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Finite control set model predictive control scheme of four-switch three-phase rectifier with load current observer

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ABSTRACT

Three-phase rectifier is typically realized by six power switches. However, this rectifier is fault sensitive in power switches. To enable continued controllable operation, the grid phase with fault rectifier leg can be connected to center tap of the dc-link capacitors, known as the four-switch three-phase rectifier (FSTPR), using hardware reconfiguration. However, the symmetry of three-phase currents and reliable operation of the FSTPR cannot be retained due to the offset of the two-capacitor voltages. This paper proposes a finite control set model predictive control (FCS-MPC) to obtain the balanced three-phase current with the offset of two-capacitor voltages suppressed. The PI-Controller-free FCS-MPC with a second-order Luenberger observer is adopted to improve the dynamic performance of FSTPR. The performance of the proposed control scheme is illustrated by extensive simulation and experimental results. The comparison with the conventional voltage-oriented-control, which is based on PI controller and pulse width modulation (PWM), is also presented to show the superiority of the proposed FCS-MPC.

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1. Introduction

Six-switch three-phase rectifier (SSTPR) has been increasingly employed in recent years owing to its advantages of bidirectional power flow, sinusoidal line current, controllable power factor and good dc-link voltage regulation ability (Malinowski, Kazmierkowski, & Trzynadlowski, 2003; Rodriguez, Dixon, Espinoza, Pontt, & Lezana, 2005; Singh et al., 2004). According to the investigation, about 38% of the faults in SSTPR result from the failures of the power devices such as insulated-gate bipolar transistors (IGBTs) (Im, Kim, Lee, & Lee, 2013), a complicated phenomenon , which depends on multi-physics of electrical energy consumption devices as well (Yu, Wang, & Cheng, 2016, 2017). In case of an open-switch in one of the rectifier legs, the four-switch three-phase rectifier (FSTPR), which connects the grid phase with the fault rectifier leg to center tap of the dc-link capacitors, is a possible solution for fault-tolerant operation. The concept of FSTPR is illustrated in Fig. 1.

However, there are several shortcomings which hinder the application of FSTPR. First, with the same ac supply, the lower output voltage bound is much higher than that of a SSTPR (Pan, Chen, & Hwang, 2001). Typically, the lower output voltage bound of the FSTPR is increased by 173.2%. The high output voltage feature limits its application. Second, the symmetry of three-phase current and reliable operation of the system cannot be retained due to the offset of the two-capacitor voltages.

Several papers adopted conventional control scheme based on pulse width modulation (PWM) to achieve high performance control of FSTPR (Klima, Skramlik, & Valouch, 2007; Lee & Liu, 2011; Shieh, Pan, & Cuey, 1997). However, these schemes cannot yield balanced three-phase current. Because in a FSTPR, only two-phase line-line modulating waveforms can be generated and the voltages applied to each phase are not equal due to the capacitor voltage fluctuation of the center tap.

Meanwhile, the imbalanced current flowing in the two capacitors can cause the capacitors' voltage deviation which is related to the reliable operation of the FSTPR. Regarding this issue, several papers have been published. In the work of Ounie and Zolghadri (2009), a space vector modulation approach is proposed to control a FSTPR with power factor correction and to compensate the effect of the capacitor voltage ripple. But it is an open loop strategy with poor dynamic performance. And they propose an additional controller in the current loop to compensate the dc voltage offset of the capacitors based on small signal model (Ouni, Shahbazi, & Zolghadri, 2013). However, the effect of the additional controller is not investigated yet. Zeng et al. investigates the control schemes based on space vector approach. Several optimized methods are

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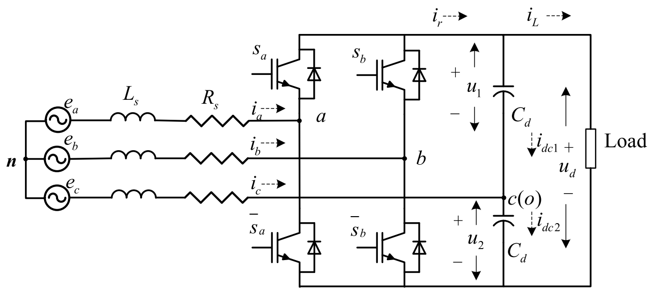

Fig. 1. Power circuit of the three-phase four-switch voltage source rectifier.

proposed to improve the performance of the FSTPR (Zeng, Zheng, Zhao, Zhu, & Yuan, 2016a, b). In Anzalchi, Moghaddami, Moghaddasi, Pour, and Sarwat (2016) and Anzalchi, Moghaddami, Moghaddasi, Sarwat, and Rathore (2016) new type of higher order power filter is designed to attenuate high frequency harmonics. The parameter design process is in detail presented. The modified filter improves the total harmonic distortion (THD) and keeps the variation of the maximum power factor unchanged.

Recently, owing to the fast development of powerful control platforms, increasing attention has been paid to the application of model predictive control (MPC) in power electronics (Cortés, Kazmierkowski, Kennel, Quevedo, & Rodríguez, 2008; Geyer, Papafotiou, & Morari, 2009; Kouro, Cortés, Vargas, Ammann, & Rodríguez, 2009; Papafotiou, Kley, Papadopoulos, Bohren, & Morari, 2009; Xia, Liu, Shi, & Song, 2014), especially the finite control set model predictive control (FCS-MPC) which directly applies the control action to the converter without coordinates transformation or modulators (Rodriguez et al., 2013). Intensive researches have been carried out on SSTPR using FCS-MPC (Cortes, Rodríguez, Antoniewicz, & Kazmierkowski, 2008; Kwak, Moon, & Park, 2014; Pérez, Fuentes, & Rodríguez, 2011; Quevedo, Aguilera, Pérez, & Cortés, 2010; Quevedo, Aguilera, Pérez, Cortés, & Lizana, 2012; Zhang, Xie, Li, & Zhang, 2013). In Cortes et al. (2008), the active and reactive power is controlled by a FCS-MPC scheme with the cost function. The active power reference for the regulation of the dc-link voltage is obtained using a linear PI controller. In Quevedo et al. (2010, 2012), a FCS-MPC method for calculating a compatible reference for both the active power and the dc-link voltage is proposed to improve the dynamic performance. But the non-zero steady-state error exists in this approach. Because the value of load resistor is directly used in the calculation of the dynamic reference.

In this paper, a discrete-time state–space model in the stationary frame of the FSTPR is derived to carry out FCS-MPC. The balanced three-phase current and reliable operation of the system are achieved with the offset of two-capacitor voltage suppressed. To improve the dynamic performance, PI-Controller-free FCS-MPC is utilized in the reference calculation. The main characteristic of this control method is its no need for liner current controller, coordinates transformation or modulators. Meanwhile, a second-order Luenberger observer is designed to estimate the load current without extra current sensor. Experimental results of the conventional voltage-oriental-control based on PI controller and PWM (known as PI-PWM) (Lee & Liu, 2011) are also provided to show the superiority of the proposed designs. The rest of this paper is organized as follows. In Section 2, the model of FSTPR is illustrated. The proposed FCS-MPC for FSTPR is shown in Section 3. Simulation based analysis of the proposed scheme is presented in Section 4. In Section 5, experimental results are shown. The conclusions are drawn in Section 6.

2. Model of FSTPR

This work focuses on the FSTPR shown in Fig. 1, where e_a, e_b, e_c are the ac-side source voltages, i_a, i_b, i_c are the ac-side source currents, u_a, u_b, u_c are the converter voltages, R_s is the equivalent series resistance, L_s is the filter inductance, C_d is the capacitance of the two dc-link capacitors, u_1, u_2 are the voltages of the two capacitors, s_a, s_b are the switching states of the two converter legs, i_r is the rectifier current, i_L is the load current, i_{dc1}, i_{dc2} are the upper and lower capacitor currents, u_d is the total dc-link voltage. This rectifier has two legs with each leg connected to one phase and the third phase connected to the center tap of two capacitors. The rectifier is connected to the three-phase voltage $\vec{e}_s$ using the LC filter.

2.1. Continuous-time model

Assuming that the potential-c equal to potential-o (o is the neutral point of the rectifier and n is the neutral point of the grid), the phase-to-phase voltages can be expressed as

$$\begin{aligned} u_{ao} &= s_a u_1 + (s_a - 1)u_2 \\ u_{bo} &= s_b u_1 + (s_b - 1)u_2 \\ u_{co} &= 0 \end{aligned} \tag{1}$$

where the switching variables s_a and s_b are equal to 1 if the associated switches are on, and equal to 0 if they are off. Then the phase-to-neutral voltages (Zeng et al., 2016b) are expressed as:

$$\begin{aligned} u_{an} &= (\frac{2}{3}s_a - \frac{1}{3}s_b)u_1 + (-\frac{1}{3} + \frac{2}{3}s_a - \frac{1}{3}s_b)u_2 \\ u_{bn} &= (-\frac{1}{3}s_a + \frac{2}{3}s_b)u_1 + (-\frac{1}{3} - \frac{1}{3}s_a + \frac{2}{3}s_b)u_2. \\ u_{cn} &= (-\frac{1}{3}s_b - \frac{1}{3}s_a)u_1 + (\frac{2}{3} - \frac{1}{3}s_a - \frac{1}{3}s_b)u_2 \end{aligned} \tag{2}$$

The dynamic function of the total dc-link voltage $u_d(t)$ is characterized via

$$C_d\frac{du_1(t)}{dt} = i_{dc1}(t), C_d\frac{du_2(t)}{dt} = i_{dc2}(t) \tag{3}$$

$$u_d(t) = u_1(t) + u_2(t). \tag{4}$$

2.2. Discrete-time model

The FCS-MPC control scheme is operated in discrete time with fixed sampling period $T_s > 0$. To obtain a discrete time model of the system, we define $\mathbf{i_s}(k) = \begin{bmatrix} i_a(k) & i_b(k) \end{bmatrix}^{\mathrm{T}}$, $\mathbf{e_s}(k) = \begin{bmatrix} e_a(k) & e_b(k) \end{bmatrix}^{\mathrm{T}}$, $\mathbf{s}(k) = \begin{bmatrix} s_a(k) & s_b(k) \end{bmatrix}^{\mathrm{T}}$, $\mathbf{u}(k) = \begin{bmatrix} u_1(k) & u_2(k) \end{bmatrix}^{\mathrm{T}}$ where $k \in \mathrm{N}$ refers to the sampling instant kT_s. The Euler-based discretized state equations of the FSTPR are shown as:

$$\begin{aligned} \mathbf{i_s}(k+1) = {} & \frac{T_s}{L_s}(-\mathbf{M}\mathbf{s}(k)\boldsymbol{\Lambda}_1^T + \mathbf{N})\mathbf{u}(k) \\ & + (1 - \frac{R_s T_s}{L_s})\mathbf{i}_s(k) + \frac{T_s}{L_s}\mathbf{e_s}(k) \end{aligned} \tag{5}$$

$$\mathbf{u}(k+1) = \mathbf{L_c}\mathbf{u}(k) + \frac{T_s}{C_d}(\boldsymbol{\Lambda}_1\mathbf{s}(k)^{\mathrm{T}} - \boldsymbol{\Lambda}_2)\mathbf{i_s}(k) \tag{6}$$

where $\mathbf{M} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$, $\mathbf{N} = \frac{1}{3}\begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix}$, $\boldsymbol{\Lambda}_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$, $\boldsymbol{\Lambda}_2 = \begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix}$, $\mathbf{L_c} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \frac{T_s}{C_d R_L}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$.

The state vector of the FSTPR is defined as follows:

$$\mathbf{x}(k) = \begin{bmatrix} \mathbf{u}(k) \\ \mathbf{i}_s(k) \end{bmatrix}. \tag{7}$$

Then, the state–space model of FSTPR can be expressed as follows

$$\mathbf{x}(k+1) = \mathbf{A}_{\mathbf{s}(k)}\mathbf{x}(k) + \mathbf{B}e_s(k) \tag{8}$$

where $\mathbf{A}_{\mathbf{s}(k)} = \begin{bmatrix} \boldsymbol{\Gamma} & \frac{T_s}{C_d}(\boldsymbol{\Lambda}_1\mathbf{s}(k)^{\mathrm{T}} - \boldsymbol{\Lambda}_2) \\ \frac{T_s}{L_s}(-\mathbf{M}\mathbf{s}(k)\boldsymbol{\Lambda}_1^T + \mathbf{N}) & (1 - \frac{R_s T_s}{L_s})\mathbf{I}_2 \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} 0_{2\times2} \\ \frac{T_s}{L_s}\mathbf{I}_2 \end{bmatrix}$, $\boldsymbol{\Gamma} = \begin{bmatrix} 1 - \frac{T_s}{C_d R_L} & -\frac{T_s}{C_d R_L} \\ -\frac{T_s}{C_d R_L} & 1 - \frac{T_s}{C_d R_L} \end{bmatrix}$, $\mathbf{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$.

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