Interconnection of Voltage Source Converter to Utility Grid with LCL Filter using Resonance Damping Controllers

Dekka Udhaya Bhanu[1], Ch. Venkata Rao[2]

[1]M. Tech (PSCA), Department of Electrical and Electronics Engineering, Gayatri Vidya Parishad College of Engineering (A), Visakhapatnam, Andhra Pradesh, India.
[2]Assistant Professor, Department of Electrical and Electronics Engineering, Gayatri Vidya Parishad College of Engineering (A), Visakhapatnam, Andhra Pradesh, India.

Abstract: *In recent years, distribution generation has been expanding considerably. While interfacing the distributed generation to utility grid, power electronic devices are widely used to maximize the power transfer from DG to grid. The main aim of the power system is to ensure quality power to the customers. Thus, passive harmonic filters such as LCL filters are often preferred to mitigate the harmonics in Voltage Source Converters that are interconnected to the grid. The LCL filters however result in a resonant frequency that needs to be damped. The thesis proposes a current control technique to damp the resonant frequency in the grid-connected VSC with LCL filter. The harmonics in the system are analysed through the Fast Fourier Transform approach and the Total Harmonic Distortion of the VSC with and without filters is identified. The entire work is carried out in MATLAB/Simulink and resonance induced by the filters is damping by implementing current control techniques.*

Key Words: Voltage Source Converter, LCL Filter, Active Damping, Current Control, Internal Model Control, Passive Damping, Distributed Generation.

1. INTRODUCTION

The interconnection of renewable energy sources to the utility grid has become quite popular in the recent Power and Energy developments. To increase the power transfer between the distributed generation and utility grid, power converters are used. VSIs produce sinusoidal waveforms that have harmonic components [1]. Low power applications with high switching frequency simple first-order inductor placed in series with the output of the inverter to reduce the switching harmonics. However, high power applications with low switching frequency single inductors are costly and bulky. In order to overcome these limitations, the LCL low-pass filter is preferred. In order to overcome these limitations, the LCL low-pass filter is preferred. The low-pass filter behaviour of the LCL filter is similar to that of an L filter but the LCL filter has improved damping performance at high frequencies. Resonance occurred at one point by using the LCL Filter.

This resonance complicates the design of the current controller to preserve system stability [2], [10]. Consequently, appropriate resonance damping methods should be employed for VSCs with an LCL filter. Generally, damping strategies can be classified into passive and active strategies. Passive damping strategies use a physical resistor in series with grid side inductor, converter side inductor, and capacitor to dissipate power [3] and are effective means for low-cost and low-power applications. However, medium and high-power applications call for sophisticated control strategies that damp out the resonance using high-order filters and controllers instead of physical components. These control strategies are referred to as active damping strategies and can provide higher efficiencies compared with passive damping strategies. Active damping techniques can be classified into two categories. The first group consists of schemes which includes filters that don't require additional sensors. Another institution includes greater feedback (multi-loop) based on AD manipulate processes. The implementation of the latter procedures needs extra sensors, which certainly boom normal system price and complexity. In order to triumph over this limit, several estimations primarily based sensor-less AD methods have been proposed. This paper proposes a novel active resonance damping controller based on current control of an LCL filtered VSC using internal model control (IMC). The controller is implemented in the d-q reference frame. The proposed IMC active damping controller

- Take the decoupling terms for the d- and q- axes into account to achieve better transient behaviour.
- Is simultaneously both the controller and filter due to the internal model principle
- Has a very simple design procedure with only one tuning parameter and
- Does not need additional sensors.

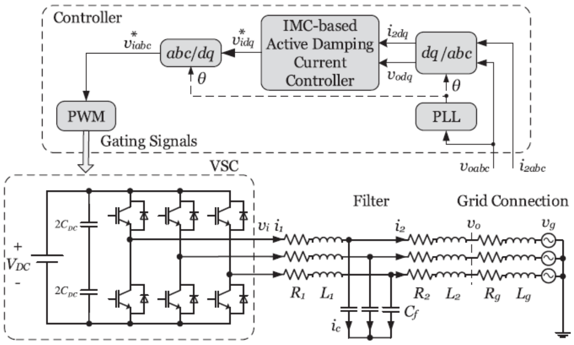

Fig -1: Block diagram of the DG unit with Controller, VSC, LCL Filter, Grid Connection, and Grid Voltage

The rest of the paper is organized as follows. Section II design of LCL filter section III overview of the internal model controller structure and the proposed IMC-based active damping current controller section IV and V simulation results section IV conclusion

2. DESIGN OF LCL FILTER

The following parameters are needed for the filter design:

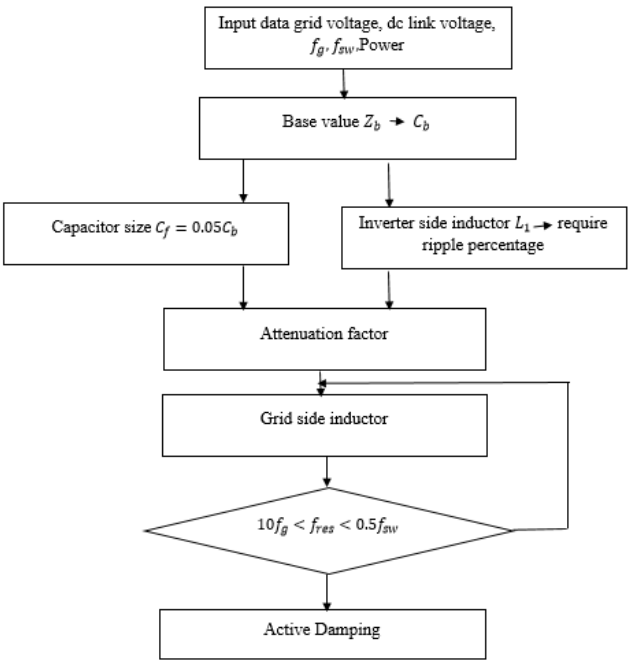

Fig – 2: Flow chart of LCL Filter Design

3. INTERNAL MODEL-BASED CONTROLLER

The salient feature of this control approach is that the process model is directly embedded in the controller structure. In this section, review the principle of internal model control (IMC) showing the structure and generic design procedure for the proposed IMC-based active damping current controller for a grid-connected VSC with an LCL filter.

3.1 IMC structure:

Fig. 3 represents a general schematic diagram of IMC, in which $G_P(s)$ is the process to be controlled, $\widetilde{G_P}(s)$ is a model of the process, and $G_C(s)$ is the controller.

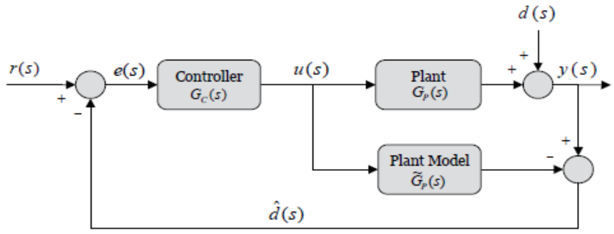

Fig -3: Schematic diagram of the IMC

Perfect tracking and disturbance rejection can be achieved if $G_P(s) = \widetilde{G_P}(s)$ and $G_c(s) = G_P^{-1}(s)$. Robustness against process model mismatch can be improved by introducing a low –pass filter $G_f(s) = \frac{1}{(\lambda s+1)^n}$ in series with the controller.

$$G_c(s) = G_P^{-1}(s)\frac{1}{(\lambda s+1)^n} \quad (1)$$

The filter order is typically chosen to make the IMC controller $G_c(s)$ proper. One of the advantages of the IMC controller $G_c(s)$ has a single tuning parameter, the filter parameter λ. In a minimum phase system, the filter parameter λ is equivalent to the time constant of the closed-loop system. The equivalent standard feedback form of the IMC controller K(s) [14] is

$$K(s) = \frac{G_C(s)}{1-G_C(s)G_P(s)} \quad (2)$$

The overall IMC-based controller K(s) is

$$K(s) = \frac{G_P^{-1}(s)}{(\lambda s+1)^n - 1} \quad (3)$$

Where it is preferred to use the smallest n that makes the controller proper to avoid complexity.

3.2 IMC-Based Active Damping Current Controller

For the study system depicted in fig 1. The system model includes a VSC (the DC link voltage V_{DC} is assumed to be constant and the output voltage V_i is pulse-width modulated), an LCL filter (L_1, R_1, L_2, R_2, C_f), and the feeder line and grid collectively modelled by its AC Thevenin equivalent (R_g, L_g, V_g). The frequency response of the LCL filter and the grid impedance in fig. 1 is [5].

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{C_f}\left(\frac{1}{L_1} + \frac{1}{L_1+L_G}\right)} \quad (4)$$

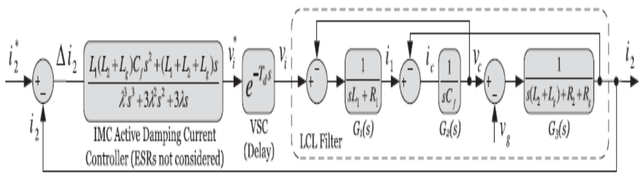

Fig -4: Simplified single-phase block diagram of the proposed IMC –based active damping current controller (with ESRs), VSC, and LCL filter

The current controller aims to control the DG unit output current i_2 by adjusting the inverter output voltage v_i. Applying basic block reduction rules $G_1(s)$, $G_2(s)$, and $G_3(s)$ in fig.4. gives the LCL filter model including equivalent series reactance of the inductor.

$$G_P(s) = \frac{I_2(s)}{V_i(s)} = \frac{G_1(s)G_2(s)G_3(s)}{1+G_1(s)G_2(s)+G_2(s)G_3(s)} \quad (5)$$

$$= \frac{1}{\alpha s^3+\beta s^2+\gamma s+\delta} \quad (6)$$

Where

$$\alpha = L_1(L_2 + L_g)\, C_f$$

$$\beta = L_1(R_2 + R_g)\, C_f + R_1(L_2 + L_g)\, C_f$$

$$\delta = R_1 + R_2 + R_3$$

$$\gamma = R_1(R_2 + R_g)C_f + L_1 + L_2 + L_g$$

Substituting s=s+ jω K(s) =

$$\frac{\alpha s^3+\beta s^2+(\gamma-3\omega^2\alpha)s+(\delta-\omega^2\beta)}{s^3\lambda^3+s^2 3\lambda^2+3\lambda s} + j\,\frac{3\alpha\omega s^2+(3\omega\beta)s+(\omega\gamma-\omega^3\alpha)}{s^3\lambda^3+s^2 3\lambda^2+3\lambda s} \quad (7)$$

Where λ is the tuning parameter

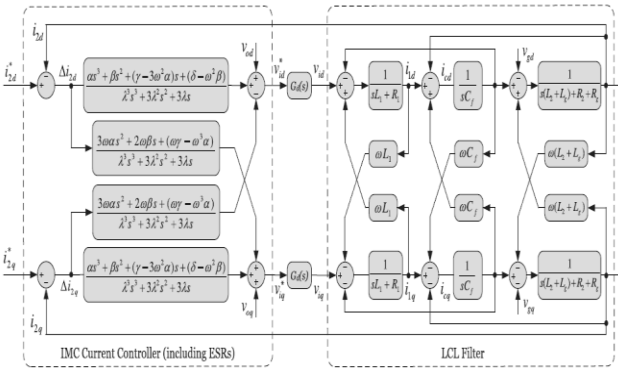

Fig -5: Block diagram of the IMC based active damping current controller (with ESRs), VSC, and LCL filter model in the d-q reference frame

Fig .5 shows the structure of the IMC-based active damping controller along with the LCL filter in d-q reference $G_d(s) = e^{-1.5s/f_{sw}}$ models the time delay of the VSC. Decoupling between d and q axes took into account. These characteristics make the performance of the proposed IMC-based active damping approach superior to existing methods.

4. FREQUENCY-DOMAIN ANALYSIS

This section studies the frequency response of the LCL filter, the proposed IMC –based active damping current controller, and their combination. V_{DC} should be chosen large enough to enable the VSC to construct the output voltage that the controller commands. For the study system, V_{DC} has been chosen to be 2.5 times the RMS value of the grid voltage. Bode plots are drawn based on the simplified control loop for the DG unit output current *i*2 in Fig.5, which does not take the *d-q* coupling terms in (20) into account. The VSC is modeled with a time delay of *Td* = 1.5/*f*sw [10].

For demonstration purposes, the ESRs of the system are not considered (no inherent system damping). In this the frequency response of the IMC-based controller $K(s)$ after a change in the order of its low-pass filter G_{LPF} (s) (n = 3, 4, 5) is investigated.

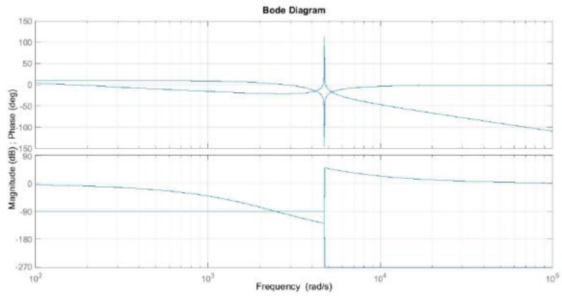

Fig -6: Bode Plot of LCL Filter and Controller

System Parameters:

Table 1. System Parameters

Parameter	Value	Parameter	Value
F	50 Hz	R_1, R_2	0.1 Ω
L_1, L_2	20 mH,12 mH	R_g	0.5 Ω
L_g	2.4 mH	V_g	230 V
C_f	3 μf	V_{DC}	400 V
f_{sw}	2 kHz	λ	0.0007

5. SIMULATION RESULTS

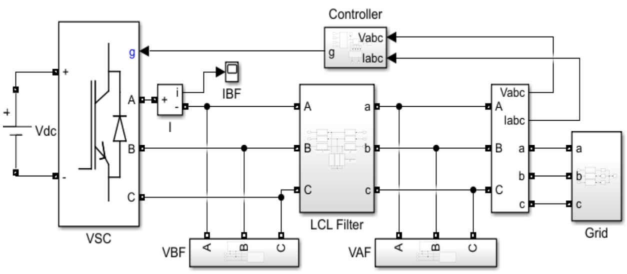

Fig -7: Grid Interface VSC and LCL Filter with the controller

To increase the power transfer between the distributed generation and utility grid, power converters are used. Most power quality issues are related to the type of electrical system interface. Fig 7 represents the interface grid with DG units by using the Voltage Source Converter. VSC converter produces harmonics to the system that can be eliminated by using the LCL filter connected in series with the VSC.

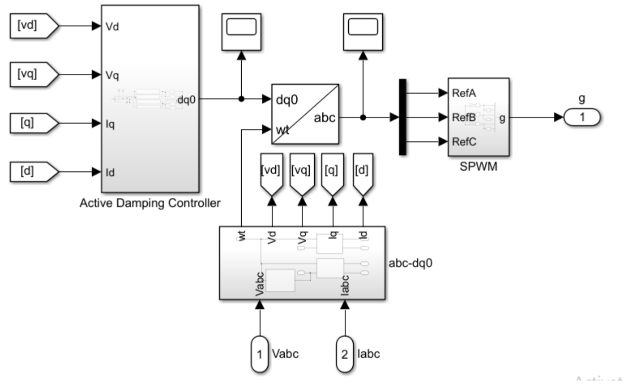

Fig -8: Active Damping Controller with the reference frame

The filter causes resonance that can be eliminated by using the IMC controller along with the reference frame. The filter output is connected to the controller input. The controller output is given to the SPWM reference signals finally SPWM output is given to the VSC.

5.1 Current step response

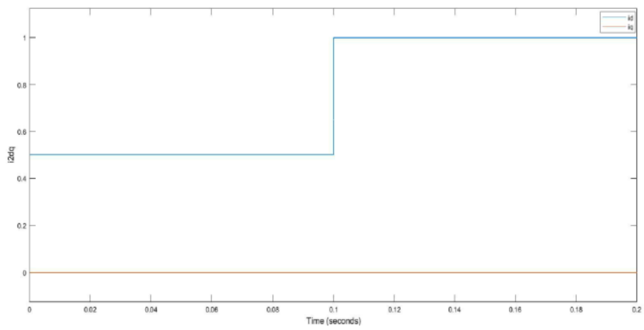

Fig -9: Three-phase currents i_{2abc} after a 0.5 pu step change in the d-component at t=0.1s

In this subsection, the current transients of the proposed IMC-based active damping method.in this method similar rise time, settling time, and d-component overshoot.

Fig.8 shows the d-q components of the current i_2 of the three tested methods for a 0.5 pu step change in the d-component reference is kept at zero. Transient oscillations in both d and q axes, the IMC-based method shows a smoother transition.

5.2 Controller Output Current

Fig 9 represents the controller output current. Using the IMC controller waveform is smoothening. The controller output is connected to the pulse width modulation. So VSC pluses are controlled by using PWM.so total harmonics are reduced.

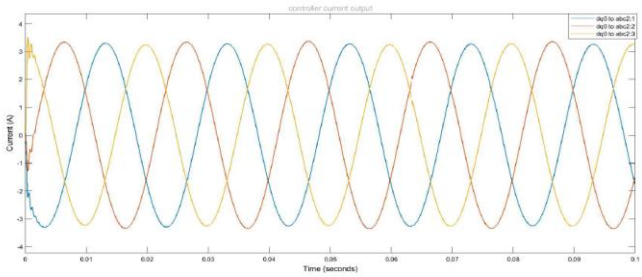

Fig -10: Three-phase currents i_{2abc} after a 0.5 pu step change in the d-component at t=0.1s

5.3 Mitigation/compensation of Harmonics

To minimize the harmonic current distortion produced by the converter system under distorted supply conditions, the harmonic impedance ideally infinite for all low order harmonics.

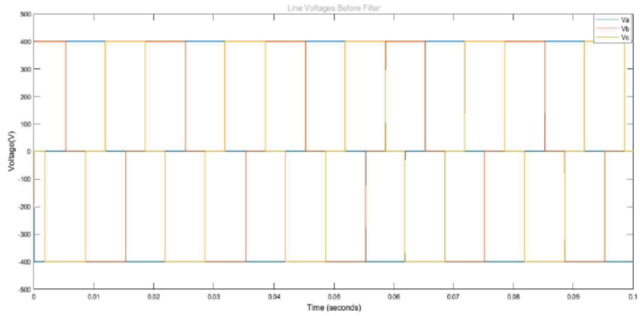

Fig -11: Inverter output voltage

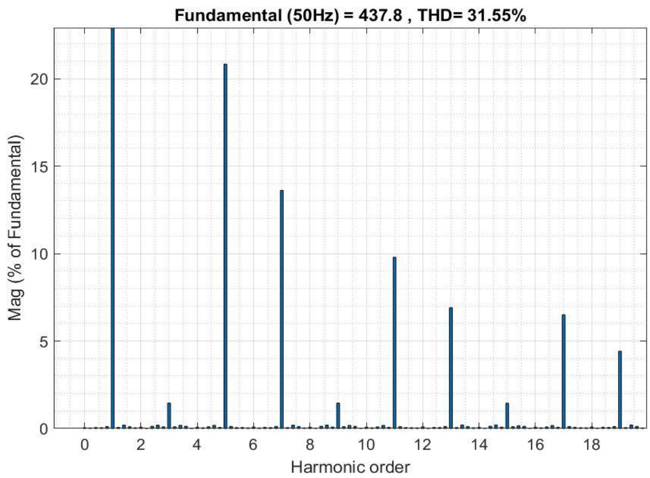

Fig -12: V-THD of Inverter output voltage

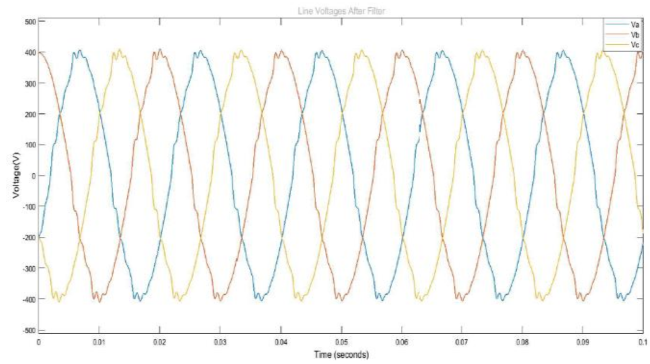

Fig -13: LCL Filter output voltage with a controller

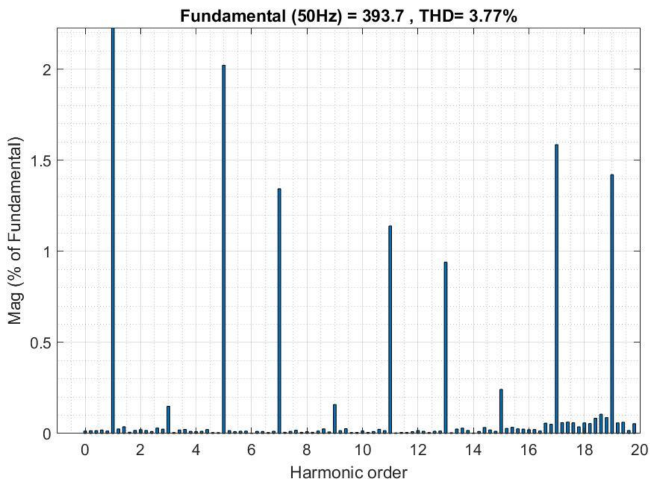

Fig -14: V-THD of LCL filter with the controller

The inverter output is non sinusoidal so harmonics are more that can be eliminated by using LCL Filter. The proposed LCL filter has been validated using a grid-connected three-phase inverter with the current controller. The output inverter phase voltage output can be seen in Fig.11, Fig.12 (before the filter), the THD is 31.55%. It can be seen in Fig 13 the voltage output from LCL filter smooth and harmonic analysis shows the effectiveness of the designed filter. The compensation has been specified for less than 4% THD.

Table 2. V-THD of Before Filter and After Filter

Voltage Total Harmonic Distortion (%)		Before Filter	After Filter
Line – Line	AB	31.55	3.77
	BC	31.55	3.79
	CA	31.09	3.82
Line-Ground	A	31.23	3.80
	B	31.42	3.76
	C	31.69	3.81

6. CONCLUSIONS

This paper proposes an Internal Modal Based Active Resonance Damping Current Control of a Grid-Connected Voltage-Source Converter with an LCL Filter. The LCL filter reduces the switching frequency. The paper describes a comprehensive and detailed design procedure of the LCL filter and the IMC controller. Total harmonic distortion within the permissible limits. The design approach is also applicable to front-end inverters used in small and medium-scale distributed dc power sources, such as photovoltaic systems, fuel cells, and wind turbine systems (with rectifiers).

The transient behavior of a power system is of great importance to prevent the operation limit violation, and it is highly influenced by the utilized model and control strategy. IMC-based control structure to obtain superior control performance, i.e., faster step response and less overshoot in the transient response.

7. REFERENCES

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