Robust Set-Based Predictive Control for Grid-Tied Inverter with LCL Filter

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***Abstract*—This paper presents a robust set-based model predictive current control algorithm for grid-tied inverter with an LCL filter. Taken into consideration are variations in grid frequency and grid impedance, as well as uncertainties in the LCL filter parameters which are modeled in polytopic linear parameter varying framework. A robust state feedback gain based on H_∞ and regional pole placement constraints is synthesized solving a linear matrix inequality (LMI) problem, using this gain robust positively invariant terminal set is computed. From the terminal set, a family of control invariant sets is computed offline. Optimization problem is solved online subject to invariant sets membership constraint steering the states of the system to terminal set in finite time. Control algorithm is tested in simulation under grid frequency disturbance and various power loads.**

***Keywords*—power converters, model predictive control, finite control set, robust control**

I. Introduction

In the last two decades controlling the power converters using model predictive control has been widely used [1], [2]. Two approaches that are seen in use are continuous-control set (CCS-MPC) and finite-control set (FCS-MPC) model predictive control. Control based on CCS-MPC solves and minimization problem on a finite horizon result of which is a continuous control signal that then applied to the converter using a modulator. Opposite to CCS-MPC, a FCS-MPC uses the fact that power converters have a fixed number of switching states by using simple brute force algorithms to find the switching state with minimal error and then applies it to the converter.

To ensure the stability and efficiency of inverters using the FCS-MPC approach additional care has to be taken as the optimization algorithm implemented only finds a suboptimal solution due to the finite set of control actions, such as estimating the error of a suboptimal control action and modelling it as a disturbance to the system [3]–[5]. Other approaches propose lengthening the control horizon but this in turn might pose an untractable problem if naive algorithms are used. To remedy this advanced search algorithms need to be used [6], [7].

The LCL filters are designed to be used at a constant switching frequency [8] which gives further advantage to the CCS-MPC approach, together with the ability to work with different systems and power levels [9].

Set invariance in control is well-established topic [10]. To represent control invariant sets in computer memory pollyhedral or ellipsoidal approximations are used. Polyhedral approximations give larger regions of attraction but their representation in memory is cumbersome and the computational cost very high or even untractable considering the fast dynamics of power inverters. Aprroximating invariant sets with ellipsoidal sets reduces this cost significantly, but at the cost of smaller regions of attraction.

Power inverters linked to LCL filters require a robust control design to deal with preturbations in filter parameters [11]. To address this problem in an unified and systematic way linear polytopic models with a LMI state feedback control have been sucessfuly used [12], [13].

In this paper a robust model predictive control algorithm for controlling a grid connected inverter with an LCL filter we presented in our previous work is extended. To address the uncertainties in filter parameters, the change in grid impedance or frequency, we formulated a linear parameter varying mathematical model. Robust ellipsoidal approximations of invariant sets are computed offline, first a robust feedback gain is synthesized form which we compute a robust terminal set, then from the terminal set family of ellipsoids is obtained. On-line the model predictive controller steers the system states to the terminal set in a finite number of steps. We tested the proposed approach in simulation using MATLAB/Simulink under extreme uncertain values of filter parameters, as well as the disturbance in grid frequency and inductance.

The paper is divided as follows: Section II presents the linear parameter varying mathematical model of a two level inverter connected to the grid through an LCL filter, Section III presents the proposed robust model predictive controller, Section IV shows the simulation results of a proposed controller and Section V concludes the paper.

II. Mathematical model of a grid connected two level inverter with an LCL filter

Consider the grid connected tree-phase converter with an LCL filter in Fig. 1, to obtain a model in synchronous reference frame, three-phase quantities $i_1 = [i_{1a}\ i_{1b}\ i_{1c}]^T$, $v_c = [v_{ca}\ v_{cb}\ v_{cc}]^T$, $i_2 = [i_{2a}\ i_{2b}\ i_{2c}]^T$ representing converter side current, capacitor voltage and grid side current respectively are transformed as follows:

$$\begin{aligned}
\begin{bmatrix} i_{1d} & i_{1q} \end{bmatrix}^T &= T_{dq} \begin{bmatrix} i_{1a} & i_{1b} & i_{1c} \end{bmatrix}^T \\
\begin{bmatrix} v_{cd} & v_{cq} \end{bmatrix}^T &= T_{dq} \begin{bmatrix} v_{ca} & v_{cb} & v_{cc} \end{bmatrix}^T \\
\begin{bmatrix} i_{2d} & i_{2q} \end{bmatrix}^T &= T_{dq} \begin{bmatrix} i_{2a} & i_{2b} & i_{2c} \end{bmatrix}^T
\end{aligned}$$

Where T_{dq} is well-known Park transformation:

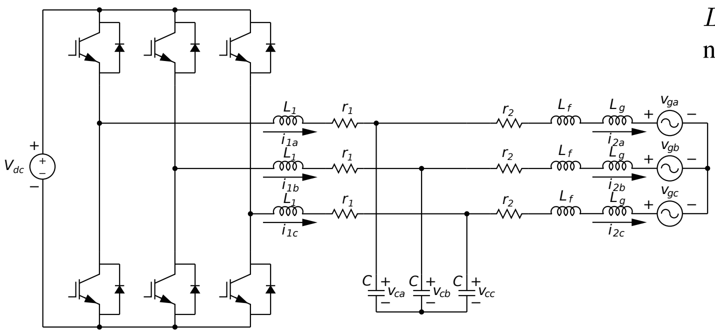

Fig. 1. Two-level grid connected converter with LCL filter

$$T_{dq} = \frac{2}{3} \begin{bmatrix} \sin\theta & \sin\left(\theta - \frac{2}{3}\pi\right) & \sin\left(\theta + \frac{2}{3}\pi\right) \\ \cos\theta & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \end{bmatrix}. \quad (1)$$

Let $x(t) = [i_{1d}(t)\ i_{1q}(t)\ v_d(t)\ v_q(t)\ i_{2d}(t)\ i_{2q}(t)]^T$ be the state vector with quantities in stationary frame. Vector $u(t) = [u_d(t)\ u_q(t)]^T$ represents the voltage applied by the inverter and vector $v(t) = [v_d\ v_q]^T$ represents the grid voltage. The controlled output $y(t)$ are the grid currents $[i_{2d}(t)\ i_{2q}(t)]$. Then the continuous time state-space linear model is given by

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Dv(t) \\ y(t) &= Cx(t) \end{aligned} \quad (2)$$

where

$$A = \begin{bmatrix} -\frac{r_1}{L_1} & \omega & -\frac{1}{L_1} & 0 & 0 & 0 \\ -\omega & -\frac{r_1}{L_1} & 0 & -\frac{1}{L_1} & 0 & 0 \\ \frac{1}{C} & 0 & 0 & \omega & -\frac{1}{C} & 0 \\ 0 & \frac{1}{C} & -\omega & 0 & 0 & -\frac{1}{C} \\ 0 & 0 & \frac{1}{L_2} & 0 & -\frac{r_2}{L_2} & \omega \\ 0 & 0 & 0 & \frac{1}{L_2} & -\omega & -\frac{r_2}{L_2} \end{bmatrix},$$

$$B = \begin{bmatrix} 1/L_1 & 0 \\ 0 & 1/L_1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -1/L_2 & 0 \\ 0 & -1/L_2 \end{bmatrix}$$

and

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

with $\omega = 2\pi f$, where f is the grid frequency.

The grid side inductance L_2 is modeled as

$$L_2 = L_f + L_g \quad (3)$$

with L_f and L_g standing for grid side filter inductance and unknown grid inductance respectively, and $L_g \in [0, L_{\max}]$.

To take LCL filter uncertanies into consideration, as well as grid frequency fluctuation we assume parameters L_1, L_2, r_1, r_2, C and f in a certain range around the given nominal values, ie.

$$\begin{aligned} L_{1,\text{nom}} - \xi_{L_1} \leq &L_1 \leq L_{1,\text{nom}} + \xi_{L_1}, \\ L_{2,\text{nom}} - \xi_{L_2} \leq &L_2 \leq L_{2,\text{nom}} + \xi_{L_2}, \\ r_{1,\text{nom}} - \xi_{r_1} \leq &r_1 \leq r_{1,\text{nom}} + \xi_{r_1}, \\ r_{2,\text{nom}} - \xi_{r_2} \leq &r_2 \leq r_{2,\text{nom}} + \xi_{r_2}, \\ C_{\text{nom}} - \xi_C \leq &C \leq C_{\text{nom}} + \xi_C, \\ f_{\text{nom}} - \xi_f \leq &f \leq f_{\text{nom}} + \xi_f. \end{aligned} \quad (4)$$

Where parameter $\theta_i := r_i/L_i,\ i \in \{1, 2\}$ is modelled as independent in range

$$\frac{r_{i,norm} - \xi_{r_i}}{L_i + \xi_{L_i}} \leq \theta_i \leq \frac{r_{i,norm} + \xi_{r_i}}{L_i - \xi_{L_i}}. \quad (5)$$

With the respect to said uncertainties the system model (2) can be written as a polytopic LPV model [14]. Vertices $(A_{c,i}, B_{c,i}, D_{c,i}, C_{c,i}),\ i \in \{1, \ldots, 64\}$ represent 64 possible combinations of extreme values of system parameters and define a polytopic matrix family

$$\mathcal{M} = \left\{ \sum_{i=1}^{64} \alpha_i (A_{c,i}, B_{c,i}, D_{c,i}, C_{c,i}) \,\middle|\, \sum_{i=1}^{64} \alpha_i = 1, \alpha_i \geq 0 \right\}. \quad (6)$$

That is, every system with parameters inside predefined intervals (4) can be written as a convex combination of vertices $(A_{c,i}, B_{c,i}, D_{c,i}, C_{c,i}),\ i \in \{1, \ldots, 64\}$.

Now, our system can be written as

$$\begin{aligned} \dot{x}(t) &= A_c(\alpha(t))x(t) + B_c(\alpha(t))u(t) + D_c(\alpha(t))v(t) \\ y(t) &= C_c(\alpha(t))x(t) \end{aligned} \quad (7)$$

where $\alpha : \mathbb{R}_0^+ \to \mathbb{R}^{64}$ is a function of time that for every $t \geq 0$ retrieves scalars $\alpha_i,\ i \in \{1, \ldots, 64\}$ which define the systems as a convex combination of vertices of a family $\mathcal{M}$, obviously $(A_c(\alpha(t)), B_c(\alpha(t)), D_c(\alpha(t)), C_c(\alpha(t))) \in \mathcal{M}$. (For brevity we omit writing the argument t of a function α in the text below.)

Discrete-time representation of a system (7) with constant sampling time T using a forward Euler discretization is

$$\begin{aligned} x(k+1) &= A_d(\alpha)x(k) + B_d(\alpha)u(k) + D_c(\alpha)v(k) \\ y(k) &= C_c(\alpha)x(k) \end{aligned} \quad (8)$$

where

$$\begin{aligned} A_d(\alpha) &= I + TA_c(\alpha), \\ B_d(\alpha) &= TB_c(\alpha), \\ C_d(\alpha) &= C_c(\alpha), \\ D_d(\alpha) &= TD_c(\alpha). \end{aligned}$$

A. Equilibrium point

An equilibrium point $[x_d\ u_d]^T$ for system (7), considering a desired reference r of the output $y = [i_{2d}\ i_{2q}]^T$ under constant grid voltage v, is computed as

$$\begin{bmatrix} x_d \\ u_d \end{bmatrix} = \begin{bmatrix} A_c(\alpha) & B_c(\alpha) \\ C_c(\alpha) & 0 \end{bmatrix}^{-1} \left(\begin{bmatrix} 0 \\ r \end{bmatrix} - \begin{bmatrix} D_c(\alpha) \\ 0 \end{bmatrix} v \right). \quad (9)$$

Define $e(k) = x(k) - x_d$ as an error around equilibrium point $[x_d\ u_d]^T$ of a system (8), for a given output reference r under constant grid voltage v, then the error dynamics is obtained

$$e(k+1) = A_d(\alpha)e(k) + B_d(\alpha)u_{\text{err}}(k), \quad (10)$$

where $u_{\text{err}}(k) = u(k) - u_d$.

It is obvious this is also a polytopic family with vertices $(A_{d,i}, B_{d,i})$, $i \in \{1, \ldots, 64\}$ and interior points given by

$$(A_d(\alpha), B_d(\alpha)) = \sum_{i=1}^{64} \alpha_i (A_{d,i}, B_{d,i}) \quad (11)$$

for $\alpha_i \in [0, 1]$ for all $i \in \{1, \ldots, 64\}$, $\sum_{i=1}^{64} \alpha_i = 1$.

III. Ellipsoidal MPC

In this section we recall the results from [15].

We say a set $\mathcal{I}$ is **control invariant** for the polytopic system (10) if for all $e \in \mathcal{I}$ and all $\alpha \in [0, 1]$ there exists control action $u_{err} \in \mathcal{U}$ such that $A_d(\alpha)e + B_d(\alpha)u_{\text{err}} \in \mathcal{I}$ holds. Given such set $\mathcal{I}$ it is possible to construct a family of sets $\{\mathcal{I}_i \mid i \in \mathbb{N}\}$ with

$$\begin{aligned} &\mathcal{I}_0 = \mathcal{I} \\ &\mathcal{I}_i = \{e \mid \exists u_{err} \in \mathcal{U},\ \forall \alpha \in [0, 1], \\ &\quad A_d(\alpha)e + B_d(\alpha)u_{\text{err}} \in \mathcal{I}_{i-1}\}. \end{aligned} \quad (12)$$

Sets $\mathcal{I}_i$ represent all the states that can be steered to $\mathcal{I}_{i-1}$ using a single control action. To ease the computational burden for finding such sets we adopt the following ellipsoidal inner approximations of sets $\mathcal{I}_i$ proposed in [16]. As shown in [17], given a stabilizing feedback gain K and an nonempty ellipsoidal control invariant set $\mathcal{E} \subset \mathbb{R}^n$, that is:

$$(A_{d,i} - B_{d,i}K)e \in \mathcal{E},\ \forall e \in \mathcal{E},\ i \in \{1, \ldots, 64\}, \quad (13)$$

there exists the family of ellipsoidal sets $\{\mathcal{E}_i \mid i \in \mathbb{N}\}$ satisfying the recursion

$$\begin{aligned} &\mathcal{E}_0 = \mathcal{E} \\ &\mathcal{E}_i = \mathbf{In}(\{e \mid \exists u_{err} \in \mathcal{U},\ \forall \alpha \in [0, 1], \\ &\quad A_d(\alpha)e + B_d(\alpha)u_{\text{err}} \in \mathcal{E}_{i-1}\}), \end{aligned} \quad (14)$$

where **In** is the operation finding inner ellipsoidal approximation of a given set.

1) Ellipsoidal sets computation (offline): To begin the recursive construction of ellipsoidal sets first we need to synthesize a feedback gain K that is stabilizing for the vertices of a system (10). Using the linear matrix inequality(LMI) approach presented in [18], by solving the following LMI feasibility problem for $i \in \{1, \ldots, 64\}$ and $j \in \{1, \ldots, 64\}$

$$\begin{bmatrix} \mathcal{P} + \mathcal{P}^T - \mathcal{S}_i & * & * & * \\ 0 & \mu I & * & * \\ \frac{1}{r}(A_{d,i} - dI)\mathcal{P} + \frac{1}{r}B_{d,i} & D_{d,i} & \mathcal{S}_j & * \\ C_{d,i}\mathcal{P} & 0 & 0 & \mu I \end{bmatrix} > 0 \quad (15)$$

for symmetric positive definite matrices $\mathcal{P}, \mathcal{S}_i \in \mathbb{R}^{6\times 6}$ and $\mathcal{R} \in \mathbb{R}^{2\times 6}$ state feedback gain

$$K = \mathcal{R}\mathcal{P}^{-1} \quad (16)$$

is guaranteed to be close loop stable for system (10). Tuning parameter μ denotes closed loop H_∞ cost, and scalars d and r define a circle with center in a point $(d, 0)$ with radii r where the closed loop poles belong.

To represent ellipsoidal set we use the usual quadratic constraints: let $\mathcal{Q}$ be a square positive semidefinite matrix then $\mathcal{E}_\mathcal{Q} = \{x \in \mathbb{R}^n \mid x^T \mathcal{Q} x \le 1\}$ is an ellipsoidal set with a center in origin. To obtain the terminal ellipsoidal set $\mathcal{E}_0$ we solve the optimization problem

$$\begin{aligned} \min_{a \in \mathbb{R}} \quad & a \\ \text{s.t.} \quad & K^T K - a\mathcal{P} \le 0, \\ & a \ge 0, \end{aligned} \quad (17)$$

and set its defining positive semidefinite matrix $\mathcal{P}_0$ to

$$\mathcal{P}_0 = \frac{a}{u_{max}^2}\mathcal{P}, \quad (18)$$

where u_{max} is the maximal magnitude of a control signal u_{err}, and $a \ge 0$ is the scaling factor.

For iterative construction of ellipsoids $\mathcal{E}_i$, $i \in \{1, \ldots n\}$ we use the following equation as proposed in [16]

$$\mathcal{E}_i = \Pi_e \left(\mathbf{In} \left(\bigcap_{j=1}^{64} \tilde{\mathcal{E}}_{i-1}^j \cap (\mathbb{R}^6 \times \mathcal{E}^\mathcal{U}) \right) \right) \quad (19)$$

where $\tilde{\mathcal{E}}_{i-1}^j$ are ellipsoids defined in the extended space $[e\ u_{err}]^T \in \mathbb{R}^8$ as

$$\tilde{\mathcal{E}}_{i-1}^j = \{[e\ u_{err}]^T \mid A_{d,j}e + B_{d,j}u_{err} \in \mathcal{E}_{i-1}\}, \quad (20)$$

$\mathcal{E}^\mathcal{U}$ is ellipsoidal representation of the set of control inputs and Π_e is projection operation to the state space from the extended space.

It is worth noting that solving the LMI problem (15) and finding the ellipsoids $\mathcal{E}_i$ using equation (19) involves solving a semidefinite optimization problem which is easily computed on modern personal computers within seconds [19].

2) Control algorithm (online): MPC algorithm that will be run online is now given as:

1) $k = 0$
2) Find $i(k) = \min\{i \mid e(k) \in \mathcal{E}_i\}$
3) If $i(k) == 0$ set $u_{err}(k) = -Ke(k)$
4) else

$$\begin{aligned} u(k) = \min \quad & J(e(k), u(k)) \\ \text{s.t.} \quad & A_{d,j}e(k) + B_{d,j}u(k) \in \mathcal{E}_{i(k)-1}, \\ j \in \{1, \dots, 64\} \end{aligned} \tag{21}$$

5) $k = k + 1$; jump to 2.

where J is some appropriate cost function.

IV. Results

Nominal system parameter values for the converter and LCL filter are given in Table I. Setting the sampling time to $T = 50\mu$s (same as PWM switching time) vertices of discrete model (10) are calculated for every combination of extreme values of uncertainties given in Table II. State feedback controller K (16) is synthesized using (15) for the parameter values of $r = 0.42$, $d = 0.5$ and $\mu = 100$ with control gains

$$K^T = \begin{bmatrix} 44.0308 & -2.2777 \\ 2.2806 & 44.0308 \\ 0.0926 & -0.2024 \\ 0.2026 & 0.0926 \\ -33.3988 & 0.5013 \\ -0.5021 & -33.3978 \end{bmatrix}. \tag{22}$$

To check the robust stability of the feedback controller K, closed loop eigenvalues are computed for every vertex $(A_{d,i}, B_{d,i})$ of a polytopic matrix family $\mathcal{M}$. Figure 2 shows all the eigenvalues inside the unit circle for every system despite the variation in parameters. Next, using the procedure described in section III we calculate the family of robust ellipsoidal sets offline.

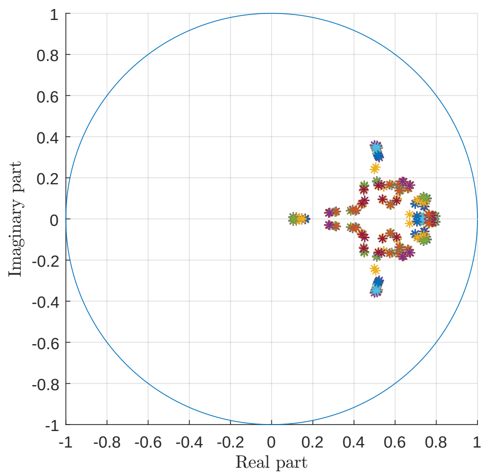

Fig. 2. Eigenvalues of a closed loop system for 64 combinations of extreme parameter values

TABLE I
NOMINAL CONVERTER AND GRID PARAMETERS

Symbol	Description	Value	Unit
r_1	Inverter resistance	0.5	Ω
L_1	Filter inductance	1.7	mH
C	Filer capacitance	5	μF
r_2	Grid resistance	0.5	Ω
L_f	Filter inductance	1.7	mH
L_g	Grid inductance	0–1	mH
V_{dc}	DC link voltage	500	V
v_g	Grid peak voltage	180	V
f	Grid frequency	60	Hz
f_{PWM}	PWM frequency	20	kHz

TABLE II
CONVERTER AND GRID PARAMETER UNCERTAINTIES

Symbol	Description	Value	Unit
ξ_{r_1}	Inverter resistance uncertainty	± 0.1	Ω
ξ_{L_1}	Filter inductance uncertainty	± 0.1	mH
ξ_C	Filer capacitance uncertainty	± 0.1	μF
ξ_{r_2}	Grid resistance uncertainty	± 0.1	Ω
ξ_{L_g}	Grid inductance uncertainty	0–1	mH
ξ_f	Grid frequency uncertainty	± 3	Hz

For the model predictive controller cost function we chose

$$J = (A_d e(k) + B_d u(k))^T \mathcal{P} (A_d e(k) + B_d u(k)) \tag{23}$$

to obtain minimal time control, where $\mathcal{P}$ is matrix representing the terminal invariant ellipsoid $\mathcal{E}_0$ and A_d and B_d are system matrices corresponding to the nominal system.

Experiments were conducted in simulation using MATLAB/Simulink, inverter with PWM algorithm and an LCL filter was modelled using Simulink blocks, with control algorithm written in MATLAB. The following experiments were performed; response of the nominal system to tracking the grid current reference, response of the system with perturbed filter parameters to tracking the grid current reference, and behaviour of the system under grid frequency change.

Nominal system results are shown in Fig. 3. Grid current reference was set to peak value of 10A, and then changed to 20A at 0.02s. System shows fast transient behaviour and very low higher harmonic content as shown in Fig. 4, with an THD of 1.84% [20].

When perturbing the LCL filter parameters simulated results featured higher harmonic content and overall THD, but very similar dynamic response. Results are show for one extreme case with $\xi_{L_1} = -0.1$mH and $\xi_C = +0.1\mu$F in Fig. 5 and 6 showing higher but acceptable [21] harmonic content of grid current.

When changing the grid frequency from 57Hz to 63Hz at 0.02s 7 systems stays stable, also by changing the current reference to -10A at 0.1s it is demonstrated that algorithm supports two way energy flow, to and from grid.

V. Conclusion

In this paper we proposed an robust ellipsoidal set based model predictive control algorithm to control a two-level grid-tied inverter connected through an LCL

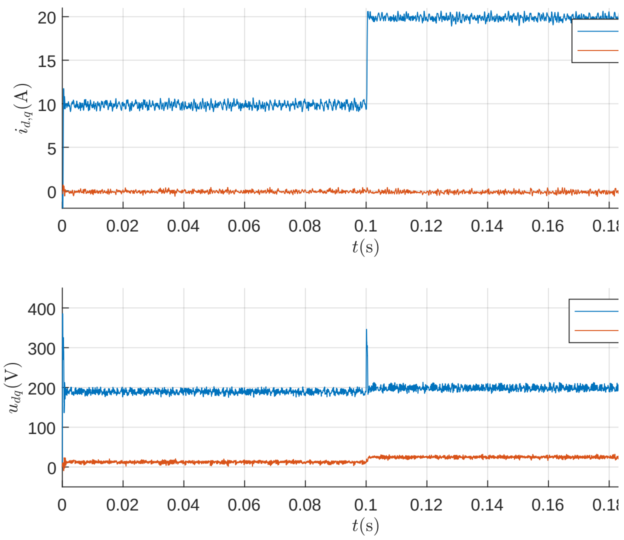

Fig. 3. Nominal system response. (top) Grid current in dq coordinates; (bot.) control signal in dq frame.

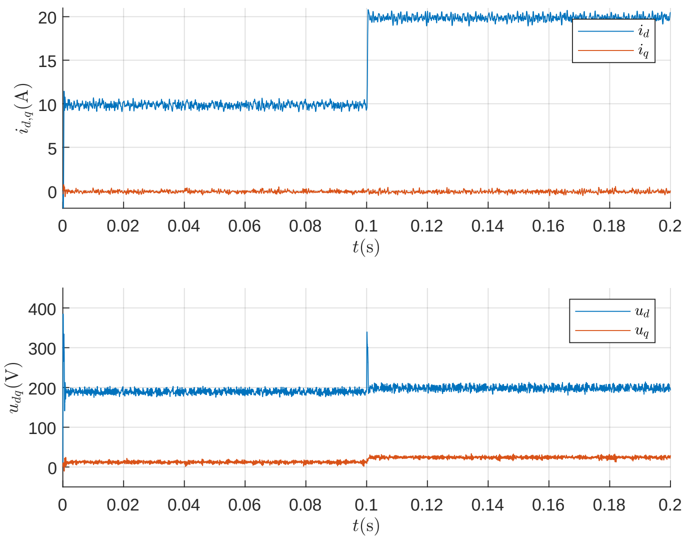

Fig. 5. System response with perturbation in filter parameters ($\xi_{L_1} = -0.1$mH, $\xi_C = 0.1\mu$F); (top) Grid current in dq coordinates; (bot.) control signal in dq frame.

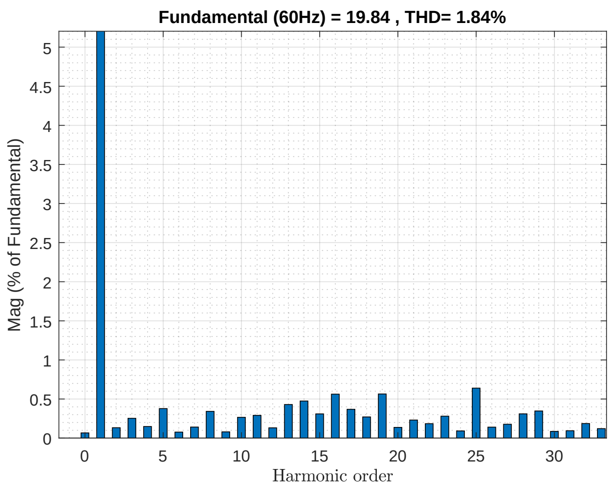

Fig. 4. Harmonic content of phase-a grid current of a nominal system.

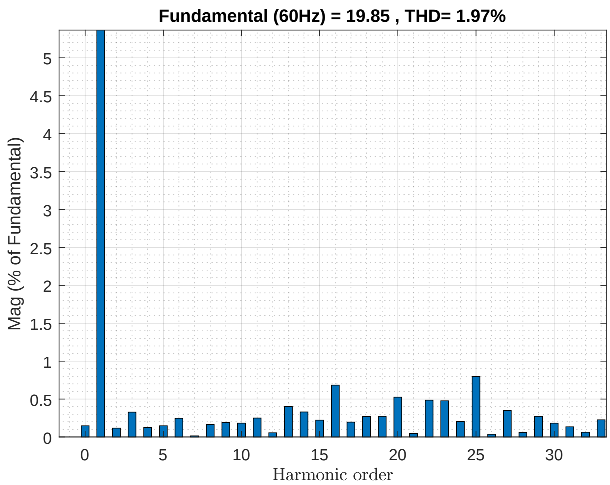

Fig. 6. Harmonic content of phase-a grid current of a system with perturbation in filter parameters.

filter to the grid. Design of the controller took under consideration filter parameter uncertainties, uncertain grid inductance conditions, as well as uncertain grid frequency. Assuming that the grid impedance, filter parameters and grid frequency all belong to predefined intervals, a robust controller is synthesized and a family of robust ellipsoidal one-step controllable sets are found offline. Online at each time step a optimization problem is solved with constraint on the system state to belong to the next smaller ellipsoid in the next time step. In that way, the system states are steered into the terminal set in a finite time. The proposed approach is verified in simulation using MATLAB/Simulink. Simulations show that the proposed control algorithm achieves robust stability regardless of the uncertainties in grid inductance, filter parameters or grid frequency.

ACKNOWLEDGMENT

This work was supported by Croatian Science Foundation under the project IP-06-2016-2519.

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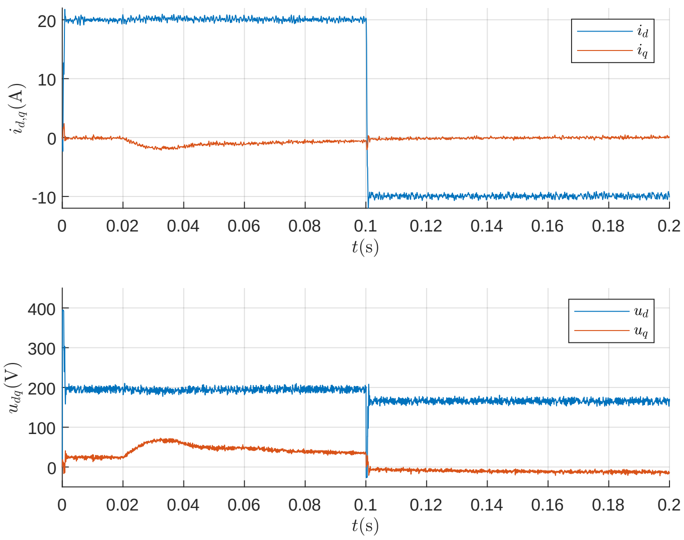

Fig. 7. System response when changing the grid frequency from 57Hz to 63Hz at $t = 0.02$s, and current reference to -10A at $t = 0.1$s; (top) Grid current in dq coordinates; (bot.) control signal in dq frame.

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