Active Damping Techniques for the LCL Filter Resonance in the Digitally Controlled Grid-Connected Converters

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論 文 名　: Active Damping Techniques for the LCL Filter Resonance in the Digitally Controlled Grid-Connected Converters
(ディジタル制御方式系統連系コンバータに用いられる LCL フィルタにおける共振に対するアクティブダンピング技術に関する研究)

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論 文 内 容 の 要 旨

Because of their higher attenuation for switching harmonics with lower weight and size, LCL filters are widely used to connect the pulse width modulated converters into the utility grid in order to limit the harmonic contents of the injected grid current to be complied with the grid codes; i.e. IEEE 519-1992. However, the resonance introduced by the LCL filters represents a challenge for control system designers.

For the digitally controlled converters, which have an inherent delay due to computations and sample and hold effect, the stability of single control loop can be maintained only for resonant frequencies higher than one-sixth of the sampling frequency. However, the stability violates if the resonant frequency decreases less than this critical value. Such decreasing in the resonant frequency can occur with the frequent increase in the grid inductance. Damping techniques have to be adopted to cope with this challenge. Compared to passive damping which causes power losses, active damping by modifying the control algorithm is more efficient.

Number of active damping methods have been presented in the literature. Capacitor-current-based active damping method is the simplest method among these methods. However, more number of sensors is needed. This, in turn, increase the overall system cost. Moreover, excitation of unstable open loop poles is mandatory for resonant frequencies more than one-sixth of the sampling frequency; this non-minimum phase behavior declines the system robustness. A differentiation of the capacitor voltage can be used to produce the damping effect; however, this method causes noise amplification. To reduce the number of sensors, grid-current-based active damping by using high-pass filter (HPF) can be employed. However, the co-design steps of this HPF along with the fundamental current regulator are very complicated.

In order to overcome the limitations of the existing active damping methods, some novel algorithms and analysis are proposed. The thesis consists of five chapters. These chapters can be summarized as follows:

In chapter one, a theoretical background about LCL filters, resonance problem and digitally controlled grid-connected converters are introduced. A literature review about the existing damping techniques along with their limitations are presented as well.

In chapter two, an observer in the control system is employed to estimate the capacitor current without the need for additional sensors. A systematic design of the observer loop is presented. The control algorithm is implemented in stationary reference frame to reduce the overall computation burden on control hardware. The results show that the observer-based system offers a good damping behavior without the need for additional sensors. This, in turn, reduces the overall cost.

In chapter three, a novel active damping method using two feedback loops of the capacitor voltage and the grid current is proposed. The proposed method is derived in the continuous time domain with a discussion for its discrete implementation. To show the superiority of the proposed method, a comparative study is presented. Compared to capacitor-current-based method, the cost is reduced by omitting the high cost current sensor. Moreover, the non-minimum phase behavior is avoided over wide range of resonant frequencies. Compared to capacitor-voltage-based method, the proposed method can behave effectively over wide range of resonant frequencies without stability violation or the need to a differentiator which amplifies the noise. Compared to grid-current-based method, straightforward co-design steps for the active damping loops along with the fundamental current regulator are proposed. The superiority of the proposed method is verified over wide range of resonant frequencies.

In chapter four, Active damping using High-pass filter (HPF) of the grid current is investigated. A detailed study for the actively damped filter in discrete time domain is introduced. Limits for the HPF parameters are derived in order to avoid the non-minimum phase behavior. Based on this investigation, the performance of this method is highly improved where the ability to avoid the non-minimum phase behavior is extended up to resonant frequencies about 0.39 of the sampling frequency. In addition, straightforward co-design steps for the HPF along with the fundamental current regulator are proposed. Numerical example and experimental work are carried out to confirm the obtained results.

In chapter five, the last chapter in the thesis, both the final summary and the conclusion outlines for the thesis are introduced. The expected future work is introduced as well.