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Robust sliding mode control for three-phase rectifier supplied by non-ideal voltage

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ABSTRACT

This paper proposes a linear feedback structure of sliding mode control for a three-phase rectifier fed by a non-ideal supply voltage. The aim of the proposed technique is to achieve power flow with unity power factor even under distorted and/or unbalanced grid voltage condition. The performance of the proposed sliding mode control strategy is investigated and compared with the traditional PI control technique. Simulation, and implementation studies are conducted to prove that the proposed scheme has better performances than traditional solutions under different operating conditions. The investigation is aimed to show proposed system robustness against grid disturbances.

1. Introduction

The best adopted topology of AC/AC conversion to supply electrical drives, is based essentially on a controllable three phase rectifier–inverter connection (Kolar, Friedli, Rodriguez, & P.W.Wheeler, 2011; Liutanakul, Pierfederici, & Meibody-Tabar, 2008; Xiao, Zhang, Wang, & Du, 2016). The operation of electrical drives at different speed and load levels leads to fluctuations of the dc-link voltage. In order to avoid this problem, a three-phase rectifier allowing for a bidirectional power flow is employed (Yin, Zhao, Lu, Yang, & Zou, 2014; Zhang, Yi, Dong, Liu, & Kang, 2015). Such, a three-phase rectifier along with adequate control algorithm has the capability of independently controlling active and reactive powers with bidirectional flow while maintaining a constant dc-link voltage. Such system combination, has other advantages such as maintaining sinusoidal line current, controlling power factor, and achieving constant dc-link voltage with a small filter capacitor (Kasmierkowski & Malesani, 1998; Malinowski, Kazmierkowski, & Trzynadlowski, 2003; Rodriguez, Dixon, Espinoza, Pontt, & Lezana, 2005).

Different strategies have been proposed for controlling three-phase rectifiers, such as Direct Power Control (DPC) (Martinez-Rodriguez, Escobar, Valdez-Fernandez, Hernandez-Gomez, & Sosa, 2014; Noguchi, Tomiki, Kondo, & Takahashi, 1998), Virtual-Flux Oriented Control (VFOC) (Malinowski et al., 2003; Norniella et al., 2014), and Voltage Oriented Control (VOC) (Malinowski, 2001). The latter is considered as the most popular because it is a Pulse-Width Modulation (PWM) based technique, operating at fixed switching frequency and it allows a high indirect control performance of active and reactive powers. The high dynamic and static performances of the power control are guaranteed via internal current closed loops based on the model obtained in synchronously rotating reference frame (Blasko & Kaura, 1997; Chen & Liao, 2014; Hengchun, Boroyevich, & Lee, 1998; Yin, Oruganti, Panda, & Bhat, 2009). The Unity Power Factor (UPF) condition is obtained by aligning the line current with the phase voltage vector of the power supply. However, the main drawback of the VOC method is that the performance highly relies on the completeness of current decoupling, the accurate tuning of PI parameters, and the grid voltage quality (Li et al., 2010; Yongsug, Yuran, & Dohwan, 2011).

Indeed, a non-ideal grid voltage, which generally refers to an unbalanced and/or distorted voltage condition eventually caused by symmetrical/asymmetrical faults, affects the power quality of the industrial drives and lead to fluctuations on the power exchanged with the grid (Abu-Rub, Malinowski, & Al-Haddad, 2014). Consequently, the system power factor is deteriorated (Li et al., 2010).

Sliding Mode Control (SMC) has been widely used due to its distinguished properties, such as non-sensitivity to parameters variation, external disturbance rejection, and fast dynamic response (Buhler, 1985; Hung, Gao, & Hung, 1993; Utkin, 1977). The SMC technique is considered as an alternative method to the PI controller due to better robustness and dynamic performances under different operating

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Nomenclature

R	Filter resistor
L	Filter inductor
C	Filter capacitor
R_l	Load resistor
U	Line-to-neutral voltage
V_{dc}	dc-link voltage
i	Current
i_l	Load current
S	Switch state
$.^*$	Desired value
$.^g$	Grid side
$.^c$	Converter side
$\cdot_{a,b,c}$	Natural 3-phase frame
$\cdot_{dq}$	Synchronous rotating reference frame quantities

conditions. A number of papers have appeared in the scientific literature dealing with the application of SMC for three-phase rectifiers (Flores-Bahamonde, Valderrama-Blavi, Martnez-Salamero, Maix-Alts, & Garca, 2014; Guzman, de Vicua, Morales, Castilla, & Matas, 2016a; Hu, Shang, He, & Zhu, 2011; Jezernik, 2013; Ma, Xie, & Shi, 2016; Mazumder, 2005; Pinto & Silva, 1999; Silva, 1999). These research works were conducted based on relay control with variable switching frequency (Flores-Bahamonde et al., 2014; Hu et al., 2011; Jezernik, 2013; Ma et al., 2016; Mazumder, 2005) or based on equivalent control at fixed switching frequency (Guzman et al., 2016a; Pinto & Silva, 1999; Silva, 1999). Good performances have been obtained despite the excessive actuator stress, especially at variable switching frequency. Linear Feedback Structure of Sliding Mode Control (LFS-SMC) has many advantages compared to the other structures, in term of robustness and less chattering effect. Indeed, this structure is based on switching, which offers better robustness performances. Furthermore, the dependency among the generated control signals and the error between the measured and controlled variables allow reducing the chattering effect and in turn reducing the actuator stress (Buhler, 1985; Hung et al., 1993; Utkin, 1977).

This paper presents the design of LFS-SMC for overall VOC of three-phase rectifier. In fact, the proposed solution is designed for the inner current loop and external dc-link voltage loop. The design for the inner-loop is based on the linearized system while the external loop design is based on the differential equation deducted from Akagi's power theory, governing the dc-link voltage for three-phase rectifier (Akter, Mekhilef, Tan, & Akagi, 2016). This design is developed considering ideal voltage condition of the grid. Therefore, a main goal of this paper is to investigate the performance of the proposed SMC strategy and to compare it with the PI controller, under sudden non-ideal voltage conditions in the grid. Simulation and implementation results are given to show that the proposed scheme is suitable for all operating conditions and has good performances even during grid disturbances.

This paper is organized as follows. In Section 2, preliminaries about modelling of three-phase rectifier and design methodology of LFS-SMC are presented. Section 3 presents the application of LFS-SMC for three-phase rectifier. In this section, application of LFS-SMC for the inner current closed loop and external dc-link voltage closed loop, are presented. Obtained simulation results are given in Section 4 while the implementation results are presented in Section 5. Concluding remarks and possible future research directions are outlined in Section 6.

2. Preliminaries

Due to the increased interest on three-phase rectifiers in industrial applications, advanced control techniques for performance optimization have become a matter of great concern for many researchers. For instance, the performance of an unbalance compensating control algorithm was tested under unbalanced grid condition by Yongsug et al. (2011). Many other research works in have been published in the scientific literature addressing the same issue with variable or fixed switching frequency algorithms. A DPC based PWM algorithm has been proposed in Sato and Noguchi (2011) and in Zhang and Qu (2015) by using SVM technique for controlling the three-phase rectifier supplied by unbalanced and distorted input voltage. Li et al. (2010) and Wu, Panda, & Xu (2008) propose the application of a PI controller in stationary frame and cascaded control block diagram respectively for the same disturbed operating conditions.

Despite its remarkable robustness against disturbances, the effectiveness of the SMC applied to three-phase rectifiers has not been tested yet at non-ideal input voltage condition. The number of related papers discussed mainly the fast dynamic performance (Huang et al., 2014; Silva, 1999), the constant switching frequency for the sliding mode controller (Guzman, de Vicua, Morales, Castilla, & Matas, 2016b), and the minimization of the chattering phenomena by integrating a model predictive approach (Curkovic, Jezernik, & Horvat, 2013; Korelic & Jezernik, 2013). On the other way, all mentioned research works are based on the relay control or the equivalent control topology. However, these two topologies are characterized by excessive excitation of the power converter and dependency on the model parameters respectively.

Thus, the main contribution of this paper is the application of a VOC based LFS-SMC for a three-phase rectifier. This structure could be considered as a good compromise between the aforementioned SMC. This proposed structure is applied for the inner current loop as well as for the outer dc-link voltage loop. The robustness of the LFS-SMC is evaluated and compared to that offered by a conventional PI controller under unbalanced and distorted input voltage conditions.

2.1. Model of three-phase PWM rectifier

Maintaining the dc-link voltage at constant value depends mainly on the power flow control between the rectifier and the power grid. This task is performed by controlling the current through the inductor by varying downstream voltage of the converter. Fig. 1 shows the schematic diagram of the three-phase rectifier for bidirectional power flow. The main objective of VOC control is to generate the desired voltages $U^c_{a,b,c}$ through switching state with the required phase shift from the supply voltage, in order to define the necessary power flow by keeping the dc-link voltage at their desired constant value. In the natural frame, the electrical equation of rectifier can be described as following:

$$\begin{cases} \dfrac{di_j}{dt} = \dfrac{-R}{L} i_j + \dfrac{1}{L} U^g_j - \dfrac{1}{L} U^c_j \\ \dfrac{dV_{dc}}{dt} = \dfrac{1}{C}\left(\sum_j S_j i_j - i_l\right) \\ U^c_j = \dfrac{2S_j - \sum_{m\neq j} S_m}{3} V_{dc} \end{cases} \tag{1}$$

where $j, m = a, b, c$.

i_j is the j-line current, U^g_j is the j-line grid voltage, U^c_j is the converter voltage vector for line j, V_{dc} is dc-link voltage, S_j is the switching state of j-legs, (R, L) are the resistor and the filtering inductor, C is the filtering capacitor and i_l is the load current.

The active and reactive powers, P and Q, drawn from the grid are calculated by using information about the line voltage U^g_j and line currents i_j, then the explicit form can be written as follows:

$$\begin{cases} P = U^g_a i_a + U^g_b i_b + U^g_c i_c \\ Q = \dfrac{1}{\sqrt{3}}[U^g_a(i_c - i_b) + U^g_b(i_a - i_c) + U^g_c(i_b - i_a)] \end{cases} \tag{2}$$

The VOC technique method is based on the transformation between the natural three-phase reference frame (a, b, c) and synchronous rotating frame (d, q) by using the matrix A defined in (3). This transformation is realized by aligning the grid voltage vector (U^g) with the d-axis of