage.

7. CONCLUSION

The influence of power supply distortion on vector control of the sinusoidal active front end was analysed using the developed simulation model. The results of this analysis show that lower harmonics in line current of the sinusoidal front end are caused by supply distortion.

One of the possible solutions to improve the behaviour of sinusoidal front end in such conditions is adopting the feed forward term in current control loop.

Also it was shown that the line current controller designed to follow the reference current as fast as possible, couldn't effectively eliminate disturbances introduced into loop.

8. REFERENCES

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