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Model predictive-based control technique for fault ride-through capability of VSG-based grid-forming converter

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Keywords

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Abstract

Increasing integration of renewable energy resources emphasizes the importance of the grid-forming virtual synchronous generator (VSG)-based converters. An important issue in the control structure of these converters is the fault ride-through (FRT) capability under fault operating condition. In this paper a model predictive-based FRT control strategy is proposed to limit the converter current while ensures high power quality during fault situation. The proposed control method provides a fast dynamic response, high power quality, improved performance, and a simpler control structure. The effective performance of the proposed control method, as well as its superior performance in comparison with the conventional PI-based control and a model predictive-based control method, are validated through simulation results in MATLAB/Simulink.

Introduction

Renewable energy-based resources are expanding quickly to respond to the increasing demand for clean electric energy. However, increasing integration of these converter-based resources is a challenge to the modern power grid. Conventional synchronous generator (SG)-based power grid inherently possesses inertia and oscillation damping features, while converter-based generators do not possess these features inherently. This is a great challenge for the modern power grid dominated by renewable energy resources. To overcome this challenge, different control techniques have been proposed to virtually add important features of the SGs to the control structure of the converters as a virtual synchronous generator (VSG) [1]-[4]. Among these, grid-forming converters have a promising potential for a fully converter-based power grid [4], [5].

Although inertia and oscillation damping features of SGs are replicable in the control of converters, providing a large short circuit current is not possible for converters. This is because of semi-conducting devices of the converter which are not able to tolerate a very large overcurrent. So, fault ride-through (FRT) ability, i.e., the ability of the converter to continue connected to the grid with a reduced voltage level during fault conditions, is a vital issue of the converter that needs to be addressed [6]-[12].

Avoiding overcurrent by simply limiting the converter reference current to a certain level of its nominal value is proposed in [6]. However, this technique causes windup in the outer control loop of the converter when the converter current saturates. Anti-windup for the PI controller of the outer voltage control loop does not work well in the case of a large fault occurrence. An indirect current limiting control technique has been proposed in [7] in which virtual impedance is employed for limiting the reference voltage and indirectly current reference of the converter. However, this method is not fast enough in limiting the converter current. A control technique is proposed in [8] in which the converter current is directly limited, and the virtual impedance is employed to avoid windup in the voltage control loop. However, this technique is dependent on the fault size and location to determine the virtual impedance. A control technique for a grid-forming VSG-based converter is proposed in [9] that combines the direct and indirect current limiting strategies. In this paper, the reference current is directly limited, and the reference active and reactive power in fault operating mode are updated based on the voltage drop to provide the appropriate voltage reference compatible with the limited current, resulting in anti-windup in the outer control loop.

The aforementioned FRT control strategies are based on PI controller. Finite-set model predictive control (FS-MPC) has been introduced as an alternative to the conventional PI-based linear control techniques. The main advantages of FS-MPC over conventional PI-based control are the fast dynamic response, simple control structure, and multi-objective control possibility. For a cascaded voltage and current control loop, at least ten parameters need to be tuned, resulting in the complexity of the PI-based control schemes.

A simple FS-MPC is proposed in [10] to control a grid-forming converter working in the islanded mode of operation. Current reference tracking and overcurrent protection are two control objectives of the control scheme. In [11], a simultaneous voltage and current tracking based on FS-MPC has been proposed in which virtual voltage vectors are employed to reduce the harmonics. In [12] an FS-MPC strategy with three control objectives has been proposed for the control of a grid-forming VSG. Current and voltage reference tracking and current limitation are three control objectives followed by this control strategy. Although this control can provide a strict current limiter, the power quality during fault situations is still a vital issue that needs to be addressed.

Thereby, in this paper, an FS-MPC-based strategy is proposed for a grid-forming VSG-based converter taking into account both vital aspects of FRT ability: overcurrent protection and power quality. A reduced total harmonic distortion (THD) of voltage and current during fault condition verifies the power quality of the proposed control technique. The remaining of the paper is organized as follows. The model under study and the proposed control technique are described in Section 2 and Section 3, respectively. The simulation results in MATLAB/Simulink are presented and discussed in Section 4. Finally, Section 5 summarizes the main outcomes of the paper.

Description of the system model

Fig. 1 shows the general model and the proposed control, a VSG-based grid-forming converter connected to the grid through an LCL filter. According to Fig. 1, the equation representing the AC-side dynamics of the converter are expressed in $\alpha\beta$ reference frame as follows:

$$L_{fc}\frac{di_c}{dt}+R_{fc}i_c+v_c=u_c \tag{1}$$

$$C_f\frac{dv_c}{dt}+i_o=i_c \tag{2}$$

where L_{fc} and C_f are filter inductance and capacitance, $i_c=i_{c,\alpha}+ji_{c,\beta}$ and $v_c=v_{c,\alpha}+jv_{c,\beta}$ represent the inductor current and the capacitor voltage, respectively. $i_o=i_{o,\alpha}+ji_{o,\beta}$ and $u_c=u_{c,\alpha}+ju_{c,\beta}$ represent the output current and the converter terminal voltage, respectively.

Based on the AC-side dynamics given in (1),(2), the continuous-time state-space model of the system is defined in (3), considering i_c, v_c as state variables and u_c, i_o as input variables.

$$\begin{bmatrix}\frac{di_c}{dt}\\ \frac{dv_c}{dt}\end{bmatrix}=\underbrace{\begin{bmatrix}\frac{-R_{fc}}{L_{fc}} & \frac{-1}{L_{fc}}\\ \frac{-1}{C_f} & 0\end{bmatrix}}_{A}\begin{bmatrix}i_c\\ v_c\end{bmatrix}+\underbrace{\begin{bmatrix}\frac{-1}{L_{fc}} & 0\\ 0 & \frac{-1}{C_f}\end{bmatrix}}_{B}\begin{bmatrix}u_c\\ i_o\end{bmatrix} \tag{3}$$

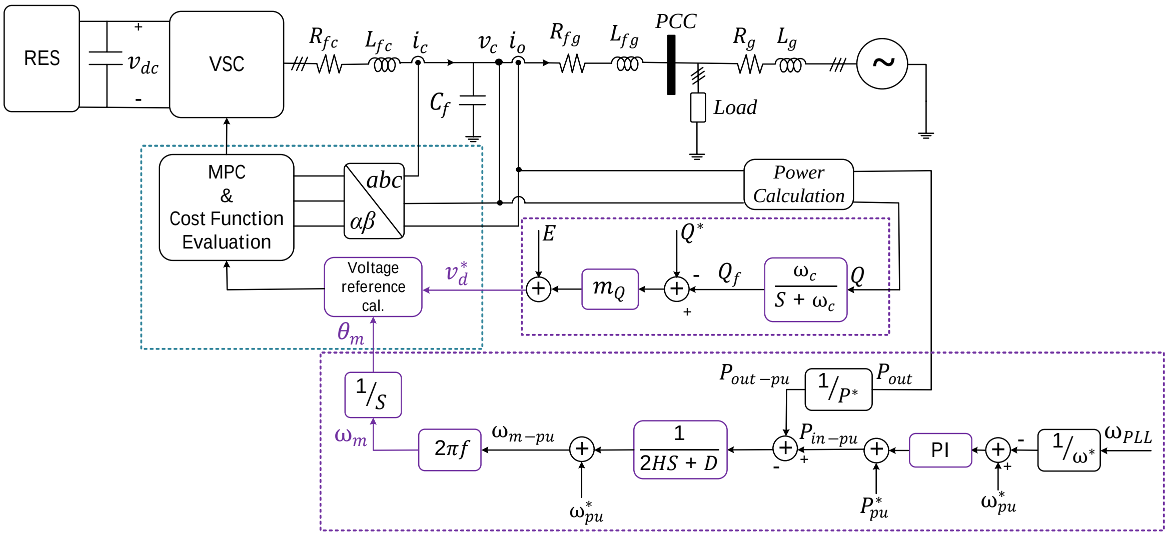

Fig. 1: The general model and the proposed control.

Description of the proposed control

The proposed control structure of the grid-forming converter includes two parts, the inner control part, and the outer control part. In the inner control part, a model predictive-based FRT control strategy is proposed to obtain desired performance in both normal and fault condition. In the outer control part, a VSG scheme is used to emulate the inertia and oscillation damping characteristics of SGs in the control structure of the converter.

Model predictive control

For the inner control part, a model predictive control is proposed instead of the conventional PI-based cascaded voltage and current control loop, resulting in a simpler control structure. In the conventional cascaded voltage and current control loop, at least ten parameters should be tuned, resulting in a complex control design. However, MPC can provide a simpler control structure with faster dynamic response. In principle MPC determines the performance of the system for the equivalent voltage vectors of the voltage source converter (VSC) in each of the eight possible switching states of the 2-level VSC. In fact, by employing a cost function, which follows some objectives, the cost function for each of these eight cases are estimated, and finally the optimal performance and switching state are predicted. These switching states are immediately used for the switching of the VSC without any modulator which is employed by PWM-based control. All the possible switching states and the equivalent voltage vectors of the 2-level voltage source converter are given in the Table 1.

Table I: Switching States and the Equivalent Voltage Vectors of the 2-level VSC

Index n	Switching state $\{S_{abc}\}$	Voltage Vectors
0	$\{000\}$	0
1	$\{100\}$	$\frac{2V_{dc}}{3}$
2	$\{110\}$	$\frac{V_{dc}}{3}+j\frac{\sqrt{3}V_{dc}}{3}$
3	$\{010\}$	$\frac{-V_{dc}}{3}+j\frac{\sqrt{3}V_{dc}}{3}$
4	$\{011\}$	$\frac{-2V_{dc}}{3}$
5	$\{001\}$	$\frac{V_{dc}}{3}-j\frac{\sqrt{3}V_{dc}}{3}$
6	$\{101\}$	$\frac{V_{dc}}{3}-j\frac{\sqrt{3}V_{dc}}{3}$
7	$\{111\}$	0

As model predictive control algorithm needs discrete model, the discrete-time equivalent of the model given in (3) considering a sampling period of T_s is represented as:

$$\begin{bmatrix} i_{c,k+1} \\ v_{c,k+1} \end{bmatrix} = \underbrace{\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}}_{A_d} \begin{bmatrix} i_{c,k} \\ v_{c,k} \end{bmatrix} + \underbrace{\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}}_{B_d} \begin{bmatrix} u_{c,k} \\ i_{o,k} \end{bmatrix} \tag{4}$$

where subscript k and $k+1$ define the current sampling instant and the next sampling instant in discrete mode, respectively and A_d and B_d matrices are discrete equivalent of matrices A and B, defined as:

$$A_d = e^{AT_s}, B_d = \int_0^{T_s} e^{A\tau} \cdot B \cdot \mathrm{d}\tau \tag{5}$$

In order to make sure that all the state variables are immediately affected by the control input action of u_c, an algorithm with prediction horizon of two is employed. Therefore, sampling instant of $k+2$ is predicted using the following equation:

$$\begin{bmatrix} i_{c,k+2} \\ v_{c,k+2} \end{bmatrix} = \underbrace{\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}}_{A_d} \begin{bmatrix} i_{c,k+1} \\ v_{c,k+1} \end{bmatrix} + \underbrace{\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}}_{B_d} \begin{bmatrix} u_{c,k+1} \\ i_{o,k+1} \end{bmatrix} \tag{6}$$

Model predictive control algorithm employs a prediction process to generate switching signals of the converter. In this prediction process, a cost function is defined containing three control objectives, tracking reference voltage, tracking reference current, and limiting current as FRT ability. The cost function is defined in (7) and all the eight switching states are employed to predict the minimum value of the cost function, resulting in extracting the optimum switching state of the converter.

$$CF = \|v_{c,ref} - v_{c,k+2}\|^2 + \lambda \|i_{c,ref} - i_{c,k+2}\|^2 \tag{7}$$

where $v_{c,k+2}$ and $i_{c,k+2}$ are the predicted value of capacitor voltage and inductor current at time instant $k+2$, λ is the weighting factor of the cost function, and $v_{c,ref}$ and $i_{c,ref}$ are the reference of the capacitor voltage and inductor current. The voltage reference, $v_{c,ref}$, comes from the $Q-V$ droop control that is briefly described in the following subsection. The current reference, $i_{c,ref}$, is extracted from voltage reference provided by outer control part as follow:

$$i_{c,ref} = i_{o,k} + jC_f \omega_{m,k} v_{c,ref} \tag{8}$$

The proposed control includes a constraint for the time when the converter current exceeds its maximum allowable current, i.e., $I_{max} = 1.2pu$. When the converter current exceeds $1.2pu$, a new reference current, as expressed in (9), substitutes the previous reference current. This new reference current along with employing a new weighting factor for fault situation guarantee the FRT ability of the converter while THD of the voltage and current during fault are quite low which ensures high power quality.

$$i_{c,ref} = \begin{cases} I_{max} \frac{i_{c,ref}}{|i_{c,ref}|}, & \text{if } |\, i_{c,ref} \,| > I_{Max} \\ i_{c,ref} & \text{otherwise.} \end{cases} \tag{9}$$

Outer control loop

In the outer control part, as a VSG, the important features of SGs, i.e., inertia and oscillation daming features, are virtually emulated in the control structure of the VSC. To do so, the swing equation, expressed in (10), is implemented in the outer control part.

$$2H \frac{d(\omega_m - \omega_0)}{dt} = P_{in-pu} - P_{out-pu} - D(\omega_m - \omega_{PLL}), \frac{d\theta_m}{dt} = \omega_m \tag{10}$$

where, P_{in-pu} and P_{out-pu} are the input and output power of the converter in per unit and D, H represent the damping factor and inertia constant, respectively.

As shown in Fig. 1, the outer control part also includes $P-f$ droop control, expressed in (11), to provide frequency regulation. This outer control part defines the reference phase angle and the angular frequency for the inner control part. The $Q-V$ droop control, expressed in (12), is also employed to provide the reference voltage for the inner control part.

$$P^* = P_0 + \frac{1}{m_p}(\omega_0 - \omega_{PLL}) \tag{11}$$

$$v^* = E + m_Q(Q^* - Q_f) \tag{12}$$

where, m_p and m_Q represent the active and reactive power droop coefficients, Q^* and Q_f are the reference reactive power and the output reactive power of the converter, respectively.

Simulation results

To verify the performance of the proposed model predictive-based FRT control strategy simulation results are presented and discussed in this section. Parameters of the model and the proposed control technique, depicted in Fig. 1, are listed in Table II.

Table II: Parameters of the model and the proposed control method

Parameters	Values	Parameters	Values
Nominal voltage (v)	230 V	Damping factor (D)	240
Nominal frequency (f)	50 Hz	Inertia costant (H)	6 s
DC-Link voltage (V_{DC})	750 V	$P-f$ droop coefficient (m_p)	0.04
Reference power (P^*, Q^*)	12 kW	$Q-V$ droop coefficient (m_Q)	0.002
LCL filter (L_{fc}, C_f, L_{fg})	3.3 mH, 8.8 µF, 3 mH	Sampling time (T_s)	10 µs
Grid Impedance (R_g, L_g)	0.22 Ω, 7 mH	weighting factor (λ)	3/40

The grid-forming VSG-based converter is connected to the grid and is intended to supply a reference active power of 12 kW and reactive power of 0. At first, it operates in normal condition while after 1 s a three-phase fault with the duration of 0.15 s occurs at the line connecting the converter to the grid. Fig. 2 illustrates the capacitor voltage and the converter current during the normal and fault-mode conditions, comparing the proposed FS-MPC-based FRT with the control presented in [12], as well as the conventional PI-based cascaded controller equipped with anti-windup. As shown in Fig. 2 (e) and (f), the proposed controller in this paper provides the best performance during normal and fault conditions. It limits the converter current during fault condition while ensuring power quality with a low THD of 1.42% and 1.16% for voltage and current, respectively. Conventional PI-based cascaded controller has a more complex control structure in terms of parameter-tuning efforts and it also requires anti-windup to ensure the normal operation after fault clearance. Moreover, simulation results, shown in Fig. 2 (a) and (b), illustrate that the current limiting ability of this control technique is not reliable enough, as converter current during fault reaches $1.6pu$ instead of limiting to $1.2pu$. Fig. 2 (c) and (d) illustrate the performance of the FS-MPC-based control proposed in [12]. Although this control technique provides a strict current limiter during fault mode, power quality is very low with THD of 15.13% and 6.55% for voltage and current, respectively. THD of voltage and current waveform in all the three cases are shown in Fig. 3, comparing the power quality of the proposed controller with the other cases.

Conclusion

In this paper, an FS-MPC control is developed to improve the FRT ability of the grid-forming VSG-based converters. This control technique provides overcurrent protection for the converter while ensuring the power quality during normal operation and fault conditions. The proposed control technique is compared

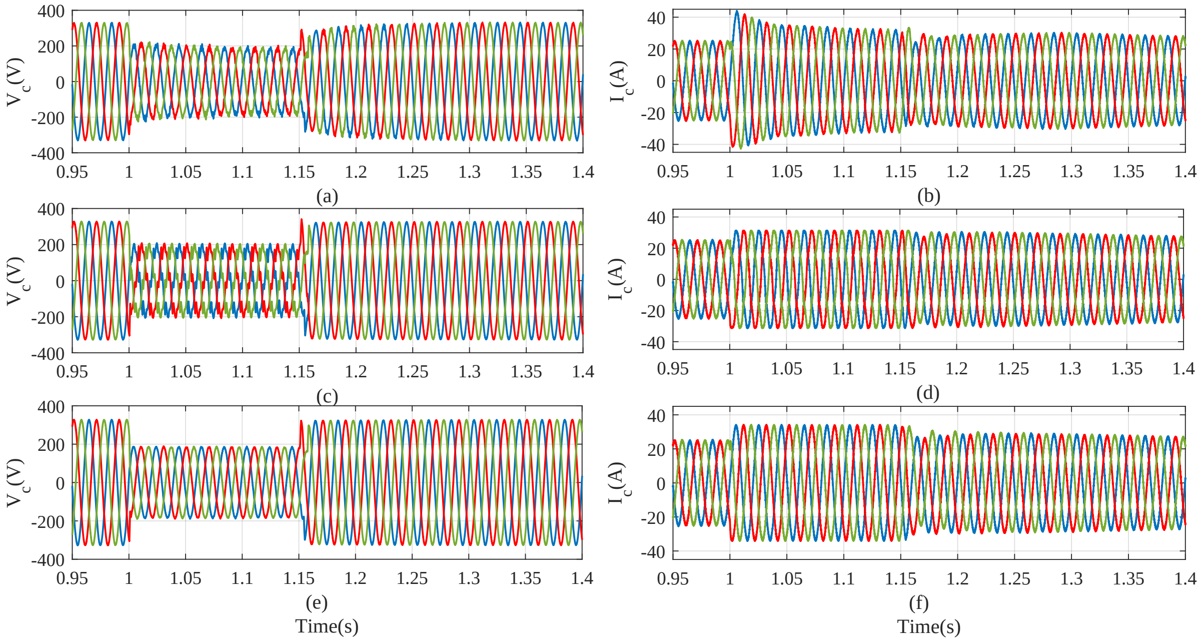

Fig. 2: Capacitor voltage and inductor current in (a),(b) the conventional PI-based cascaded controller equipped with anti-windup, (c),(d) the FS-MPC presented in [12], and (e),(f) the proposed FS-MPC-based FRT.

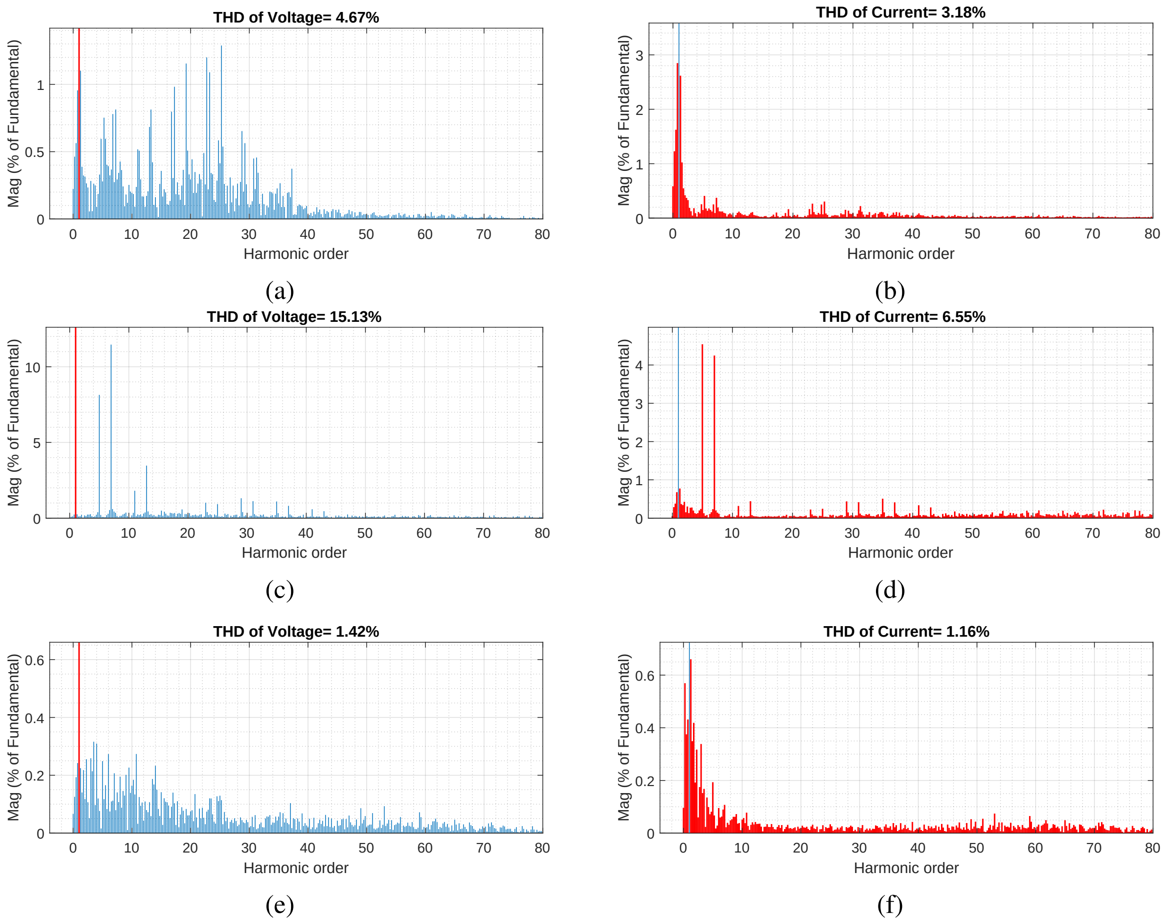

Fig. 3: THD of voltage and current waveforms in (a),(b) the conventional PI-based cascaded controller equipped with anti-windup, (c),(d) the FS-MPC presented in [12], and (e),(f) the proposed FS-MPC-based FRT.

with a PI-based control strategy as well as an MPC- based control technique with a defined current limiter as part of the cost function. Compared to the conventional PI-based cascaded controllers, it has a simple control structure without a modulator, anti-windup, and try and error for parameter-tuning. Besides, simulation results clearly confirmed that the proposed control technique is able to immediately avoid overcurrent when a fault occurs, while it is impossible for PI-based controller to avoid overcurrent so fast. In comparison with the MPC-based control with the defined current limiter, the proposed control technique shows a significant improvement in power quality.

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