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Controllability of rectifiers and three point hysteresis line current control

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ABSTRACT

This paper analyzes the stability and switching controllability properties of a single-phase PWM rectifier and its relationship with parameter uncertainty. Based on this analysis, a switching control strategy is proposed that has as objectives (i) to achieve input current tracking and low current THD (total harmonic distortion) as well as (ii) to regulate the output voltage in spite of perturbations. The proposed control does not require a PWM generation step design. Numerical simulations and experimental tests in a 1 kW prototype demonstrate the effectiveness of the proposed controller and illustrate the limits of system's controllability.

1. Introduction

More and more applications require single-phase rectifiers to have a power factor correction (PFC) and a low THD; for example, adjustable speed drives, uninterruptible power converters for electric traction among many others. Several topologies have been proposed to satisfy these requirements. Additionally, these converters must satisfy load requirements despite parametric variations and disturbances in the input voltage, such as voltage sags or swells (Bollen, 2000), since nonlinear loads are particularly sensitive to these phenomena. An appropriate control scheme should be able to maintain the output DC voltage regulated to a desired level; however, one of the difficulties to design such an appropriate control scheme relies on the fact that the PWM rectifiers usually have a slow dynamic response with respect to the current dynamics, due to the presence of an output filter capacitor used to regulate the output DC voltage (Li & Wang, 2011; Mattavelli, Polo, Dal Lago, & Saggini, 2008). Therefore, the control scheme is usually designed to provide a trade-off between (i) a fast dynamic response and the reduction of the harmonic distortion at the input current and (ii) the regulation of the DC output voltage.

Taking into account the above, the control scheme design of PWM rectifiers is usually performed using two control loops. The first loop is constituted by a fast dynamics loop to control the input current, while a second slow dynamics loop regulates the output voltage (Rioual, Pouliquen, & Louis, 1994; Zeman, Blahnik, Peroutka, & Michalík, 2011). The fast dynamics of the input current in a full-bridge type PWM rectifier can be controlled by adjusting both the AC-side voltage magnitude at the bridge circuit terminals and its phase with respect to the angular deviation of the input current (Sato, Ishizuka, Nezu, & Kataoka, 1998).

There exists in the literature a variety of controllers proposed to satisfy the above rectifier specifications (see for example, Rioual et al., 1994; Sato et al., 1998; Zeman et al., 2011). Such strategies usually take into account an averaged model of the converter and they use either the theory of instantaneous power (PQ) or the theory of synchronous reference frame (DQ transformation) (Gonzalez, Cardenas, & Pazos, 2004) to deal with the time-varying system. In particular, the DQ transformation has been widely used due to its simplicity but also because it can be used as a method to detect voltage variations (sags or swells) (Escobar, Martinez-Montejano, Valdez, Martinez, & Hernandez-Gomez, 2011; Lira, Nunez, Cardenas, & Alvarez, 2006). The transformation to this framework allows the system to be described as DC driven, i.e. the model description uses only peak current and voltage magnitudes. On the other hand, the controllability conditions of these converters are usually analyzed under the PQ or DQ transformation, therefore the results are limited by the assumptions of the model

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derivation. Moreover, the role of time varying signals and switching actions on the controllability of the rectifier is not clear yet.

Among the controllers that use the PQ or DQ transformation, it is usually required the estimation of the reactive power. In these cases, it may be necessary to measure both input and output voltages and currents of the converter (Escobar et al., 2011; Gonzalez et al., 2004; Lira et al., 2006; Sato et al., 1998; Somkun, Sehakul, & Chunkag, 2005; Zeman et al., 2011), and/or to estimate the output ripple (Somkun et al., 2005), or to design observers to generate the peak current references. Since the models derived from DQ or PQ transformation are time-invariant and the system is continuously measured, the use of simple controllers such as PI or GPI suffices to lead the rectifier to the desired operating point despite some perturbations (Lira, Visairo, Nunez, Ramirez & Sira-Ramirez, 2012; Salaet, Alepuz, Gilabert, Bordonau, & Peracaula, 2002). However, once the control action is designed, an additional strategy must be used to generate the switching sequences. Most common used switching strategies are sinusoidal pulse width modulation (SPWM) and space vector modulation (SVM). Although many variations of these techniques have been proposed, it is difficult to avoid or minimize the harmonic distortion of the current because they require accurate synchronization between the carrier and the modulating signal in the case of SPWM or accurate comparison with the sampled reference signal in the SVM.

A recent alternative to generate the switching signals and to minimize harmonic distortion is to use the natural dynamics of the input current during each operation stage of the rectifier, examples of this kind of strategies are the hysteresis-type current controllers (Anshuman, Arindam, & Avinash, 2011; Donald & Reza, 2013; Prasad, Reddy, Chakkravaarthy, & Ankam, 2012). Based on this principle, in Prasad et al. (2012) the design of a sliding surface is proposed to generate the switching signals. The control action proposed in Prasad et al. (2012) improves the power factor and it has an appropriate response to load changes; Nishida, Miyashita, Haneyoshi, Tomita, and Maeda (1997) propose a design of three control schemes to improve power factor and to control the input current waveform. In Khazraei, Sepahvand, Ferdowsi, and Corzine (2013), an hysteresis type control, that uses a double band to envelope the input current, is designed in order to generate the switching signals. The objective of this double band is to contain the input current trajectory and to avoid the so-called *instability* problems of the rectifier operation at the zero-current crossing conditions. In Khazraei, et al. (2013) the advantages of the double band design are shown performing its comparison with respect to a control design of a rectifier in the DQ reference frame. It is worthy noticing that the above referenced phenomenon of instability has also been noticed in Marchesoni (1992), Wu, Zhang, and Wu (2014) for the case of inverters, in Zhang, Liu, and Zhang, Sun (2004), Qu and Ruan (2006), Bodetto, El Aroudi, Cid-Pastor, and Martinez-Salamero (2014) for the case of Single-Phase PFC Converters, in Chen and Liao (2015) for Three-Level Boost PFC Converters, in Yao, Lv, Zhang, and Lin (2014) for Vienna Rectifiers and in De Gussemé, Van de Sype, Ryckaert, De Vleeschauwer, and Melkebeek (2005) for PWM rectifiers; in every case, it is stated that the phenomenon of instability appears when the input current reaches the value of zero (the input voltage equals the voltage at the bridge circuit terminals for the PWM rectifier).

At this regard, the objective of this paper is twofold. On one hand, to take the case of a single phase PWM rectifier as a benchmark to study the controllability properties of the piecewise description of the converter and to establish their limitations in terms of system parameters and; on the other hand, to derive a switching control strategy that takes into account the controllability limitations of the system. As a result, in this paper it is found that the phenomenon of stability loss of the input current at the zero-current crossing conditions reported in the literature can be explained by a lack of controllability related to some switched modes. The conditions of controllability derived in this work, which are also derived for the system with uncertain parameters, naturally serves as guides for constructing alternatives switching sequences.

The proposed control scheme is designed using a piecewise continuous description of the system constituted by all the ON-OFF switching conditions; therefore it is not limited by assumptions made for the derivation averaged models or operation conditions, such as a switching frequency range. Two control loops are used, a switched current loop and a PI voltage loop to provide compensation against perturbations of the voltage. The switched control uses a single envelope for the inductor current and it can be designed as close to the reference $i_{in,ref}$ as desired,[1] leading to a control of the input current ripple and therefore to a control of its THD. The current control can also improve the power factor or deal with lagging or leading current references.

An advantage of the proposed scheme is that the output of the current controller gives directly the ON–OFF sequences of the switches; therefore, strategies such as SPWM and SVM are not necessary. Numerical simulations and experimental tests in a 1 kW PWM rectifier were carried out to demonstrate the advantages of the proposed control strategy. Comparison of the proposed scheme with respect to other controllers in the literature (Khazraei et al., 2013; Lira et al., 2012; Marchesoni, 1992; Wu et al., 2014) are performed to demonstrate the advantages of the proposed switching control scheme in terms of harmonic distortion. Variations in load and voltage sags were also induced to evaluate experimentally the designed control scheme.

Our contribution with respect to other recent controllers (Attaianese, Di Monaco, & Tomasso, 2013; Bodetto et al., 2014; Khazraei et al., 2013) is that in our approach, the input current ripple can be totally controlled, even in regions where the input current reference is near to zero. Secondly, the point of view of switched systems allows us to derive controllability conditions that lead to stable switching actions even in the presence of uncertainty. Thirdly, since the control action is a switching sequence, our approach do not make use of SPWM or vectorial techniques and the control action is obtained directly. Finally, our approach guarantee a finite maximal switching frequency, so chattering about zero current is avoided.

This paper is organized as follows: in Section 2 the structure, operation principle and different modes of rectifier operation are presented, as well as the switched model and theoretical foundation of the control strategy. The design of the control algorithm, the case of lagging or leading current references and the implementation of the strategy is presented in Sections 3, 4 and 5 respectively. Finally, some conclusions are shown in Section 6.

2. Description and operation principle of the single-phase PWM rectifier

Let us consider the PWM rectifier shown in Fig. 1. As can be seen, this rectifier has four controlled switches (Q_1, Q_2, Q_3, and Q_4) to properly operate the system. Rectifier operation requires two activated switches for each operation interval and two switches from the same leg cannot operate simultaneously, i.e. Q_1 operates complementarily to Q_2 as well as Q_3 to Q_4. These restrictions limit the number of valid modes, which are given in Table 1. As shown,

[1] Theoretically speaking; however experimentally, the maximum switching frequency of the semiconductor will define the closest envelope to $i_{in,ref}$ that can be used.