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Design and Analysis of Second Order Passive Filters for Grid Connected Inverter with Series and Parallel Damping Resistors

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Abstract

Background/Objectives: Grid connected inverters are widely used to integrate renewable sources into the grid. The suitable power quality is required which can be either achieved using active or passive filters. This paper focuses on second order passive filters such as inductor capacitor (LC) and LC inductor (LCL) which can be used to attenuate harmonics for grid connect inverters. **Methods/Statistical Analysis:** To overcome the resonance of LCL filters passive damping[6–8] or active damping can be used. Active power filters are more expensive because of sensors and control systems additional cost. Passive damping strategies due to simple circuit and low cost are more favored. A LCL filter equipped with series or parallel resistor with a capacitor forms a LCL filter with damped resistor Addition of resistor to filter circuit will cause an increase in power losses. The peak resonance of LCL filter depends upon the value of resistor so select a value of resistor which decline peak resonance of filter. **Findings:** At resonance frequency they have some issues related to stability. LCL filter can be equipped with damping resistor but there are some power loss and introduction of voltage, current harmonic. Mathematical characteristics of passive filters such as LC, LCL, LCL with series resistor and LCL with parallel resistors are discussed in terms of effectiveness and stability in this paper. **Application/Improvements:** It is very useful for industrial application and power electronic converter.

Keywords: Capacitor (C), Grid Voltage (U_g), Inductor (L), Inverter Voltage (U_{Inv})

1. Introduction

With the increase and uncertainty in the prices of crude oil, world is trending away of conventional fuels towards the energy from renewables[1,2]. Conventional energy production methods are also responsible for rise in the average temperature of earth and adding greenhouse gases in our atmosphere. Integration of the electrical energy from renewables with the grid is the main obstacle here, power quality improvement is also desirable for which filters are used[3]. First order L type filters have large size issue similarly second order passive filters (LC) also have issues of size, resonance frequency and time delay. Comparatively Third order filters (LCL) are smaller in size and have low cost but have resonance frequency issues[4,5]. To overcome the resonance of LCL filters passive damping or active damping can be used[6–8]. Active power filters are more expensive because of sensors and control systems additional cost. Passive damping strategies due to simple circuit and low cost are more favored. A LCL filter equipped with series or parallel resistor with a capacitor forms a LCL filter with damped resistor Addition of resistor to filter circuit will cause an increase in power losses. The peak resonance of LCL filter depends upon the value of resistor so select a value of resistor which decline peak resonance of filter. In this paper characteristic of second order filter, third order filter, parallel and series damping LCL filter are discussed. A good power quality is essential for stable operation of system[9].

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2. Principal of Passive Filter

Renewable energy sources can be integrated with power systems by using grid connected converters. Harmonics injected by converters can be removed by inserting an input filter of high inductance. Inductive filters are easy to design but practically in application above several kilowatts inductive filters become expensive due to large size of inductor and the dynamic response of system becomes poor.

3. LC filter

LC filter consist of a parallel capacitor and a series inductor shown in Figure 1. By using a parallel capacitor, inductance of inductor can be decreased thus cost of filter and losses also reduced as compare to L filter. But the use of a parallel capacitor causes problems like high capacitance current, high in rush currents at fundamental frequency[10]. The transfer function this filter is shown in Equation (1) and the corresponding bode plot is shown Figure 2.

$$G(S) = \frac{U_g}{U_{Inv}} = \frac{1}{S^2 LC + 1} \tag{1}$$

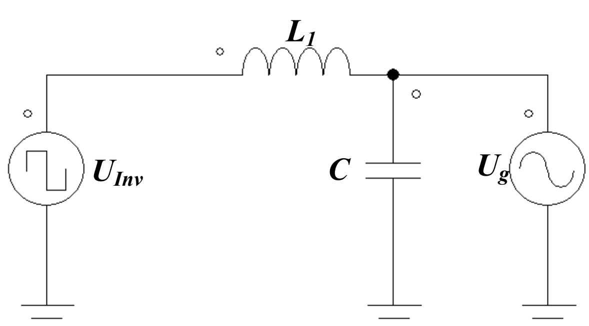

Figure 1. LC filter.

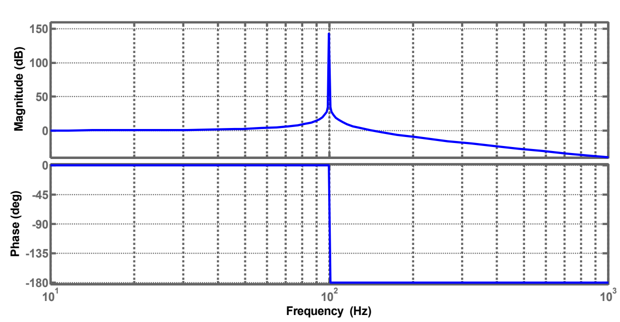

Figure 2. Bode plot of LC filter.

4. LCL filter

LCL filters can be used to get rid of issues related to second and first order filters. LCL filter is shown in Figure 3. By using LCL filter in the range of hundreds of kilovolt amperes, excellent results can be achieved but value of inductor and capacitor is still very small[10]. LCL filter will give improve decoupling between grid and filter, as compare with first order filter. A superb attenuation of -60dB/decade to switching frequency in bode is noted, but the impedance of power grid is very small, which is bounced back to the converter side. Oscillation can stay permanently and can damage our whole system, if resonance gets excited. Around the resonant frequency, instability in current and voltage can be introduced by this resonance.

To solve this issue a damping resistor is added to LCL circuit. By adding this damper, the damping and attenuation reduces (factor Q). The bode plot of LCL filter is shown in Figure 4. The transfer function of LCL filter is given as,

$$G(S) = \frac{I_2}{U_{Inv}} = \frac{1}{S^3(L_1 L_2 C) + (L_1 + L_2)S} \tag{2}$$

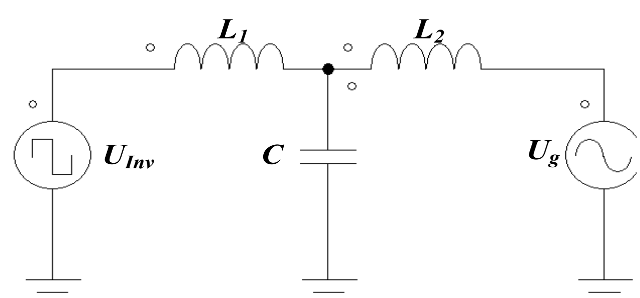

Figure 3. Grid connected LCL filter.

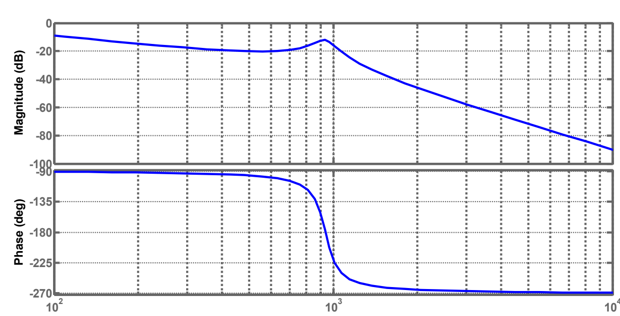

Figure 4. Bode plot of LCL filter.

5. LCL Filter with Series Damping Resistor

From LCL filter transfer function, it can be seen that gain of its frequency is high (infinite Q). By adding a series resistor with a capacitor will reduce the factor Q as resonance in LCL filter depends upon capacitor current. Series damped LCL filter is shown in Figure 5. An Equation (3) show transfer function and bode is shown in Figure 6. Table 1 shows the value of phase and gain margins on different values of resistor.

$$G(S)=\frac{I_2}{U_{Inv}}=\frac{1+SRC}{(L_1L_2C)S^3+RC(L_1L_2)S^2+(L_1+L_2)S} \quad (3)$$

Figure 6 shows that by increasing series resistance in above equation the effect of damping decreases as peak resonance becomes acceptable. But filter response is better at high frequency. As value of resistance increases the effect of damping also increases, which decreases the factor Q.

6. LCL Filter with Parallel Damping Resistor

Resonance in LCL filter can also be removed by using a capacitor with a parallel resistor, shown in Figure 7.

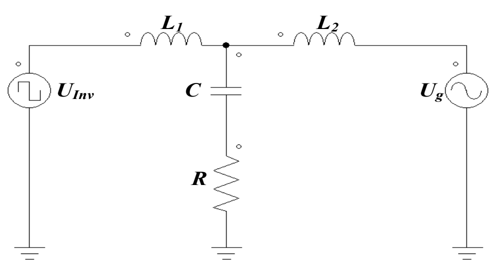

Figure 5. Grid connected LCL filter with series damping resistor.

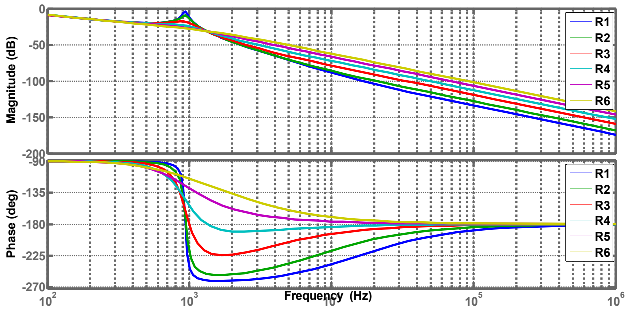

Figure 6. Bode plot of LCL filter with series damping resistor.

Table 1. Different values of phase and gain margin on different value of resistances

Resistance	Values()	Gain margin	Phase margin
R1	0.25	1.56	89.99
R2	0.50	3.16	89.99
R3	1.41	9.90	89.99
R4	3	37.50	89.99
R5	6	Infinity	89.99
R6	10	Infinity	89.99

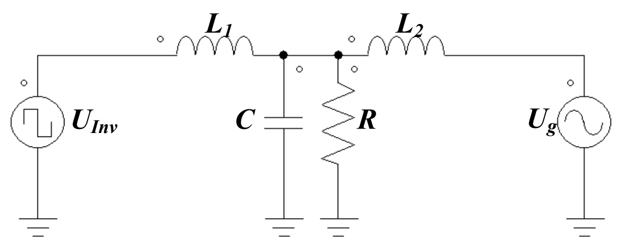

Figure 7. Grid connected LCL filter with parallel damping resistor.

Equation (4) shows the transfer function of this filter. Bode plot of this filter is also shown in Figure 8.

$$G(S)=\frac{I_2}{U_{Inv}}=\frac{R}{(L_1L_2RC)S^3+(L_1L_2)S^2+R(L_1L_2)S} \quad (4)$$

The effect of different resistance on bode plot of LCL filter with parallel resistor is shown in Figure 8. From this diagram it can be observed that at high and low frequency filter will give same response. But by increasing the resistance value, peak resonance also increases, because of which filtration will be different around resonance frequency on different values of resistor.

7. Designing Parameters of LCL Filters with Series/Parallel Damping Resistor

Figure 1 shows second order filter low pass LC filter. All high order harmonics coming from PWM of inverter will get ejected by this filter, to get a pure 60 Hz sinusoidal wave. To decline total harmonics of currentless than 5%, particular value of Cut off frequency (f_C) is selected[11]. By declining the cut off frequency of filter in opposite to inverter switching frequency, the effect of attenuation of LC filter could be enhanced according to this relation

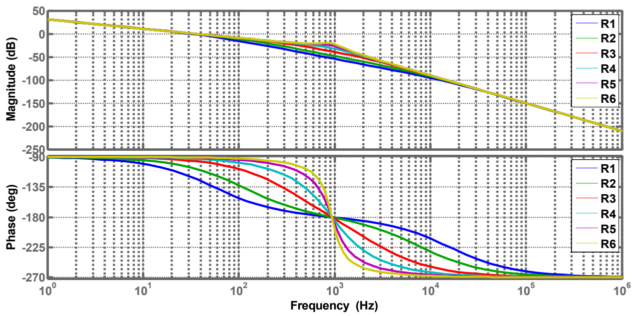

Figure 8. Bode plot of LCL filter with parallel damping resistor.

$40\log\left(\frac{f_{SW}}{f_{Cutt-off}}\right)$. That is indicated in the Figure 2, but cut off frequency of filter restricts the bandwidth of control of inverter systems. Control bandwidth can be increased for absolute voltage compensation without experiencing delay in phase at higher order harmonics and rapid operation of inverter. There is an adjustment between control bandwidth and attenuation effect. Generally value of fc is taken below than 1/10 value of switching frequency of inverter[12]. Inductor L is selected in such a way that the drop of voltage across inductor should always be less than 3% of output voltage of inverter[13,14]. Value of L can be calculated by,

$$f_C \propto \frac{1}{10} f_{SW} \quad (5)$$

$$I_{L\max}(2\pi f\ L) \propto 0.03U_{Inv} \quad (6)$$

Where reference frequency is f, the output voltage is U_{inv}, the load current maximum RMS value is $I_{L\max}$. The relation of filter capacitance with resonance frequency is

$$C = \frac{1}{(2\pi f_C)^2 L} \quad (7)$$

We consider parameters given in Table 2 and Table 3 into account for designing of a LCL passive filter

- Under the rated circumstances, the drop of voltage across inductor is less than 5% to 10% of the voltage of network

$$\nabla V_1 \leq (0.05 - 0.1)U_g \quad (8)$$

The loss of voltage across inductor is ∇V_1 and the line voltage is U_g. The value between of rated current can be selected for ripple current. The maximum ripple current can be calculated by,

Table 2. Different values of phase and gain margin on different value of resistances

Resistance	Values()	Gain margin	Phase margin
R1	0.25	450.00	60.76
R2	0.50	225.00	72.94
R3	1.41	79.78	83.54
R4	3	37.50	86.94
R5	6	18.75	88.46
R6	10	11.25	89.08

Table 3. Filters designing parameter

Type of filter		Ω)	L1(mH)	L2(mH)
LC	42.22	-	60	-
LCL	40.00	-	3.6	0.9
LCL (series damping)	40.00	1.41	3.6	0.9
LCL (Parallel damping)	40.00	1.41	3.6	0.9

$$\nabla I_{L1\max} = \frac{U_{dc}}{8Lf_{SW}} \leq 0.2_{Irated} \quad (9)$$

Resonant frequency should be $10f_1 \propto f_{res} 0.5 f_{SW}$ where f_{SW} is switching frequency f_1 is the voltage of grid.

- Suppose that there is a flow of high order through capacitor and through inductor is flow of low order harmonics.
- System rated active power should be more than the reactive power which is absorbed by filter $Q_C \leq \alpha P_{rated}$ (10) reactive power factor is αin above equation and it should be lesser than 5%

$$\frac{(2\pi f_1)L\,P_{rated}}{3U_g \cos\varphi} \leq 0.1U_g \quad (11)$$

$$I_{rated} = \frac{P_{rated}}{3U_g \cos\varphi} \quad (12)$$

$$10f_1 \propto \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1L_2C}} \propto 0.5f_{SW} \quad (13)$$

$$Q_C = \frac{3V^2{}_{rated}}{X_C} = \frac{3V^2{}_{rated}}{(\frac{1}{c\omega})} = 3(2\pi f_1)CV^2{}_{rated} \leq 5\%\,P_{rated} \quad (14)$$

Q_C is the reactive power absorbed by capacitor. V_{rated} is the RMS value of phase voltage[15,16].

$$L_1 = (4 \sim 6)L_2 \quad (15).$$

The task of damping is that at the characteristic resonance frequency, the factor Q gets reduced. Target can be achieved by adding parallel or series resistor with a capacitor. Characteristic resonance frequency ω_{res} can be explained as,

$$\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \quad (16)$$

$$R = \frac{1}{3\omega_{res} C} \quad (17)$$

8. Conclusion

By comparing the performances of designed filters LC, LCL and damped LCL filters, it is concluded that besides the problem related to resonance frequency, the LCL filter is more preferred than LC filter. The reason for this preference is the weight, cost and size of LCL filter as compare to LC filter. LCL filter with damping resistor is recommended to get rid from instability issues in LCL filter. More harmonics are distorted by LCL series damped filter as compare to LCL parallel damped filter. The power losses of LCL series damped filter are less as compare to the LCL parallel damped filter. After considering size, price, weight, stability, power loss and harmonic injection to grid, for grid connected inverters Series damped LCL filter is best choice.

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