An Improved Control for Voltage Source Converter using Filters

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ABSTRACT

This paper proposes a novel control strategy for grid-connected voltage source inverters (VSI) with an LCL-filter. The strategy "split" the capacitor of LCL-filter into two parts, and the current flowing between these two parts is measured and used as the feedback of a current regulator to stabilize and improve the system performances. By this way, the inverter control system is simplified from third-order to first-order, and the close loop control system can easily be optimized for minimum steady-state error and current harmonic distortion. The characteristics of the inverter system with the proposed controller are investigated and compared with the traditional strategy. Simulations results are provided, and the new current control strategy has been experimentally tested on a 5kW fuel cell inverter.

KEYWORDS: *LCL-Filter, Grid-Connected Voltage Source Inverters (VSI), Close Loop Control System, The Inverter System.*

I. Introduction

Traditionally, L-filter is used as the interface between the grid network and the grid-connected voltage source inverters (VSI). With the L-filter, high switching frequency must be used to obtain high dynamic performance and sufficient attenuation of harmonics caused by the PWM . In contrast, the alternative LCL form of low-pass filter offers the potential for improved harmonic performance at lower switching frequencies, which is a significant advantage in higher-power applications [1], (e.g. fuel cell, wind generations). However, systems incorporating LCL filters are of third order, and they require more complex current control strategies to maintain system stability and are more susceptible to interference caused by grid voltage distortion because of resonance hazards and the lower harmonic impedance to the grid. Inverter output current or grid current feedback PI control is commonly used for current-controlled inverters, but these solutions have two main drawbacks: inability of the PI controller to track a sinusoidal reference without steady-state error and poor disturbance rejection capability. This is due to the definite control loop gain required for system stability at the LCL-filter resonance frequency. In order to alleviate these problems, several other control strategies are presented recently, such as grid voltage feed-forward, multi-loop control, multi-variable control, and generalized integrator (GI) or P+Resonant (PR) with infinite gain at resonance frequency [2][3]. These strategies are more complex or sensitive to variations in system parameters. This paper proposes a new control strategy for grid-connected VSI with an LCL-filter. The strategy "split" the capacitor of LCL-filter in two parts, and the current flowing between these two parts is measured and used as the feedback of a current PI regulator. By this way, the inverter control system can be degraded from third-order to first-order, and the control loop gain and PI parameters can now optimized for minimum steady-state error and current harmonic distortion as a first-order system with L-filter. The characteristics of the inverter system with the proposed controller are investigated and compared with the traditional strategy. The new current control strategy has been experimentally verified on a 5kW DSP controlled fuel cell inverter.

II. System Structure for the Inverter

Fig.1 shows the system topology for the grid-connected VSI inverter. The topology comprises a PWM single-phase inverter, a low-pass LCL-filter, and current controlled regulator. There are several considerations for the design of the LCL-filter. The main three aspects are the attenuation at the switching frequency, the current ripple out of the inverter, and the reactive power of the filter. The switching frequency current ripple is caused by the pulsed voltage Vi from the inverter due to the PWM control. In Fig.1, The transfer function from Vi to grid current i2 is shown in (1).

$$G_{i_2}(s) = \frac{I_2(s)}{V_i(s)} = \frac{1}{\alpha(1-\alpha)L^2Cs^3 + Ls} \quad \text{------------(1)}$$

Here, LLL = +1 2 , α = L L 1 . The grid inductance Lg is included in L2, and series resistance of the inductance is neglected. In the case of the 5kW inverter having DC input voltage Vdc=400V, for example, with switching frequency at 16kHz, a LCL filter has been designed having a total inductance of 3.1mH and a capacitor of 12uF.

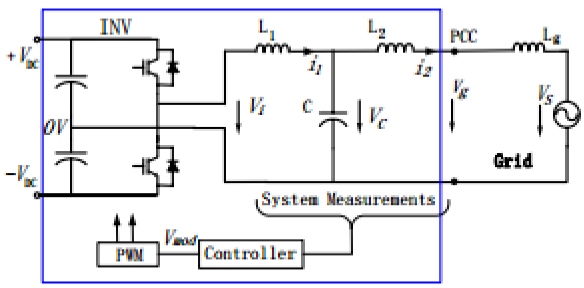

Fig.1 System topology for the utility-interactive inverter

Fig.2 shows the bode plot of the transfer function for different L1 and L2 combinations with a constant total inductance L. From the equation (1) and Fig. 2, the LCL-filter is shown to be a third-order function with a peak at the resonance frequency, and its phase change rapidly. When C=0, that means the L-filter is used, it is degraded to a first-order function (red solid line in Fig.2). From the equation (1), for a given frequency above the resonant frequency of the filter, the transfer function Gi2(s) gets the minimum amplitude at α=0.5. That is to say, for a fixed total inductance L, the filter has the maximum attenuation for high frequency switching ripple when L is split into half. (L1=L2=L/2, black solid line in Fig.2)

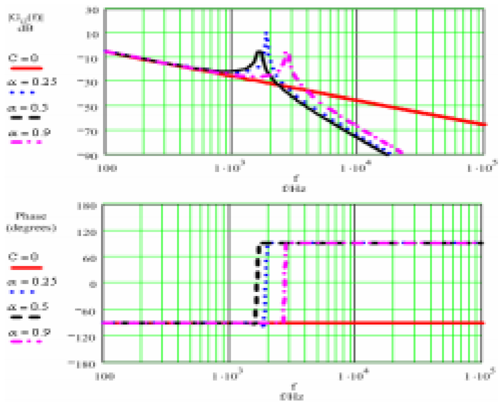

Fig.2 Transfer function for different L1 and L2 of LCL filter

III. Grid Connected VSI

The main purpose of this section is to introduce the reader to different aspects of a VSC connected to a grid. The main circuit configuration of the VSC is presented so the variables and their symbols can be defined and will be used henceforth. Furthermore, different types of grid filters and modulation techniques will be presented. Two control principles will be introduced, the voltage angle control and the vector current control principle. Finally, the modelling of the system will be described.

Main Circuit of VSC

A scheme of the main circuit of the VSC is shown in Fig. 5. The valves are of the IGBTtype. The VSC is connected to a symmetric three-phase load, which has the impedance R + jωL and the emfs e1(t), e2 (t) and e3 (t). The neutral point of the star-connected load has the potential v 0 (t), due to a floating ground. The phase potentials of the VSC are denoted as v1(t), v 2 (t) and v 3 (t). The phase voltages of the VSC are denoted as u1(t), u2 (t) and u3 (t). The current flowing from the dc-link to the converter is denoted as iv (t), the dc-link current is denoted as idc (t) and the dc-link voltage across the dc-link capacitor is denoted as udc (t).

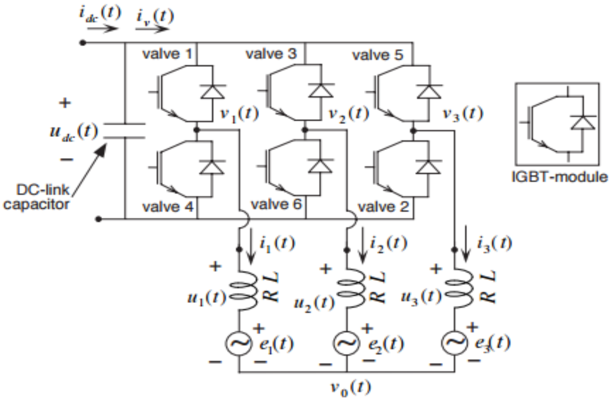

Figure 3: The main circuit of the VSC.

Grid Filters

When connecting a VSC to a grid, an inductor must be mounted between the VSC, which is operating as a stiff voltage source, and the grid, which also operates as a stiff voltage source [11]. The simplest and most common grid filter is the L-filter, which has three series connected inductors, one in each phase. The LC-filter has the same series inductors, one in each phase, as the L-filter. In addition, the LC-filter has three parallel coupled capacitors. This filter type has often been investigated for systems which are used in autonomous grids as an uninterruptible power supply and in most investigations, the load consists of resistors, one in each phase [12]. When connecting a system with the LC-filter to a public grid, problems can occur due to resonances. The resonance frequency depends on the capacitor value of the filter and the inductance value of the grid, which varies over time. It is difficult to reduce the resonance, because resonance frequency changes with grid inductance and, in addition, the harmonic distortion spectrum of the grid changes with time. The resonance problem can be reduced by using an LCL-filter [13]. The main advantages of using an LCL-filter are low grid current distortion and reactive power production. The resonance frequency can be determined almost independently of the grid configuration. The disadvantage is a more complicated system to control. The L-filter attenuation is a 20 dB/decade and the LCL-filter attenuation is a 60 dB/decade for frequencies over the resonance frequency of the filter. To improve the attenuation of the system when using the L-filter, a tuned shunt filter can be introduced which is tuned to the switching frequency of the VSC [14].

IV. Modulation

One of the advantages of the VSC over the grid-commutated converter is low harmonic distortion at low frequencies, resulting in sinusoidal grid currents. This is due to the fact that by switching the valves properly only high-frequency harmonics remain. The research field of modulation techniques has been focused on reducing the number of switching instances per cycle while still obtaining low distortion due to the current ripple caused by the switching instances [15]. The simplest modulation technique is the sixpulse modulation, where each phase switches twice per cycle. The fundamental voltage amplitude becomes high but harmonics occur at low frequencies: 5th, 7th, 11th, 13th and so on. By introducing more switching instants, the current ripple will be reduced as well as the fundamental voltage amplitude. Depending on the rated power of the VSC, the switching frequency is reduced when the rated power is increased. For small adjustablespeed drive systems, the switching frequency can be as high as 20 kHz. For converters used in high power applications, the switching frequency is reduced down to approximately 1 kHz. The most common modulation methods can be divided into two groups: either current control or voltage control. The current control method forces the valves to switch only when it is necessary to keep on tracking the reference of the current. This control principle is often called the current hysteresis control principle [16]. The second modulation type, voltage control, has as a common characteristic subcycles of constant time duration, a subcycle being defined as the total duration during which an active inverter leg assumes two consecutive switching states of opposite voltage polarity. Operation at subcycles of constant duration is reflected in the harmonic spectrum of the phase voltage by two dominating salient sidebands, centered around the switching frequency, and by additional frequency bands around integral multiples of the carrier [17]. The modulation type can be divided into two parts: a suboscillated pulse width modulation (PWM) and a space vector modulation, denoted by SVM. The latter modulation method is often used when microcontrollers are involved in the system. The suboscillation method is a classical modulation technique and employs individual modulators in each of the three phases. It is popular due to its simple implementation and is preferable when an analog system is used. The input to a space vector modulator is the voltage reference vector in the αβ-frame, explained in Appendix A. The sampled input vector is then approximated by a time sequence of three well-defined switching state vectors. The ordinary three-phase voltage source converter has 8 switching vectors, also displayed in Appendix A. The modulation algorithm ensures that the time average of the switching state vectors over a sampling interval is equal to the reference vector [18]. Compared with the sub-oscillating PWM method, the SVM method can be modified to reduce the number of valve switchings during each sample interval or to change the switching valve pattern. The SVM has the following advantages: The reference voltage vector can be decomposed in a number of ways and the selected voltage vectors can be applied to different sequences. By controlling the SVM in a smart way, it is possible to reduce the switching frequency while still obtaining the same sample frequency as in the sub-oscillated PWM. This is an advantage when the rated power of the VSC is increased. If the mid-point of the star-connected load is floating, a zero-sequence component can be added to all of the three phase reference voltages to extend the output voltage range of the converter by 15.5 % without losing the linearity from the reference voltage to the output voltage [19]. A triplen deadband PWM can be introduced to reduce the effective switching frequency, which reduces switching losses up to 33 % [20]. In this method, one leg of the converter is clamped for a certain period of time in each cycle, hence resulting in a deadband region in which no switching will occur.

V. Results and Circuit Diagram

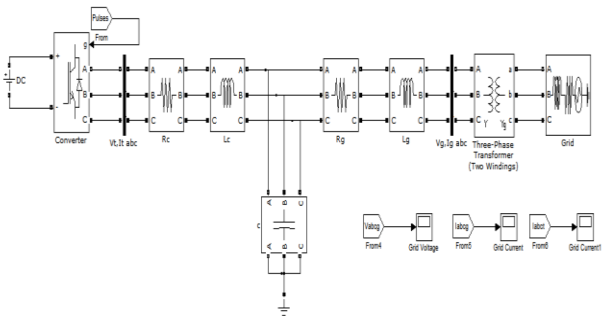

Fig 4: Circuit Diagram

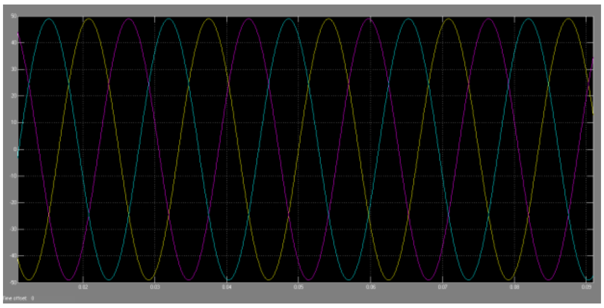

Fig5 : Grid Voltage

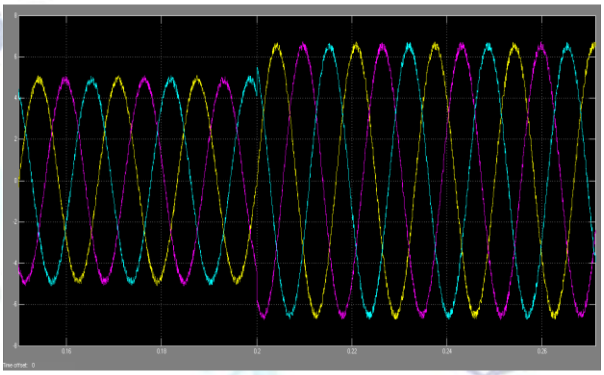

Fig 6: Grid Current

VI. Conclusion and Future Scope

A digital vector control strategy for the LCL-filter-based grid-connected VSCs is proposed in this paper. To damp the resonance phenomenon of the LCL-filter, a MIMO controller matrix is adopted, whose elements are linearly-parameterized high-order controllers with integrators. Contrary to the existing vector control schemes for VSCs with LCL-filters, the proposed approach does not require extra damping methods. Moreover, the dynamic performance of the proposed approach is similar to the existing ones while its axis-decoupling capability is superior. The design procedure of the proposed controller is based on loop shaping and has three main steps:

(1) attaining a nonparametric model of the system,
(2) determining the class of the to-be-designed controller, and
(3) solving a constrained convex optimization problem.

The performance of the controller is evaluated for several reference tracking scenarios. Based on simulation and experimental results, it is concluded that the proposed vector controller shows excellent dynamic performance in terms of reference tracking, axisdecoupling, and resonance attenuation, upon step-changes in the set-points of the dq□components of current. Moreover, despite uncertainties in the LCL-filter parameters, the dynamic performance of the controller is acceptable.

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