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Predictive Control of Grid-Connected Multilevel Inverter with Output LCL Filter

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***Abstract*—The paper deals with a control of a multilevel grid connected photovoltaic inverter with an LCL output filter. A proposed control technique uses the dynamical model of the LCL filter and ensures inherent active damping of the LCL filter oscillations. The inverter is a one-phase cascade H-bridge inverter with three galvanically separated DC sources and the model predictive control is used as a control technique. A Kalman observer is used to minimize the number of required sensors. Only the grid current and the grid voltage measurements are needed. The model predictive control ensures active damping for the LCL filter. This removes the need for a passive damping of the LCL filter and increases overall system efficiency. The design of the model predictive controller as well as the design of the Kalman observer is presented. The proposed control technique is verified by simulations and measurements on the laboratory model.**

***Index Terms*—Active damping, Kalman observer, LCL filter, model predictive control, multilevel inverter.**

I. INTRODUCTION

Multilevel inverters are enabling technology for high voltage high power applications mainly after 1990s when they become mature technology [1], [2]. However multilevel inverters have several advantages which are interesting even for low power applications. The quality of the grid current and reliability of the inverter are, among others, important parameters for grid connected photovoltaic (PV) inverter. Multilevel inverters with their lower voltage stresses, lower du/dt, lower switching frequency, lower harmonic distortion and better electromagnetic compatibility with reduced requirements for output filter [3] are interesting alternative for PV inverter.

The high performance output filter of the PV inverter is required to fulfill the grid code standards. Usually some higher-order filter such as LCL filter are used in PWM inverters [4]–[7]. Despite the high attenuation of higher-order harmonics produced by the PWM inverter, the LCL filter may become instable when excited on resonance frequencies. Thus it is required to use a damping technique to suppress those resonances. In order to increase the efficiency of the PV inverter it is advisable to use the active damping of the LCL filter [1], [5], [8].

Modern fast control systems such as DSP allow using of advanced control techniques in digital form. These modern control techniques often incorporate the model of the control system [2], [6], [9] allowing online calculations of the control law. One of the model based control techniques is model predictive control (MPC). The optimal control move is computed on-line by solving an open-loop optimization problem at each sampling time in opposite to the pre-computed control law such as PI control where the closed-loop performance is considered [10]. Advanced control techniques based on the model of the system are widely used in many areas such as sensorless control of an induction motor [2], grid connected converters [8], sensorless control of PMSM [9] and many other [11]. The advantage of the model predictive control is that it can stabilize unstable systems such as the LCL filter.

For model control it is required to know the exact state of the system in every sampling instant. One can either measure all state variables, but this approach requires several sensors. To avoid this problem it is possible to use observers and estimators [2], [9].

II. SYSTEM MODEL

The controlled system consists of a grid-connected 15-level one-phase cascade inverter with the LCL output filter [12]. The required mathematical model depends on the used control set. The MPC can be implemented with continuous or discrete control set. The continuous control set was chosen. This control technique requires using of the modulator. But on the other hand it has fixed switching frequency when compared to the discrete control set. This approach does not require the exact switching model of the inverter. The time delay of the inverter is negligible due to the high frequency PWM. However, it is necessary to focus on the discrete model of the LCL filter.

A. LCL Filter Model

The LCL filter is a dynamic system of the third order (Fig. 1). Due to the possible resonance of the LCL filter it is necessary to use a damping technique. The active damping was chosen to suppers the resonance of the LCL filter at the resonant frequency defined by (1)

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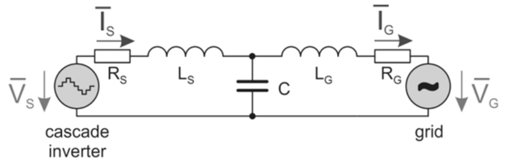
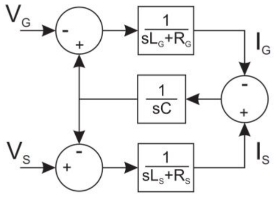
$$f_{0I_G V_S} = \frac{1}{2\pi}\sqrt{\frac{L_S + L_G}{L_S L_G C}}. \tag{1}$$

The design of the LCL filter for the cascade inverter is a complex task. The design guide can be found e.g. in [12].



(a)



(b)

Fig. 1. LCL filter topology and its dynamic model.

For easier control design and tuning it is desirable to control the PV inverter in rotating reference frame d-q. The continuous time state space description of the LCL filter in d-q reference frame is defined by (2):

$$\begin{cases} \begin{bmatrix} sI_{Gd} \\ sI_{Gq} \\ sI_{Sd} \\ sI_{Sq} \\ sV_{Cd} \\ sV_{Cq} \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{R_G}{L_G} & \mu & 0 & 0 & \frac{1}{L_G} & 0 \\ -\mu & -\frac{R_G}{L_G} & 0 & 0 & 0 & \frac{1}{L_G} \\ 0 & 0 & -\frac{R_S}{L_S} & \mu & -\frac{1}{L_S} & 0 \\ 0 & 0 & -\mu & -\frac{R_S}{L_S} & 0 & -\frac{1}{L_S} \\ -\frac{1}{C} & 0 & \frac{1}{C} & 0 & 0 & \mu \\ 0 & -\frac{1}{C} & 0 & \frac{1}{C} & -\mu & 0 \end{bmatrix}}_{\mathbf{A}_{Cdq}} \begin{bmatrix} I_{Gd} \\ I_{Gq} \\ I_{Sd} \\ I_{Sq} \\ V_{Cd} \\ V_{Cq} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_S} & 0 \\ 0 & \frac{1}{L_S} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}}_{\mathbf{B}_{Cdq}} \begin{bmatrix} V_{Sd} \\ V_{Sq} \end{bmatrix} + \underbrace{\begin{bmatrix} -\frac{1}{L_G} & 0 \\ 0 & -\frac{1}{L_G} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}}_{\mathbf{E}_{Cdq}} \begin{bmatrix} V_{Gd} \\ V_{Gq} \end{bmatrix}, \\ \overline{y} = \underbrace{\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{C}_{Cdq}} \begin{bmatrix} I_{Gd} \\ I_{Gq} \\ I_{Sd} \\ I_{Sq} \\ V_{Cd} \\ V_{Cq} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{D}_{Cdq}} \begin{bmatrix} V_{Gd} \\ V_{Gq} \\ V_{Sd} \\ V_{Sq} \end{bmatrix}. \end{cases} \tag{2}$$

The discrete time model A_{Ddq}, B_{Ddq}, E_{Ddq}, C_{Ddq}, D_{Ddq} is derived using the forward Euler rule applied to (2).

III. Model Predictive Control

Model predictive controller (MPC) is a controller with a system model and a feedback. The system model is used to predict the system state. The MPC is the most widely used advanced control technique nowadays.

The principle of the MPC is shown in Fig. 2.

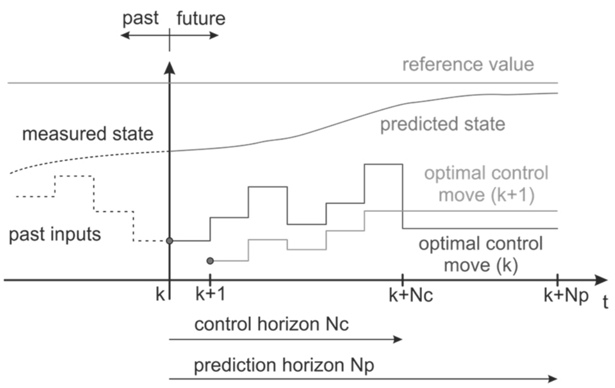


Fig. 2. Control with receding horizon.

At time instant kT the online optimization problem is solved on prediction horizon N_P and control horizon N_C and the series of optimal control moves is calculated. Only the first control move is used and the whole optimization problem is solved again at time *(k+1)T*.

The significant advantage of the MPC controller is that it can stabilize the unstable LCL filter without implementation of any further active damping technique.

A. Prediction Model

The prediction model is used in the augmented form (3) [13]. The addition of the integrator ensures zero steady state error for step changes of the reference value of the grid current I_g:

$$\begin{cases} \underbrace{\begin{bmatrix} \Delta\mathbf{x}(k+1) \\ \mathbf{y}(k+1) \end{bmatrix}}_{\mathbf{x}(k+1)} = \underbrace{\begin{bmatrix} \mathbf{A}_{\mathbf{D}dq} & \mathbf{0}^T \\ \mathbf{C}_{\mathbf{D}dq}\mathbf{A}_{\mathbf{D}dq} & 1 \end{bmatrix}}_{\mathbf{A_{dd}}} \underbrace{\begin{bmatrix} \Delta\mathbf{x}(k) \\ \mathbf{y}(k) \end{bmatrix}}_{\mathbf{x}(k)} + \\ + \underbrace{\begin{bmatrix} \mathbf{B}_{\mathbf{D}dq} \\ \mathbf{C}_{\mathbf{D}dq}\mathbf{B}_{\mathbf{D}dq} + \mathbf{D}_{\mathbf{D}dq} \end{bmatrix}}_{\mathbf{B_{dd}}} \Delta\mathbf{u}(k), \\ \mathbf{y}(k) = \underbrace{\begin{bmatrix} \mathbf{0} & 1 \end{bmatrix}}_{\mathbf{C_{dd}}} \begin{bmatrix} \Delta\mathbf{x}(k) \\ \mathbf{y}(k) \end{bmatrix}. \end{cases} \tag{3}$$

System response in time for series of control moves *u(k)* without external error is defined by (4)

$$\begin{bmatrix} \mathbf{y}(k|k) \\ \mathbf{y}(k+1|k) \\ \mathbf{y}(k+2|k) \\ \vdots \\ \mathbf{y}(k+N_P|k) \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{C_{dd}} \\ \mathbf{C_{dd}A_{dd}} \\ \mathbf{C_{dd}A_{dd}^2} \\ \vdots \\ \mathbf{C_{dd}A_{dd}^{N_P}} \end{bmatrix}}_{\mathbf{F}} \mathbf{x}(k|k) +$$

$$+\underbrace{\begin{bmatrix} \mathbf{D_{dd}} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{C_{dd}B_{dd}} & \mathbf{D_{dd}} & \cdots & \mathbf{0} \\ \mathbf{C_{dd}A_{dd}B_{dd}} & \mathbf{C_{dd}B_{dd}} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C_{dd}A_{dd}^{N_P\text{-}1}B_{dd}} & \mathbf{C_{dd}A_{dd}^{N_P\text{-}2}B_{dd}} & \cdots & \mathbf{C_{dd}A_{dd}^{N_P\text{-}N_c}B_{dd}} \end{bmatrix}}_{\mathbf{S}} \times$$

$$\times \begin{bmatrix} \Delta\mathbf{u}(k|k) \\ \Delta\mathbf{u}(k+1|k) \\ \Delta\mathbf{u}(k+2|k) \\ \vdots \\ \Delta\mathbf{u}(k+N_c-1|k) \end{bmatrix}. \tag{4}$$

The control goal is to minimise the control error on prediction horizon N_P based on the system state *x(k)* at time *kT* and the reference value *r(k)* at time *kT*. The goal of the MPC is to minimise the cost function. The cost function in matrix form can be expressed by (5)

$$J(k) = \left(\tilde{\mathbf{y}}_\mathbf{k} + \mathbf{S}\Delta\mathbf{u_k} - \mathbf{r_k}\right)^T \mathbf{Q}\left(\tilde{\mathbf{y}}_\mathbf{k} + \mathbf{S}\Delta\mathbf{u_k} - \mathbf{r_k}\right) + \\ + \Delta\mathbf{u_k^T R}\Delta\mathbf{u_k}, \tag{5}$$

where $\mathbf{r}_k$ – is vector of reference values on *Np*, $\tilde{\mathbf{y}}_\mathbf{k}$ – is vector of the free system response, $\mathbf{S\Delta u_k}$ – is vector of the system response to control moves, **Q** – is weight positive-definite diagonal state matrix, **R** – is weight positive-definite diagonal control move matrix.

After derivation of (5) *dJ/du* the optimal control move vector $\mathbf{u_k}$ on prediction horizon N_P is (6)

$$\mathbf{u_k^*} = -\left(\mathbf{S}^T\mathbf{QS} + \mathbf{R}\right)^{-1}\left[\mathbf{S}^T\mathbf{Q}\left(\tilde{\mathbf{y}}_\mathbf{k} - \mathbf{r_k}\right)\right]. \tag{6}$$

Equation (6) in more compact form is (7)

$$\mathbf{u_k^*} = -\mathbf{Mx}(k) + \mathbf{Gr_k}, \tag{7}$$

with matrixes **M** and **G**:

$$\mathbf{M} = \left(\mathbf{S}^T\mathbf{QS} + \mathbf{R}\right)^{-1}\mathbf{S}^T\mathbf{QF}, \tag{8}$$

$$\mathbf{G} = \left(\mathbf{S}^T\mathbf{QS} + \mathbf{R}\right)^{-1}\mathbf{S}^T\mathbf{Q}. \tag{9}$$

Because only the first control move is applied just the first element of the vector $\mathbf{u_k}$ is considered (10)

$$\mathbf{u}^*(k) = -\mathbf{K_x x}(k) + \mathbf{K_r r}(k), \tag{10}$$

with matrixes $\mathbf{K_x}$ and $\mathbf{K_r}$:

$$\mathbf{K_x} = \mathbf{m_1^T}, \tag{11}$$

$$\mathbf{K_r} = \left[\mathbf{C_d}\left(\mathbf{I} - \mathbf{A_d} + \mathbf{B_d K_x}\right)^{-1}\mathbf{B_d}\right]^{-1}. \tag{12}$$

IV. KALMAN OBSERVER

The MPC controller needs to know the exact state of the system. If this information is not available it needs to be observed. The Kalman observer is suitable for stochastic systems (e.g. deterministic system with process noise).

The dynamical system is described by (13):

$$\begin{cases} \mathbf{x}(k+1) = \mathbf{A_D x}(k) + \mathbf{B_D u}(k) + \mathbf{E_D z}(k) + \mathbf{G_D w}(k), \\ \mathbf{y}(k) = \mathbf{C_D x}(k) + \mathbf{D_D u}(k) + \mathbf{H_D w}(k) + \mathbf{K_D v}(k). \end{cases} \tag{13}$$

It is a classical representation of a discrete time-invariant system with measured error ($\mathbf{A_D}$, $\mathbf{B_D}$, $\mathbf{C_D}$, $\mathbf{D_D}$, $\mathbf{E_D}$) influenced by process noise ($\mathbf{G_D}$, $\mathbf{H_D}$) and sensor noise ($\mathbf{K_D}$).

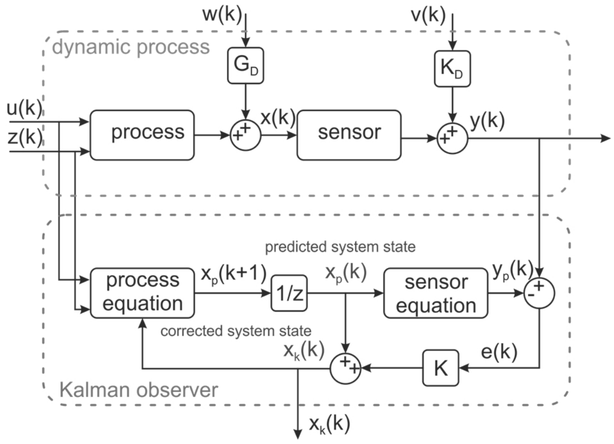


Fig. 3. Structure of Kalman observer.

The auto-covariance process noise matrix $\mathbf{Q_K}$ and the auto-covariance sensor noise matrix $\mathbf{R_K}$ are defined. The output of the Kalman observer is the vector of observed system state $\mathbf{x_k}$ (k) defined by (14)

$$\mathbf{x_k}(k) = \mathbf{x_p}(k) + \mathbf{Ke}(k). \tag{14}$$

The static Kalman gain matrix **K** is defined by (15)

$$\mathbf{K}(k) = \mathbf{P_p}(k)\mathbf{C_D^T}\left[\mathbf{C_D P_p}(k)\mathbf{C_D^T} + \mathbf{R_K}\right]^{-1}. \tag{15}$$

The auto-covariance matrix of the prediction $\mathbf{P_P}$(k) is calculated in the previous step (16)

$$\mathbf{P_p}(k+1) = \mathbf{A_D P_k}(k)\mathbf{A_D^T} + \mathbf{G_D Q_K G_D^T}, \tag{16}$$

and the auto-covariance matrix of the state estimate is (17)

$$\mathbf{P}_k(k) = \left[\mathbf{I} - \mathbf{K}(k)\mathbf{C_D}\right]\mathbf{P_p}(k). \tag{17}$$

To tune the Kalman observer it is needed to change the auto-covariance matrixes $\mathbf{Q_K}$ and $\mathbf{R_K}$. The sensor noise auto-covariance matrix $\mathbf{R_K}$ can be calculated based on the sensor measurement of the random variable. However the process noise auto-covariance matrix $\mathbf{Q_K}$ cannot be easily calculated and often needs to by tune by trail-error method.

In the real system only the grid current I_g is measured and the inverter current I_s and the capacitor voltage V_C are observed.

V. THE LABORATORY SETUP

The controlled dynamic system consists of a one phase grid-connected cascade H-bridge inverter created by three H-bridge inverters connected in series at its output [14]. The H-bridge inverters are supplied by three galvanically isolated voltage sources U_A = 120 V, U_B = 60 V and U_C = 30 V. The switching frequency is 5 kHz and the opposition disposition modulation technique was used. The output LCL filter parameters are described in Table I. The system is controlled in the rotating reference frame d-q. The control structure of the system is shown in Fig. 6

TABLE I. PARAMETERS OF THE LCL FILTER AND INVERTER.

Parameter	Symbol	Value
Apparent power	S	1.2 kVA
Switching frequency	f_{SW}	5 kHz
Inverter side inductor	L_S	2.11 mH
Grid side inductor	L_G	1.03 mH
Capacitor	C	9.14 µF
Resistance of L_G	R_G	33 mΩ
Resistance of L_S	R_S	63 mΩ
First H-bridge DC link	U_A	120 V
Second H-bridge DC link	U_B	60 V
Third H-bridge DC link	U_C	30 V

The one-phase grid voltage V_g is sensed and the virtual two-phase system in stationary reference frame ($V_{g\alpha}$, $V_{g\beta}$) is created. The grid phase is detected by a PLL circuit. The one-phase grid current at the output of the LCL filter is sensed. Than the virtual two-phase system in stationary reference frame ($I_{g\alpha}$, $I_{g\beta}$) is created.

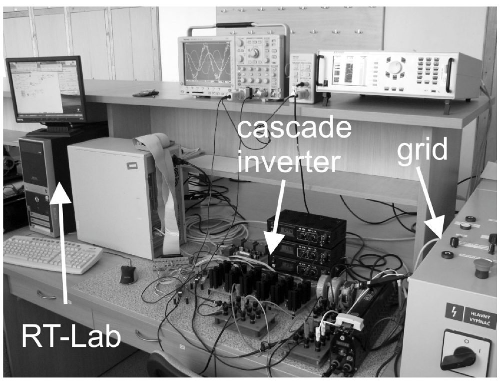


Fig. 4. The laboratory setup.

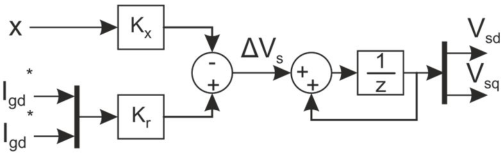


Fig. 5. MPC controller structure.

The grid current in the stationary reference frame is converted to rotating reference frame (I_{gd}, I_{gq}). Because only one state variable of the LCL filter (the output current I_g) is measured, the Kalman observer is used to reconstruct the missing two state variables: the inverter side current I_S and the capacitor voltage V_C. The full state of the LCL filter is fed to the MPC controller which creates the compensating inverter voltages in the rotating reference frame (V_{sd}, V_{sq}). Next the voltages are summed with the grid voltage and are transformed into the stationary reference frame. Then only the $V_{s\beta}$ voltage is used to control the modulator of the multilevel inverter.

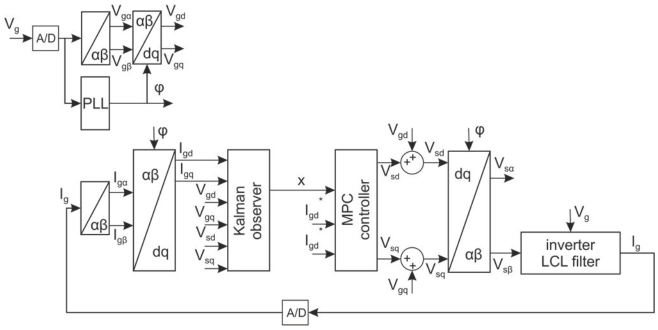


Fig. 6. Control structure in the rotating reference frame.

The structure of the MPC controller is shown in Fig. 4. The Fig.4 is described by (10).

The parameters of the MPC controller and the Kalman observer are shown in Table II.

TABLE II. PARAMETERS OF THE PI CONTROLLER.

Parameter	Symbol	Value
Prediction horizon of the MPC	N_P	10
Control horizon of the MPC	N_C	3
Matrix Q of the MPC	**Q**	$10*I_{20}$
Matrix R of the MPC	**R**	$0.3*I_6$
Auto-covariance process noise matrix	$\mathbf{Q}_K$	$\begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix}$
Auto-covariance sensor noise matrix	$\mathbf{R}_K$	$0.1*I_2$
Kalman gain	**K**	$\begin{bmatrix} 0.7389 & 0 \\ 0 & 0.7389 \\ 0.2420 & 0.0012 \\ 0.0012 & 0.2420 \\ 1.8341 & -0.0174 \\ -0.0174 & 1.8341 \end{bmatrix}$
Sampling period	T	200 µs

A. Simulation Results

First the performance of the controller (Fig. 6) was simulated using MATLAB/Simulink. The grid voltage was set to 120 V/50 Hz. The simulation results for step change of I_{gq} are shown in Fig. 7 and Fig. 8. The I_{gd} current reference was held constant and the I_{gq} reference was stepped.

The initial oscillation of current is caused by a virtual two phase generator with second order filter. If the control system was used for a three-phase system this oscillation would not be presented.

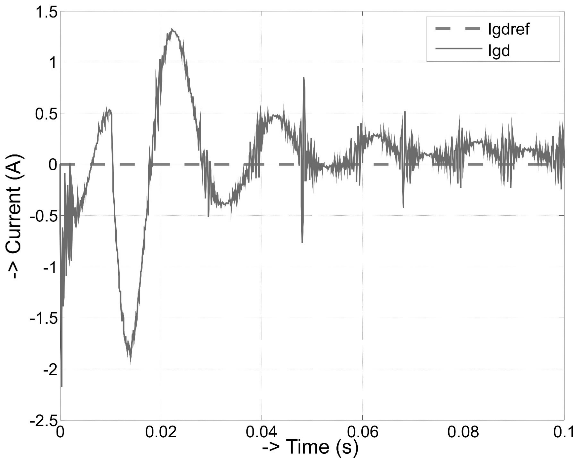


Fig. 7. The simulated reference and actual value of I_{gd} for step change in I_{gq} in 0.01 s from 0 A to 6 A.

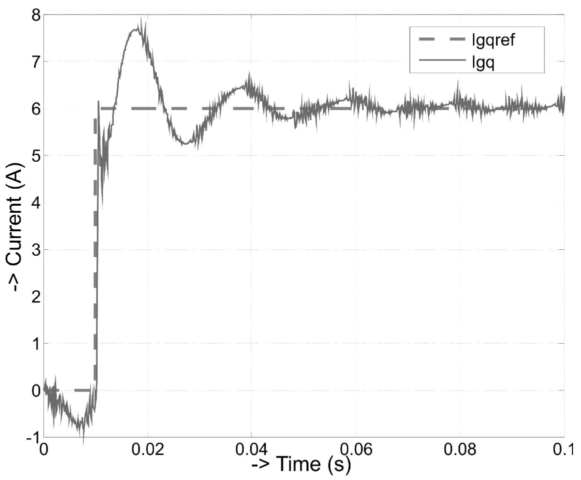


Fig. 8. The reference and actual value of I_{gq} for step change in I_{gq} in 0.01 s from 0 A to 6 A.

Even though there is no additional active or passive damping technique used, the LCL filter is stable. This is the natural consequence of the MPC controller.

B. Measurement Results

The laboratory model of the one-phase grid-connected 15-level cascade H-bridge inverter with the output LCL filter was built with parameters shown in Table I. The system was controlled by RT-Lab with DAQ card. The master computer and the DAQ card have no hardware ability to generate the multilevel PWM. Thus the Texas Instrument DSP TMS320F28335 was used to generate the PWM. Even though the DSP had the sampling time of 10 μs, the PWM modulator had low resolution. The other parameters were the same as in the simulation.

The measured results are shown in Fig. Felektr9 and Fig. 10. The measurements are unfiltered real results from the LEM current sensor output sensed by the computer DAQ card. The I_{gd} current reference was held constant and the I_{gq} reference was stepped. The measurements show two major results.

The first one is that the LCL filter is stable even for step changes of the grid current. Only one current sensor (grid current I_g) and one voltage sensor (grid voltage V_g) are needed to stabilize the LCL filter. This is the significant advantage of the suggested control technique.

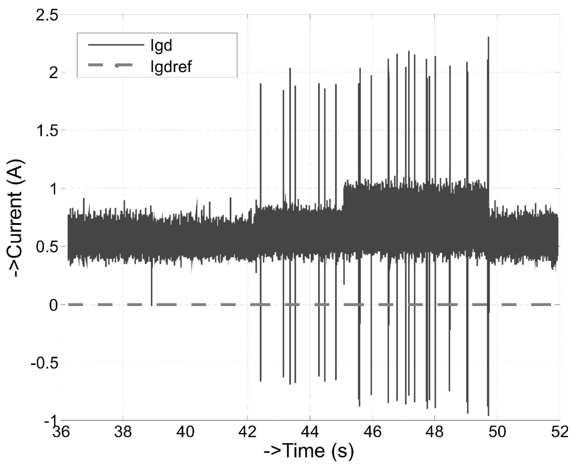


Fig. 9. The measured reference and actual value of I_{gq} for step change in I_{gq} from 0 A to 3 A.

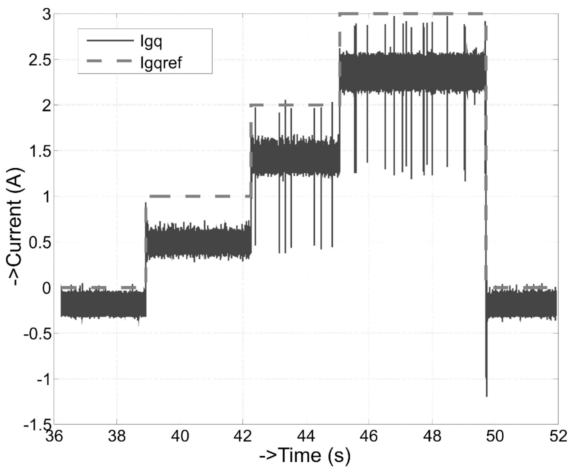


Fig. 10. The measured reference and actual value of I_{gq} for step changes in I_{gq} from 0 A to 3 A.

The second one is the difference between the reference and the actual values of currents. The MPC controller relays on the dynamical model of the system. The dynamical model of the LCL filter is defined by (2). However after connection of the LCL filter to the grid, the dynamical model is influenced by the grid inductance, which is now a part of the system. This will result in a steady state error in the grid current which can be seen in Fig. 9 and Fig. 10. The scaling of the system matrix A_{Cdq} does not help. For the model predictive control it is necessary to know the exact parameters of the controlled system. The identification of the grid parameters needs to be added to the control system. This complicates the design of the controller but allows using of the multilevel inverter without tuning for any particular grid connection.

VI. CONCLUSIONS

The paper presents model predictive control technique for the one-phase grid-connected cascade inverter with the output LCL filter. The suggested control technique requires only measuring of the grid voltage and the grid current which minimizes sensor costs. The control technique also provides natural active damping for the LCL filter which enables to increase the overall efficiency of the system. The biggest disadvantage of the proposed control technique is a need for exact system model, mainly the LCL filter and grid model. To ensure zero steady state error it is needed to add the grid parameters identification to the control system. It will be a part of the next work.

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