Flexible Lyapunov Function based Model Predictive Direct Current Control of Permanent Magnet Synchronous Generator

Tin Bariša*, Šandor Ileš*, Damir Sumina*, Jadranko Matuško*
*University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb, Croatia
tin.barisa@fer.hr, sandor.iles@fer.hr
damir.sumina@fer.hr, jadranko.matusko@fer.hr

***Abstract*—In this paper a dual-mode model predictive direct current control (MP-DCC) algorithm for a permanent magnet synchronous generator (PMSG), which minimizes switching losses in a two-level synchronous generator side converter (SGSC), is proposed. The algorithm consists of two different modes, namely tracking mode where the control objective is to steer the stator currents to a control invariant set where they are ultimately bounded and a minimization of switching losses mode once inside this set. The size of the control invariant set can be arbitrarily chosen within bounds defined with PMSG and SGSC parameters, therefore switching losses can be more or less penalized in the steady state. In order to guarantee recursive feasibility and stability of the proposed algorithm, regardless of a cost function, a flexible control Lyapunov function (CLF) is employed as an optimization problem constraint which enables penalizing switching losses even in the transient state. In that way a desired trade-off between low stator current ripple and a minimization of switching losses can be achieved by properly choosing the objective function for the corresponding optimization problem.**

***Index Terms*—Model predictive control, flexible Lyapunov function, permanent magnet synchronous generator**

I. Introduction

Recently, wind energy conversion systems (WECS) based on permanent magnet synchronous generator (PMSG) have gained significant attention [1], [2]. The use of PMSG has increased due to its advantages such as high efficiency, high power factor, compact design and wide speed operating range. Typically, a WECS consists of a wind turbine, a wind generator, a back-to-back converter and an LCL filter.

With increased development of digital signal processors (DSP), model predictive control (MPC) has gained wide application in control of power electronics and drives. The main advantage of MPC over standard control structures is prediction of future system states based on discrete system model while taking into account input and state constraints. In control of electrical drives and power converters, MPC can be distinguished whether modulation scheme such as pulse width modulation (PWM) is used (Continous Control Set - CCS) or power converter is treated as discrete system with a finite number of voltage vectors (Finite Control Set - FCS) [3].

Little has been published regarding model predictive control of permanent magnet synchronous wind generators. FCS-MPC has been applied to the grid current control and the DC link capacitor voltage balancing of a four-level converter [4] and a three level NPC converter [5], [6]. In [7] CCS-MPC torque control and FCS-MPC active and reactive power control have been applied to a two-level back-to-back converter.

On the other hand, both CCS-MPC and FCS-MPC have been widely applied to permanent magnet synchronous motors (PMSM). Regarding CCS-MPC, both explicit and implicit MPC have been applied to speed and torque control [8], [9]. Regarding FCS-MPC, model predictive direct torque control (MP-DTC) [10], [11] and model predictive direct speed control (MP-DSC) [12] have been reported. In [13] and [14] MP-DTC based on extension of feasible switches which achieves significantly longer prediction horizon has been proposed. However, this approach is restricted to the cost function which minimizes switching losses. In the aforementioned papers feasibility and stability of FCS-MPC has not been discussed.

Recent works address the problem of stability and feasibility of FCS-MPC. A quadratic Lyapunov function based FCS-MPC has been proposed in [15], [16] which guarantees both stability and recursive feasibility by treating the discrete nature of the power converter as a bounded quantization error of the control signal. Since the worst case is considered, such approach may be overly conservative. In [17] a control Lyapunov function based MPC has been proposed which guarantees both feasibility and a convergence of the system states to a control invariant set in the stationary $\alpha\beta$ reference frame. Even though this approach guarantees feasibility and stability of the overall control system, its performance can be conservative due to a control Lyapunov function constraint.

To alleviate the introduced conservatism by using a classical control Lyapunov function constraint, it can be augmented with additional variables such as center and radius in order to enable non-monotone convergence to the terminal set. Such approach is called a flexible control Lyapunov function approach [18]. It has been shown that a non-monotone decrease of a Lyapunov function can lead to a better performance compared to the classical one.

In this paper the idea of utilizing a control Lyapunov function constraint for guaranteeing both stability and recursive feasibility of FCS-MPC presented in [17] is extended by converting it to a flexible control Lyapunov function constraint

978-1-5090-1797-3/16/$31.00 ©2016 IEEE

[18]. In that way a minimization of switching losses is enabled even in the transient state instead of steering the stator currents to the control invariant set as fast as possible as in [17]. In order to enable a minimization of switching losses in the steady state as well, a dual-mode model predictive direct current control (MP-DCC) is proposed. The first mode ensures tracking of stator current references in order to reach a control invariant set. Once the control invariant set is reached, the second mode which penalizes switching losses in the steady state becomes active. The size of the control invariant set can be arbitrarily chosen depending on PMSG and synchronous generator side converter (SGSC) parameters, therefore switching losses can be more or less penalized in the steady state. The proposed algorithm achieves energy efficient control of SGSC while ensuring the recursive feasibility and stability at each sampling instant.

The paper is organized as follows. Typical WECS based on PMSG is described in Section II. In Section III a discrete mathematical model of a PMSG is presented. Dual-mode MP-DCC algorithm of a PMSG is proposed in Section IV. Results are presented in Section V. Finally, conclusion is given in Section VI.

II. Permanent Magnet Synchronous Generator based Wind Generation

A proposed structure of a wind generation system based on a PMSG and a two-level back-to-back converter is shown in Fig.1. Variable speed wind turbine captures a maximum wind power at any wind speed by optimally adjusting shaft speed. For each wind speed value there is an optimal turbine shaft speed which results in the maximum extraction of wind power. In order to achieve the optimal speed, the optimal torque reference is generated which achieves the desired shaft speed at the steady state. In such a way, maximum power point tracking (MPPT) is achieved.

The torque reference is forwarded to a SGSC which calculates optimal stator current references in the dq reference frame according to maximum torque per ampere (MTPA) algorithm. In such a way, the desired generator torque is achieved with a minimum copper loss. In this paper, a control of a SGSC is obtained using a dual-mode MP-DCC algorithm which guarantees both stability and recursive feasibility. In such a way, tracking of the stator currents is ensured while switching losses can be significantly reduced comparing to standard control structures based on PWM.

Control of a power grid side converter (PGSC) is achieved by voltage oriented control (VOC) which obtains independent control of active and reactive power injected to the grid. Outer control loop keeps the DC link voltage at a reference value while inner control loops secure tracking of the grid current references in the dq reference frame using PI controllers. Between the PGSC and the grid an LCL filter is placed in order to mitigate harmonics caused by PWM. In such a way, total harmonic distortion (THD) of grid voltage and current is achieved which complies with grid code requirements.

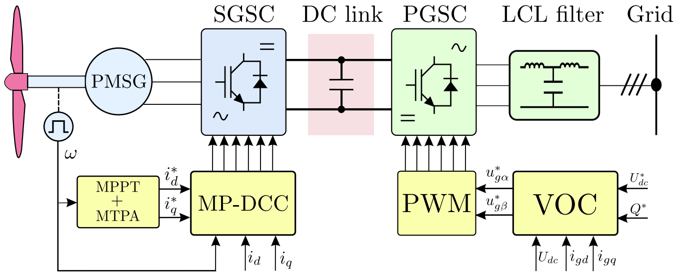


Fig. 1: Permanent Magnet Synchronous Generator based Wind Energy Conversion System

III. Discrete mathematical model of a PMSG

A discrete mathematical model of a PMSG in the synchronous dq reference frame can be obtained using forward Euler discretization with a sampling time T_s as follows[1]:

$$\begin{aligned} x(k+1) &= f(x(k), u(k), \theta(k), \omega) \\ &= Ax(k) + B(\theta(k))u(k) + G\omega, \end{aligned} \tag{1}$$

where $x(k) = \left[i_d(k)\, i_q(k)\right]^T, u(k) = \left[u_\alpha(k)\, u_\beta(k)\right]^T$ and

$$A = \begin{bmatrix} 1 - \frac{RT_s}{L_d} & \omega\frac{L_qT_s}{L_d} \\ -\omega\frac{L_dT_s}{L_q} & 1 - \frac{RT_s}{L_q} \end{bmatrix} G = \begin{bmatrix} 0 \\ -\frac{\psi_m T_s}{L_q} \end{bmatrix}, \tag{2}$$

$$B(\theta(k)) = \begin{bmatrix} \frac{T_s}{L_d}\cos(\theta(k)) & \frac{T_s}{L_d}\sin(\theta(k)) \\ -\frac{T_s}{L_q}\sin(\theta(k)) & \frac{T_s}{L_q}\cos(\theta(k)) \end{bmatrix}, \tag{3}$$

R_s is the stator resistance, L_d and L_q are the $d-$ and the $q-$axis inductances and ψ_m is the permanent magnet flux linkage. Since the mechanical time constant is significantly larger than the electrical time constant in the case of a PMSG, the electrical rotor speed ω is treated as a slow-varying parameter. The electrical rotor angle $\theta(k)$ can be expressed as follows:

$$\theta(k+1) = \theta(k) + T_s\omega. \tag{4}$$

If magnetic saturation is neglected, the stator flux can be expressed in the dq reference frame as follows:

$$[\psi_d(k)\, \psi_q(k)]^T = L[i_d(k)\, i_q(k)]^T + \Psi, \tag{5}$$

where $L = diag(L_d, L_q)$ and $\Psi = [\psi_m\, 0]^T$. Neglecting the voltage drop on the stator resistance, the stator current reference values must be limited due to voltage and current limitations of a power converter and a PMSG as follows:

$$\left\| \left[i_d^*(k)\, i_q^*(k)\right] \right\| \le I_r, \tag{6}$$

$$|\omega| \left\| \left[(L_d i_d^*(k) + \psi_m)\, L_q i_q^*(k)\right] \right\| \le U_{dc}/\sqrt{3} - \delta, \tag{7}$$

where $i_d^*(k)$ and $i_q^*(k)$ are stator current reference values, I_r is the maximum permissible current, U_{dc} is the DC link voltage and δ is a safety factor which provides robustness to model uncertainties but also reduces the available voltage.

[1]Control input i.e. the stator voltage is expressed in the stationary $\alpha\beta$ reference frame since it is more convenient regarding the proposed FCS-MPC algorithm.

IV. Dual-mode Model Predictive Direct Current Control

In this paper a dual-mode model predictive direct current control (MP-DCC) algorithm for a minimization of switching losses in a two-level SGSC is proposed. The proposed algorithm consists of two different modes, namely tracking mode where the control objective is to steer the stator currents to a control invariant set which contains the equilibrium point defined by a desired reference signal and a switching losses minimization mode once inside this set.

The reference values of the stator currents in the dq reference frame are obtained from the MTPA curve. At every sampling instant the stator currents are measured and transformed into the dq reference frame. For each of eight switching states of the SGSC, the prediction of the future behaviour of the dq stator currents over the prediction horizon is obtained. Switching states which violate constraints are discarded while the remaining are compared according to a cost function and the optimal switching state is applied to a SGSC. This procedure is then repeated in a receding horizon manner.

In order to make a trade-off between the reference tracking and switching losses a quadratic cost function has been chosen. In the case of a two-level SGSC, due to the discrete nature of the converter, it is not always possible to achieve a perfect tracking of the reference signal. Instead, in the steady state, the stator current will be contained in a closed neighborhood of the reference stator current signal given with the set $\mathcal{B}$. As a consequence a substantial harmonic distortion in the stator current signal will exist, resulting in persistent stator current pulsations. By increasing the switching frequency the lower harmonic distortion can be accomplished, however this leads to increased switching losses.

To distinguish two different modes of the SGSC operation a variable m is defined as follows:

$$m = \begin{cases} 0, x \notin \mathcal{B}, \\ 1, x \in \mathcal{B}. \end{cases} \tag{8}$$

To enable a different cost function for each mode, the objective function is defined as follows:

$$\begin{aligned} J(x(k), \vec{u}(k), m) = F(x(k+N), m) + \\ + \sum_{j=0}^{N-1} l(x(k+j), u(k+j), m), \end{aligned} \tag{9}$$

where $l(x, u, m)$ is a stage cost and $F(x, m)$ is a terminal cost. The proposed finite-time optimal control problem is written as follows:

$$\begin{aligned} &\min_{\vec{u}(k)} J(x(k), \vec{u}(k), m) \\ &\text{s.t.}\; x(k+j+1) = f(x(k+j), u(k+j), \theta(k+j), \omega(k)), \\ &\quad x(k+j) \in \mathcal{X}, j = 0, \ldots, N \\ &\quad u(k+j) \in \mathcal{U}, j = 0, \ldots, N-1. \end{aligned} \tag{10}$$

where $\vec{u}(k) = [u(k)\, u(k+1)\, \ldots, u(k+N-1)]$, $\mathcal{X}$ is a set representing the state constraints, $\mathcal{U}$ is a finite control set representing control input constraints defined by eight voltage vectors in the stationary $\alpha\beta$ reference frame as follows:

$$\begin{aligned} \mathcal{U} = U_{dc} \Bigg\{ &\underbrace{\begin{bmatrix} 0 \\ 0 \end{bmatrix}}_{u_0}, \underbrace{\begin{bmatrix} \frac{2}{3} \\ 0 \end{bmatrix}}_{u_1}, \underbrace{\begin{bmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{bmatrix}}_{u_2}, \underbrace{\begin{bmatrix} -\frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{bmatrix}}_{u_3}, \underbrace{\begin{bmatrix} -\frac{2}{3} \\ 0 \end{bmatrix}}_{u_4}, \\ &\underbrace{\begin{bmatrix} -\frac{1}{2} \\ -\frac{\sqrt{3}}{2} \end{bmatrix}}_{u_5}, \underbrace{\begin{bmatrix} \frac{1}{2} \\ -\frac{\sqrt{3}}{2} \end{bmatrix}}_{u_6}, \underbrace{\begin{bmatrix} 0 \\ 0 \end{bmatrix}}_{u_7} \Bigg\}. \end{aligned} \tag{11}$$

To guarantee that the neighbourhood of the reference signal $\mathcal{B}$ is reached in a finite time, a control Lyapunov function (CLF) can be employed.

In [17] it has been shown that for all $x \in \mathcal{X} \backslash \mathcal{B}$ there exists a CLF $V(x) \geq 0$, $u \in \mathcal{U}$, $\gamma > 0$, $b(k) > 0$, such that the following condition holds:

$$V(f(x, u, \omega, \theta)) \leq \max(V(x) - b(k), \gamma), \tag{12}$$

where $\mathcal{B}$ is defined as a sublevel set of the Lypaunov function defined by a parameter γ as follows:

$$\mathcal{B} = \{x : V(x) \leq \gamma\} \subset \mathcal{X}, \tag{13}$$

and parameter $b(k)$ defines how fast the Lyapunov function decreases and can be chosen as follows [17]:

$$b(k) \in (0, 1/\sqrt{3} - V(y(k))], \tag{14}$$

$$y(k) = -(\bar{\psi}^*_{\alpha\beta}(k) - \bar{\psi}^*_{\alpha\beta}(k+1)). \tag{15}$$

If $b(k)$ is chosen to be large, control algorithm becomes more robust to model uncertainties since Lyapunov function decreases faster but the available voltage is decreased as well. In that way (12) can be used as a stabilizing constraint which guarantees recursive feasibility of the optimization problem and a finite-time convergence of the system states to the set $\mathcal{B}$.

In the case that the set $\mathcal{X} = \mathbb{R}^2$, a control Lyapunov function is defined in normalized stator flux space [17] as follows:

$$V(\Delta\bar{\psi}_{\alpha\beta}) = \left\| H \Delta\bar{\psi}_{\alpha\beta} \right\|_\infty, \tag{16}$$

where

$$H = \begin{bmatrix} 0 & 1 \\ \sqrt{3}/2 & 1/2 \\ \sqrt{3}/2 & -1/2 \\ 0 & -1 \\ -\sqrt{3}/2 & -1/2 \\ -\sqrt{3}/2 & 1/2 \end{bmatrix}, \tag{17}$$

$$\Delta\bar{\psi}_{\alpha\beta} = (\bar{\psi}_{\alpha\beta} - \bar{\psi}^*_{\alpha\beta}) = (\psi_{\alpha\beta} - \psi^*_{\alpha\beta})(T_s U_{dc})^{-1}. \tag{18}$$

In the previous equations, $\psi_{\alpha\beta}$ and $\psi^*_{\alpha\beta}$ are the stator flux and its reference value, respectively. In [17] it is shown that such Lyapunov function contains hexagonal sublevel sets defined as:

$$\Omega(\gamma) = H\Delta\bar{\psi}_{\alpha\beta} \leq \gamma. \tag{19}$$

For $\gamma \geq 1/\sqrt{3}$ calculated preset of the sublevel set defined with (19) is a convex set which contains original sublevel set.

That proves that each sublevel set with $\gamma \geq 1/\sqrt{3}$ is a control invariant set. Since it can be set to any value larger than $1/\sqrt{3}$, in this paper γ is treated as a tuning parameter which can be used to make a compromise between a high stator current ripple and a low switching frequency. It determines when the other mode of operation in (8) becomes active.

Since the mathematical model of a PMSG and control problem are written in the dq reference frame, it is convenient to transform Lyapunov function to the same reference frame. The stator flux can be transformed from the stationary $\alpha\beta$ reference frame to the rotating dq reference frame using the following transformation:

$$\psi_{dq} = T_{dq}(\theta(k))\psi_{\alpha\beta}, \tag{20}$$

where $T_{dq}(\theta(k))$ is Park's transform as follows:

$$T_{dq}(\theta) = \begin{bmatrix} \cos(\theta(k)) & \sin(\theta(k)) \\ -\sin(\theta(k)) & \cos(\theta(k)) \end{bmatrix}. \tag{21}$$

Transformation from the stator flux space to the stator current space in the dq reference frame can be easily obtained using (5).

However, instead of (12), a so called flexible control Lyapunov function constraint can be used [18]. In this paper the following flexible control Lyapunov function constraint is proposed:

$$V(f(x, u, \omega, \theta)) \leq \max(V(x) + \lambda(k) - b(k), \gamma), \tag{22}$$

where $\lambda(k) \geq 0$ is a time-varying function with the following property:

$$\lambda(k + j) = 0, \forall j \geq k_1, k_1 \in \mathbb{Z}_+, \tag{23}$$

where k_1 is a time instant when the flexible Lyapunov function constraint becomes the standard one. In this way the recursive feasibility is guaranteed regardless of the mode dependent objective function since the constraint (12) is relaxed. By adding a flexibility to a CLF a minimization of switching losses is enabled in the transient state.

V. RESULTS

The benefits of the proposed approach, are demonstrated using simulation tests with parameters of the PMSG and SGSC given in Table I.

TABLE I: PARAMETERS OF THE PMSG and SGSC

Symbol	Description	Value	Unit
P_n	Nominal power	375	kW
n_n	Nominal speed	1500	rpm
U_n	Nominal voltage	400	V
I_n	Nominal current	596	A
T_n	Nominal torque	2389	Nm
R_s	Stator phase resistance	8.05	mΩ
L_d	d-axis inductance	0.72	mH
L_q	q-axis inductance	1.06	mH
ψ_m	Permanent magnet flux linkage	0.6913	Vs
p	Pole pairs	3	
U_{dc}	DC link voltage	650	V
T_s	Sampling time	25	μs

The mode dependent stage cost and mode dependent terminal cost are chosen as follows:

$$l(x(k), u(k), m) = \begin{cases} \|x(k)\|_Q^2 + \|\Delta u(k)\|_R^2, & \text{if } m = 0 \\ \|\Delta u(k)\|_R^2, & \text{if } m = 1, \end{cases} \tag{24}$$

while the mode dependent terminal cost is chosen as:

$$F(x(k), u(k), m) = \begin{cases} \|x(k)\|_P^2, & \text{if } m = 0 \\ 0, & \text{if } m = 1, \end{cases} \tag{25}$$

where $\|z\|_X$ denotes an X weighted Euclidean norm $\sqrt{z^T X z}$. The matrices Q, R and P are chosen as $Q = I$, $R = rI$, $P = Q$. With this choice of objective function, the only available tuning parameter in the objective function is r. However, it is important to note that the tuning parameter r does not smoothly affect the stator current response due to the finite number of control inputs.

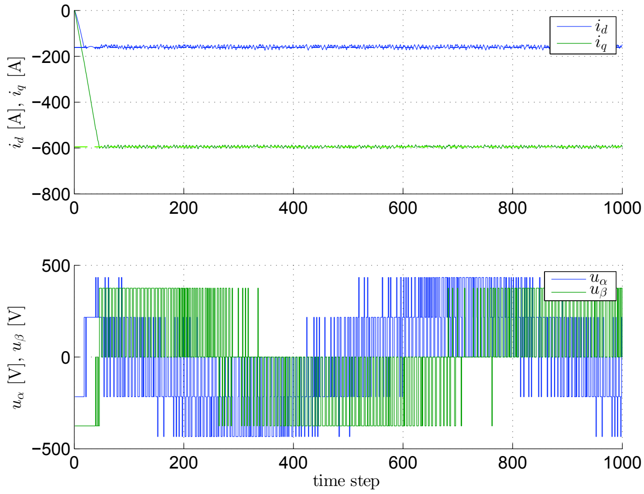
The simulation results are provided for $r = 0$ and $r = 0.2$. The prediction horizon is selected to be $N = 1$.

The parameter b is set to the maximum allowed value according to (14). Since in [17] it has been shown that for $\gamma = \left[\frac{1}{\sqrt{3}}, \infty\right)$ the corresponding sublevel set of the Lyapunov function is an invariant set, the parameter γ can be seen as a tuning parameter for selecting the maximum allowed stator current ripple. The simulation results were provided for various multiples of $\gamma = \frac{1}{\sqrt{3}}$, which corresponds to the minimum control invariant set, in order to demonstrate effect on stator current ripple and switching frequency.

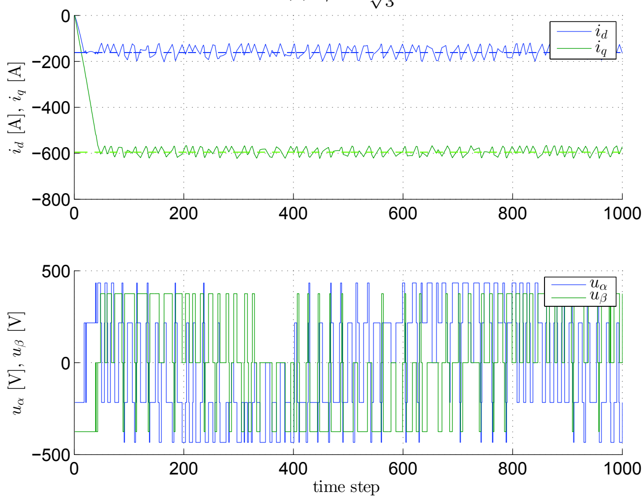
The relaxing variable $\lambda(k)$ is chosen to evolve according to the following law: $\lambda(k+1) = \max(0, \rho\lambda(k) - \epsilon)$, where the initial condition is set to $\lambda(0) = 15$, ρ is set to 0.95 and ϵ to 10^{-10}. It is assumed that the parameter $\lambda(k)$ is reset to the initial condition for every reference change.

Simulation was conducted for electromagnetic torque reference value -2000 Nm at rotor speed 1000 rpm. The d- and the q-axis stator current reference values, calculated according to MTPA algorithm, were equal to -161 A and -595 A, respectively. The stator current transient response together with the control input for $\gamma = \frac{1}{\sqrt{3}}$ and $\gamma = \frac{3}{\sqrt{3}}$ are shown in Fig. 4. It can be seen that an increased γ leads to a higher stator current ripple and a lower switching frequency. A significant reduction of switching frequency can be seen in the stator voltage response. Since $\gamma = \frac{3}{\sqrt{3}}$ results in a high stator current ripple, in further tests $\gamma = \frac{2}{\sqrt{3}}$ is selected as a compromise between a high stator current ripple and a low switching frequency.

The comparison between the standard control Lyapunov function and the flexible control Lyapunov function is provided in Figs. 7 and 10 for $r = 0$ and $r = 0.2$, respectively. It can be seen that in the case when $r = 0$, the standard control Lyapunov function and the flexible Lyapunov function approach result in the same transient response since the cost function already prefers a decrease of the Lyapunov function. However, when $r = 0.2$ the cost function exploits the added flexibility in the flexible Lyapunov function leading to a less

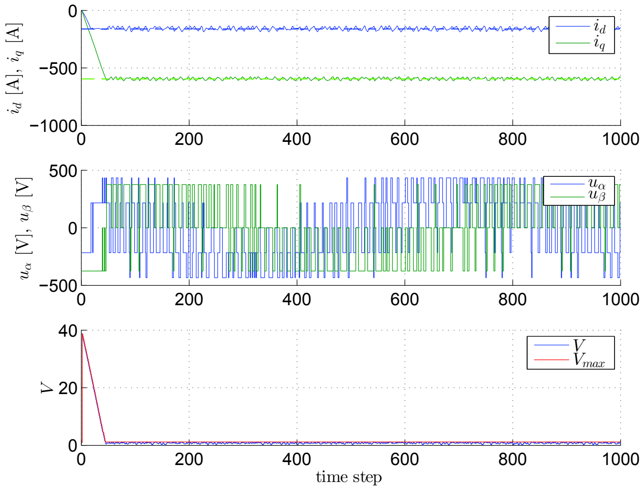


(a) $\gamma = \frac{1}{\sqrt{3}}$

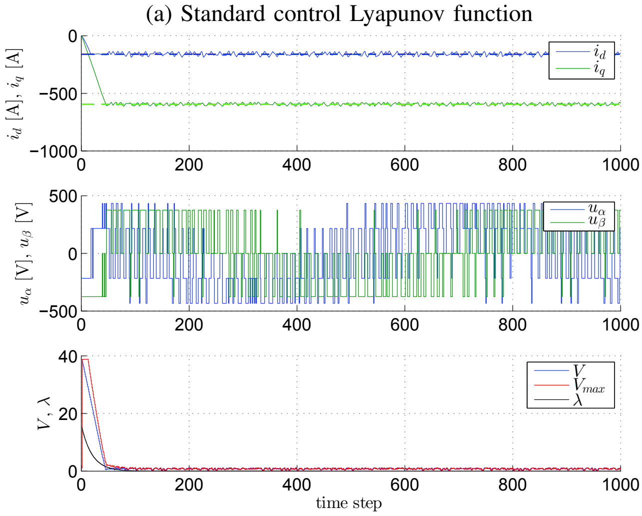


(b) $\gamma = \frac{3}{\sqrt{3}}$

Fig. 2: The stator current transient response with different values of γ



(a) Standard control Lyapunov function



(b) Flexible control Lyapunov function

Fig. 3: The stator current transient response with $\gamma = \frac{2}{\sqrt{3}}$ and $r = 0$ with different stabilizing constraint

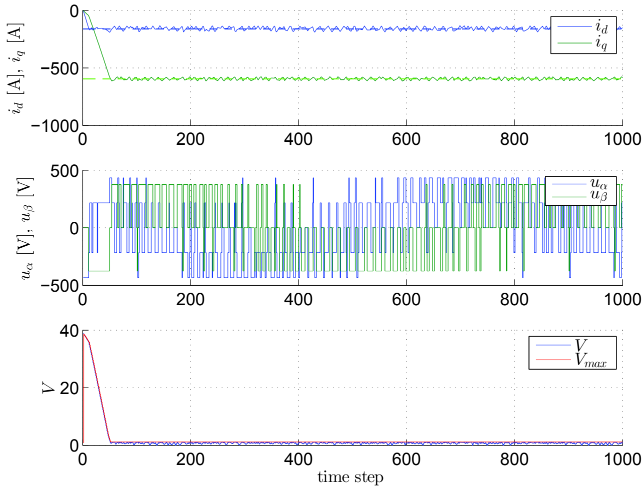
conservative response. In that way a reduction of switching frequency is achieved even in the transient state which can be seen in the stator voltage response.

VI. Conclusion

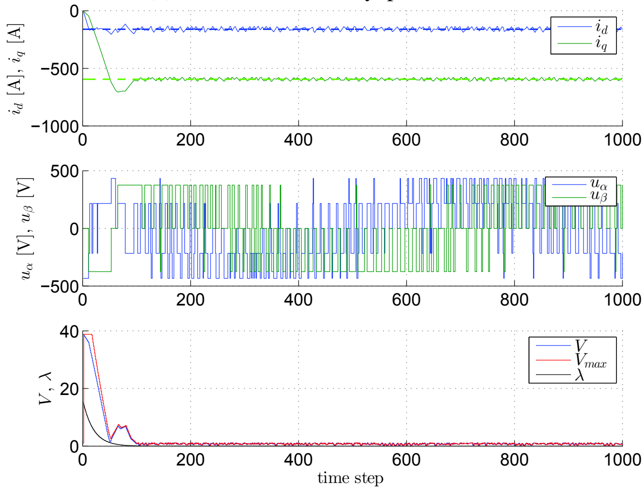
In this paper a flexible Lyapunov function based model predictive direct current control (MP-DCC) of permanent magnet synchronous generator (PMSG) applied to a two-level synchronous generator side converter (SGSC) is proposed. The proposed algorithm consists of two modes, namely tracking mode which steers the stator currents to a control invariant set and a minimization of switching losses mode once the aforementioned set is reached. Size of the control invariant set can be arbitrarily chosen within bounds defined with the parameters of a PMSG and a SGSC, therefore switching losses can be more or less penalized in the second mode of operation. A flexible control Lyapunov function (CLF) guarantees recursive feasibility and stability of the proposed algorithm regardless of the chosen cost function. Since a flexible CLF is a non-monotonically decreasing function, it is not as restrictive regarding the optimization problem as a standard monotonically decreasing CLF reported in [17]. In that way the proposed algorithm achieves a less conservative response by allowing a minimization of switching losses even in the transient state.

Simulation results verify that the proposed control algorithm successfully tracks the stator current reference values while minimizing switching losses. Since finite control set (FCS) of available inputs is defined by eight voltage vectors of a SGSC, it is not possible to achieve perfect tracking of the stator currents. By adjusting weighting matrices of the cost function, the desired trade-off between low stator current ripple and a minimization of switching losses can be achieved.

In the future work the proposed algorithm will be imple-



(a) Standard control Lyapunov function



(b) Flexible control Lyapunov function

Fig. 4: The stator current transient response with $\gamma = \frac{2}{\sqrt{3}}$ and $r = 0.2$ with different stabilizing constraint

mented in digital system and verified on the laboratory model. Robustness of the proposed algorithm to variation of PMSG parameters and the DC link voltage will be examined as well.

ACKNOWLEDGMENT

This work has been fully supported by the Croatian Science Foundation under the project number UIP-2013-11-7601.

REFERENCES

[1] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," *Energy Conversion, IEEE Transactions on*, vol. 21, no. 1, pp. 130–135, 2006.

[2] S. Morimoto, H. Nakayama, M. Sanada, and Y. Takeda, "Sensorless output maximization control for variable-speed wind generation system using ipmsg," in *Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the*, vol. 3. IEEE, 2003, pp. 1464–1471.

[3] M. Preindl and S. Bolognani, "Comparison of direct and pwm model predictive control for power electronic and drive systems," in *Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE*. IEEE, 2013, pp. 2526–2533.

[4] V. Yaramasu, B. Wu, M. Rivera, and J. Rodriguez, "A new power conversion system for megawatt pmsg wind turbines using four-level converters and a simple control scheme based on two-step model predictive strategypart ii: simulation and experimental analysis," *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, vol. 2, no. 1, pp. 14–25, 2014.

[5] V. Yaramasu, B. Wu, S. Alepuz, and S. Kouro, "Predictive control for low-voltage ride-through enhancement of three-level-boost and npc-converter-based pmsg wind turbine," *Industrial Electronics, IEEE Transactions on*, vol. 61, no. 12, pp. 6832–6843, 2014.

[6] V. Yaramasu and B. Wu, "Predictive control of a three-level boost converter and an npc inverter for high-power pmsg-based medium voltage wind energy conversion systems," *Power Electronics, IEEE Transactions on*, vol. 29, no. 10, pp. 5308–5322, 2014.

[7] Z. Zhang, C. Hackl, F. Wang, Z. Chen, and R. Kennel, "Encoderless model predictive control of back-to-back converter direct-drive permanent-magnet synchronous generator wind turbine systems," in *Power Electronics and Applications (EPE), 2013 15th European Conference on*. IEEE, 2013, pp. 1–10.

[8] S. Bolognani, S. Bolognani, L. Peretti, and M. Zigliotto, "Design and implementation of model predictive control for electrical motor drives," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 6, pp. 1925–1936, 2009.

[9] M. Preindl, S. Bolognani, and C. Danielson, "Model predictive torque control with pwm using fast gradient method," in *Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE*. IEEE, 2013, pp. 2590–2597.

[10] M. Preindl and S. Bolognani, "Model predictive direct torque control with finite control set for pmsm drive systems, part 1: Maximum torque per ampere operation," *Industrial Informatics, IEEE Transactions on*, vol. 9, no. 4, pp. 1912–1921, 2013.

[11] ——, "Model predictive direct torque control with finite control set for pmsm drive systems, part 2: Field weakening operation," *Industrial Informatics, IEEE Transactions on*, vol. 9, no. 2, pp. 648–657, 2013.

[12] ——, "Model predictive direct speed control with finite control set of pmsm drive systems," *Power Electronics, IEEE Transactions on*, vol. 28, no. 2, pp. 1007–1015, 2013.

[13] T. Geyer, G. Papafotiou, and M. Morari, "Model predictive direct torque controlpart i: Concept, algorithm, and analysis," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 6, pp. 1894–1905, 2009.

[14] G. Papafotiou, J. Kley, K. G. Papadopoulos, P. Bohren, and M. Morari, "Model predictive direct torque controlpart ii: Implementation and experimental evaluation," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 6, pp. 1906–1915, 2009.

[15] R. P. Aguilera and D. E. Quevedo, "On stability and performance of finite control set mpc for power converters," in *Predictive Control of Electrical Drives and Power Electronics (PRECEDE), 2011 Workshop on*. IEEE, 2011, pp. 55–62.

[16] ——, "Predictive control of power converters: Designs with guaranteed performance," *Industrial Informatics, IEEE Transactions on*, vol. 11, no. 1, pp. 53–63, 2015.

[17] M. Preindl, "Robust control invariant sets and lyapunov-based mpc for ipm synchronous motor drives," *IEEE Transactions on Industrial Electronics*, vol. PP, no. 99, pp. 1–1, 2016.

[18] M. Lazar, "Flexible control lyapunov functions," in *American Control Conference, 2009. ACC'09.* IEEE, 2009, pp. 102–107.