PASSIVE DAMPING FILTER DESIGN AND APPLICATION FOR THREE-PHASE PV GRID-CONNECTED INVERTER

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Abstract- Second and third-order passive filters (LC and LCL) are interesting filters to use for grid-connected PWM inverters. Because of the stability problems of this filter around resonance frequency, series and damping resistor can be add to an LCL filter. However, the resistor value has impact on the filter respond, voltage and current harmonic distortion and system power loss. In this paper, the mathematic characteristics of LC, LCL filter, series and parallel damping LCL filters will be described with their design to apply in 3-phase PV grid-connected inverter. And, simulations are used to validate the theoretical analysis of the filters on filter performance and power quality of the grid in 3-phase grid-connected inverter.

Keyword- filter design, LCL filter, Passive resonance damping, harmonic, Grid-connected inverter and power quality

I. INTRODUCTION

Filters are main parts of a renewable energy system. First- order passive filters are L type which are generally use for controlling grid-connected inverter. The disadvantage of this type of filters is their big size. Another type of the passive filters is LC filters (second-order). Because of the big size of the inductor, the size of this filter is large. Moreover, time delay and resonance frequency are another drawbacks of LC filters. Compared with a first-order and second-order filters, a third-order LCL filter has lower coast and smaller size in applications above several kilowatts. However, resonance frequency is still as a problem of these filters.

To repress the resonances of an LCL filter, active damping [1]–[4] or passive damping [5]–[8] can be used. The price for active filter is high due to the additional cost of the sensors and control system. Because of the low cost and simple circuit in a stiff grid application, a passive damping strategy is more preferred. A simple damped LCL filter is an LCL filter with series or parallel resistor with capacitor. By adding a resistor to the filter circuit, the power loss will increase. So, finding the optimum resistor value to decrease the peak resonance of LCL filter is very important.

Therefore, in this paper characteristics of LC, LCL filter, series and parallel damping LCL filters will be discussed. Since maintaining a good power quality is important for the reliable operation of the system and loads [9], these filters will be applied to a three-phase PV system. Then, the inverter output will be filtered in order to obtain low voltage and current distortion. And also, the impacts of the resistor value on the filter respond and also current and voltage harmonic will be discussed.

II. PRINCIPLE OF PASSIVE FILTERS

First, grid-connected converters are the interface to connect renewable energy sources to the power system. To reduce the harmonics injected by the converters a high value of input inductance should be used. However, L filter design is easy but in application above several kilowatts it becomes expensive because of using large filter reactor. Moreover, the system dynamic response becomes poor.

A. LC Filter

The filter consists of an inductance in series with the inverter and a capacitance in parallel with the grid (Fig. 1). By using this parallel capacitance, the inductance can be reduced, thus reducing costs and losses compare with L filter. By using a large capacitance, other problems such as high inrush currents and high capacitance current at the fundamental frequency or dependence of the filter on the grid impedance for overall harmonic attenuation will appear [10].

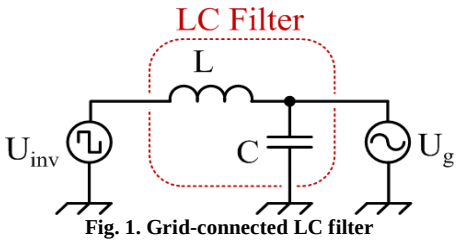


Fig. 1. Grid-connected LC filter

The LC filter transfer function of grid side voltage and inverter input voltage in grid-connected mode of operation is given in (1).

$$G(s)=\frac{U_g}{U_{inv}}=\frac{1}{S^2LC+1} \qquad (1)$$

By substitute the value of L and C which is presented in Table 1, transfer function in (1) can be rewrite as below. The bode plot is given in Fig 2.

$$G(s)=\frac{U_g}{U_{inv}}=\frac{1}{S^2(2.533\times10^{-6})+1}$$

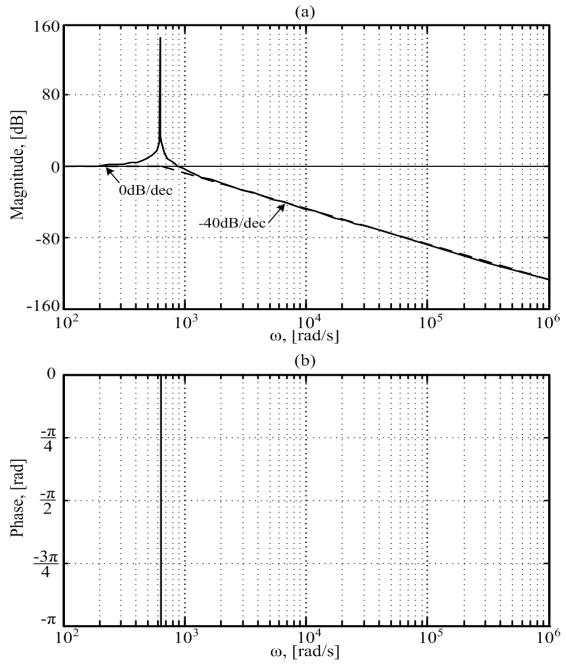


Fig. 2. Bode plot for LC filter

B. LCL Filter

An alternative and attractive solution of first and second order filter problems is to use an LCL filter as shown in Fig. 3. With this solution, optimum results can be obtained in the range of power levels up to hundreds of kilovolt amperes, still using quite small values of inductors and capacitors [11].

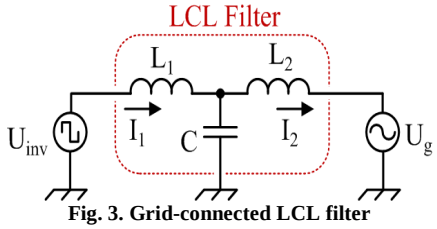


Fig. 3. Grid-connected LCL filter

Compared with a first-order L filter, an LCL filter can better decoupling between filter and power grid. Moreover, excellent attenuation of bode -60 dB/decade to the switching frequency will obtain. But, grid impedance reflected back to the converter side is generally very less so, if the resonance is excited, the oscillation of that can continue forever and it can make the entire system very vulnerable. This resonance effect can cause instability voltage or current around the resonant frequency.

In order to solve this problem, damping resistor can be add to the LCL circuit. The purpose of applying this damper is to reduce the attenuation and damping (Q-factor) at the characteristic resonance frequency, as it is indicated in Fig. 4. The LCL filter transfer function of line side current and inverter input voltage in grid-connected mode of operation is given below.

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1}{S^3L_1L_2C+(L_1+L_2)S} \qquad (2)$$

By substitute the amount of L_1, L_2 and C which are listed in Table 1, G (s) can be written as below:

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1}{S^3(3.24\times10^{-12})+(4.5\times10^{-3})S}$$

The bode diagram for this filter is shown in Fig.4.

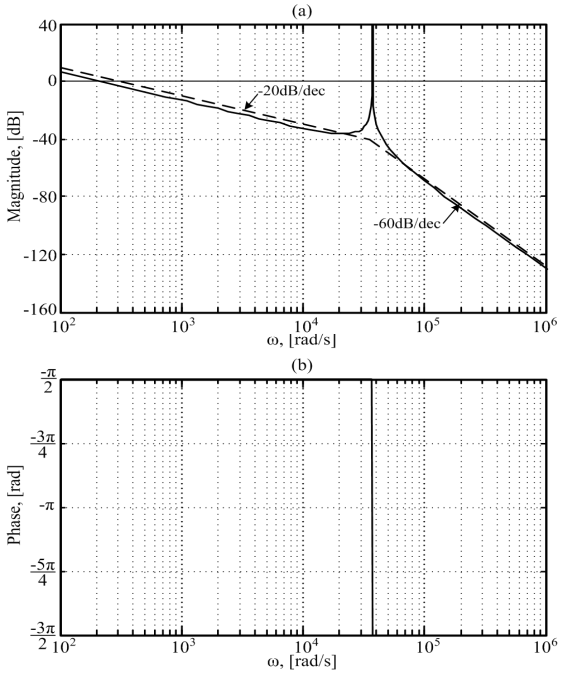


Fig. 4. Bode plot of LCL filter

C. LCL Filter with Series Damping Resistor

From the transfer function of LCL filter it is clear that, at the frequency of $\frac{1}{2\pi\sqrt{(L_1\|L_2)C}}$ it has high gain (infinite 'Q'). The simplest solution may be the addition of series resistance with the capacitor to reduce the 'Q' as the capacitor current is most responsible for resonance in LCL filter. Fig. 5 shows the series damping topology.

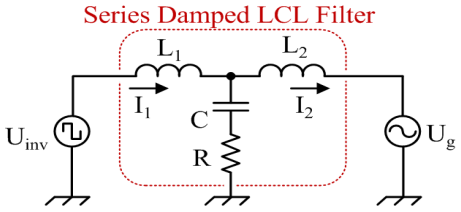


Fig. 5. Grid-connected series damped LCL filter

It is also clear from the frequency response of capacitor current. It carries basically resonant component and very less fundamental as well as switching component. Transfer function for this filter is shown as (2).

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1+SRC}{(L_1L_2C)S^3+RC(L_1+L_2)S^2+(L_1+L_2)S} \qquad (2)$$

As it is shown in Fig. 6 by increasing the series resistor value in (2), damping effects to suppress of the peak resonance become well. However, in high frequency the filter respond is better as indicated it Fig.6.

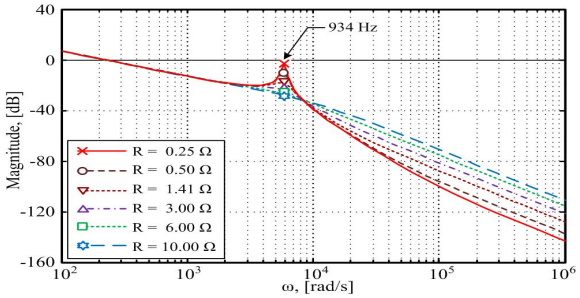


Fig. 6. Damping by changing series resistor

G(s) can be rewrite as below by replacing the value of L_1, L_2, C and R in (2) from Table1.

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1+S(5656\times10^{-6})}{(1296\times10^{-12})S^3+(0.255\times10^{-6})S^2+(4.5\times10^{-3})S}$$

The bode plot is given for the line side current Vs inverter output voltage in Fig. 7. As it clear from (2) by increasing the value of resister the damping effect in Fig.5 become well as it is indicated in Fig. 6. Then, the Q factor becomes lower.

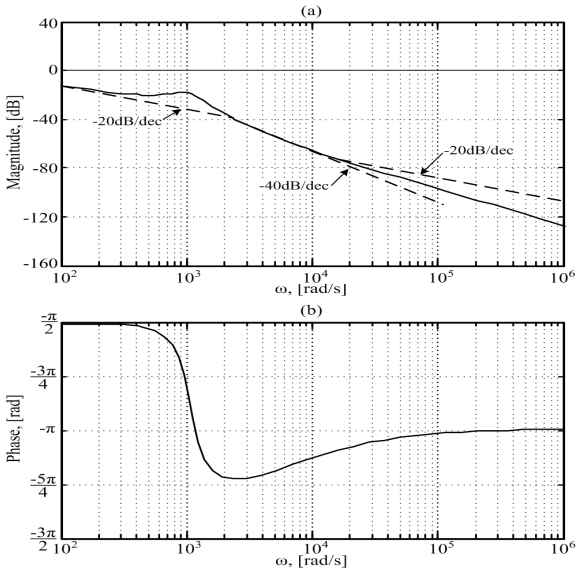


Fig.7. Bode plot of LCL filter with series damping resistor

D. LCL Filter with Parallel Damping Resistor

Another way to suppress the resonance in LCL filter is using a parallel resistor with the capacitor as it shown in Fig.8.

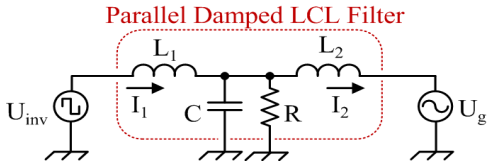


Fig. 8. Grid-connected parallel damped LCL filter

The transfer function of parallel damped LCL filter is:

$$G(s)=\frac{I_2}{U_{inv}}=\frac{R}{(L_1L_2RC)S^3+(L_1L_2)S^2+R(L_1+L_2)S} \qquad (3)$$

Fig. 9 presents the bod plot of the parallel damped LCL filter for different resistors. As it indicated in this figure, in low and high frequency filter has a same action. But, the peak resonance will be increased by increasing the resistors value. So, the filter action is different around resonance frequency with different resistors.

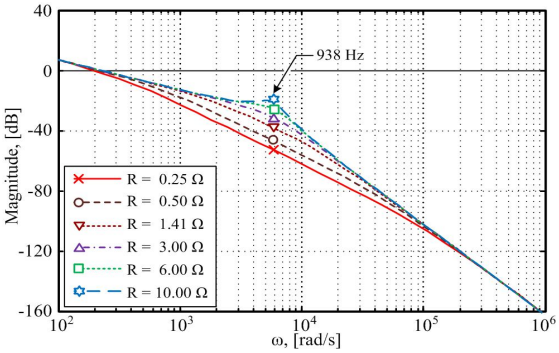


Fig. 9. Damping by changing parallel resistor

By applying L_1, L_2, C and R from Table 1, G(s) will be written as:

$$G(s)=\frac{I_2}{U_{inv}}=\frac{1.41}{(0.183\times10^{-9})S^3+(3.24\times10^{-6})S^2+(6.36\times10^{-3})S}$$

The bode plot is presented in Fig.10 for this filter.

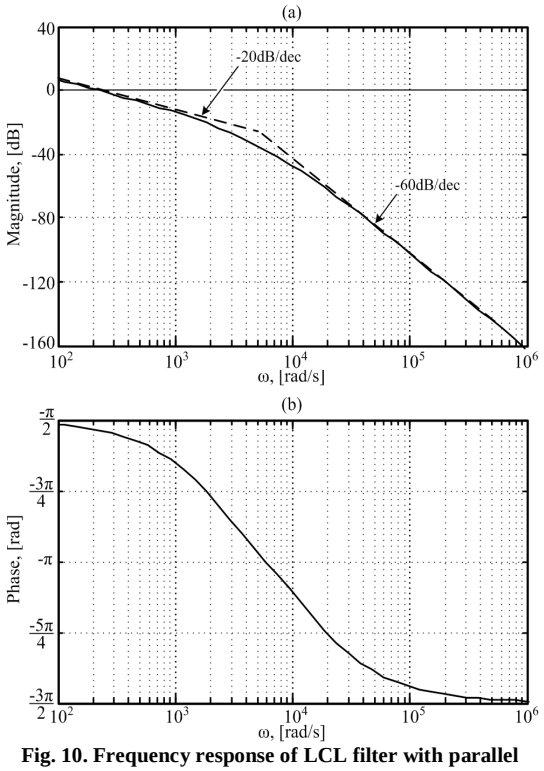


Fig. 10. Frequency response of LCL filter with parallel damping resistor

III. FILTER DESIGN

A typical low pass LC filter is shown in Fig.1. The LC low pass filter is a second order filter which eliminates all high order harmonics from the PWM output of the inverter so that the input voltage of the grid become a pure sinusoidal wave of 60 Hz. The cut-off frequency (fc) of the low pass filter is selected such that the output voltage THD is less than 5% [12]. The attenuation effect of LC filters can be increased by decreasing the filter cut-off frequency against the switching frequency of inverters according to -40log ($f_{sw}/f_{cutt-off}$) as it indicated in Fig.2. However, the filter cut-off frequency limits the control band-width of inverter systems. Increasing the control bandwidth is important for fast operation of the inverter system and also for precise voltage compensation without a phase delay at higher-order harmonics. Thus, there is a trade-off between the attenuation effect and the control bandwidth in the design of LC filters. Generally, the value of fc is kept below 1/10th of the inverter switching frequency [13]. The selection of the filter inductance, Lf, should be such that the voltage drop across the inductor is less than 3% of the inverter output voltage [14]. Then, the value of L can be calculated using (4) - (6).

$$f_c \prec \frac{1}{10} f_{sw} \tag{4}$$

$$I_{L\max}(2\pi fL) \prec 0.03U_{inv} \tag{5}$$

Where $I_{L\max}$ is the maximum RMS value of the load current and f is the frequency of the output voltage, U_{inv}. The filter capacitance can be calculated from the resonance frequency as below:

$$C = \frac{1}{(2\pi f_c)^2 L} \tag{6}$$

To design an LCL passive filter several rules should be considered as listed in below.

1. The voltage drop of the filter inductor is smaller than $5\%-10\%$ of the network voltage under the rated circumstances [15].

$$\Delta V_l \le (0.05 \sim 0.1)U_g \tag{7}$$

2. Where ΔV_l is the inductor voltage loss and U_g is the line voltage. Typically, the ripple current can be chosen as $0.15 \sim 0.25$ of rated current. In this paper, the ripple current is selected as 20% of the rated current. The maximum current ripple can be derived as in (8) [16]:

$$\Delta I_{L1\max} = \frac{U_{dc}}{8Lf_{sw}} \le 0.2I_{rated} \tag{8}$$

3. The resonant frequency should be $10f_1 \prec f_{res} \prec 0.5f_{sw}$ where f_1 is the grid voltage frequency and f_{sw} is the switching frequency.

4. Let the high order harmonic flow through the capacitance, and the low order harmonic flow through the inductance.

5. Moreover, generally the reactive power absorbed by the filter-capacitor should be less than the rated active power of the system. Then,

$$Q_c \le \alpha P_{rated} \tag{9}$$

Where α is the reactive power factor and it must be less than 5%. Therefore, by considering the above constraints in this paper:

$$\frac{(2\pi f_1)LP_{rated}}{3U_g \cos\varphi} \le 0.1U_g \tag{10}$$

Where,

$$I_{rated} = \frac{P_{rated}}{3U_g \cos\varphi} \tag{11}$$

$$10f_1 \prec \frac{1}{2\pi}\sqrt{\frac{L_1+_2}{L_1L_2C}} \prec 0.5f_{sw} \tag{12}$$

$$Q_c = \frac{3V_{rated}^2}{X_c} = \frac{3V_{rated}^2}{(1/c\omega)} = 3(2\pi f_1)CV_{rated}^2 \le 5\%P_{ratec} \tag{13}$$

Where V_{rated} is the phase voltage (RMS), P_{rated} is the rated power [17]. Q_c is the absorbed reactive power by capacitor.

Moreover, inverter-side inductor can be considering as 4 to 6 times bigger than the grid-side inductor [15]:

$$L_1 = (4\sim6)L_2 \tag{14}$$

The purpose of the damping is to reduce the Q-factor at the characteristic resonance frequency. It is easy to achieve by inserting a resistor in series or parallel with the capacitor. Its characteristic resonance frequency, ω_{res}, can be defined as by (15) and (16) [16]:

$$\omega_{res} = \sqrt{\frac{L_1+L_2}{L_1L_2C_f}} \tag{15}$$

$$R = \frac{1}{3\omega_{res}C} \tag{16}$$

Table 1. Filter parameters

Filter Type	L(mH)	L1(mH)	L2(mH)	C(μF)	R(Ω)
LC	60	-	-	42.22	-
LCL	-	3.6	0.9	40	-
LCL with series damping	-	3.6	0.9	40	1.41
LCL with parallel damping	-	3.6	0.9	40	1.41

IV. SIMULATION RESULTS

The SIMULINK in MATLAB software is used to simulate the system which is shown in Fig.11. In this paper, the simulation for all filter types in PV grid-connected application is designed. In these simulations a tuned PI controller is implemented to control the grid side voltage. Then, Ki is determined as 1.585. So, the rise time will be equal to 1.39 Sec and setting time 2.47 Sec. Time domain response for this tuned PI controller is shown in Fig.12. When, the system rated power is 20 kW, the line voltage is 240 V, the switching frequency is 2 kHz and the fundamental frequency is 60 Hz.

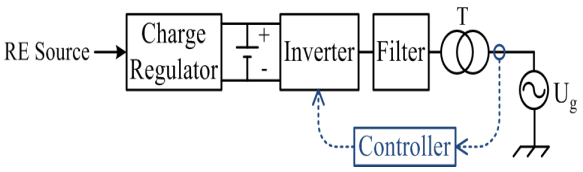


Fig. 11. Block diagram of a renewable energy system

Choosing the cut-off frequency of 100 Hz for a 2 kHz switching frequency from (4), the inverter's expected maximum load current of 200 A and the output phase voltage of 200 V , the values of L and C determined for the model were 60 mH and 42.22 μF respectively using (4) - (6) formulas. In this situation, the harmonic voltage waveform in grid-connected point is shown in Fig.15 for LC filter.

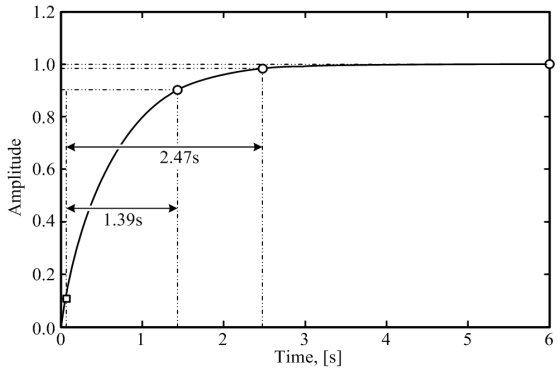


Fig. 12. Time domain response of tuned PI controller

Referring to the design procedure in the previous part, the parameters of LCL filters are calculated. Total inductor will be calculated between 1.88 mH and 4.78 mH using (9) – (11) formulas. So, in this paper total inductor is considered as 4.5 mH. By considering L1 = 4 L2 from (14), L1 and L2 are defined as 3.6 mH and 0.9 mH. Capacitor value also is limited between 35 μF and 98 μF from (12) and (13). Therefore, C could be considered as 40 μF. In this paper, damping resistor is calculated from (16), and it is equal to 1.41 Ω.

Inductor value for LC filter which is calculated from part III is around 67 times bigger than the inductor of LCL filter. However, increasing the inductor size has many disadvantages like high cost and weight of the filter. Moreover, voltage drop on the inductor will be increased which cause the system power loss.

Fig.13 shows the bode plot of LCL, series damping and parallel damping LCL filters to compare. As it shown in this figure, in high frequency, LCL filter decreases with 60dB/decade which can eliminate high-order harmonic effectively compare with damping filter. However, there is a resonant peak with high amplitude which will distort the grid current seriously. With passive damping method, the resonant peak can be suppressed with a resistor. But in high power system, it will cause unacceptable losses. Modern control theory indicates that the stability of a system greatly depends on its state and control the state variants properly can stabilize the system. As it clear in Fig.13, resonant peak is reduced with a series resistor. And also, it is completely suppressed by parallel damping resistor with the same value of resistor. Moreover, in high frequency the damping effect to eliminate the harmonic distortion of parallel resistor is better than series which is clear from the slope of the bod plot in Fig.13. It can be proving in decreasing the amount of total harmonic distortion of voltage at grid-connected which is presented in Fig.14.

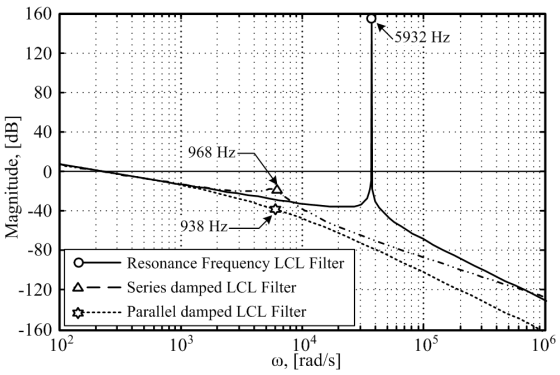


Fig.13. Bode plot comparison of LCL, series and parallel damped LCL filters

For this case study, the same damping resistor is used in both series and parallel damping LCL filter. The grid-connected voltage profile for LCL filter which is contains harmonic components is shown in Fig.14 (b) with THD equal to 7.73 %. According to IEEE-519 standard [26] it is too high.

Then, damping series and parallel LCL filters are used to reduce the voltage THD. By comparing the results for series and parallel damping filters, it is

clear that parallel has better impact to illuminate the harmonics. As it shown in Fig.18, the voltage THD is reduced by 65.1% compare with LCL filter without damping.

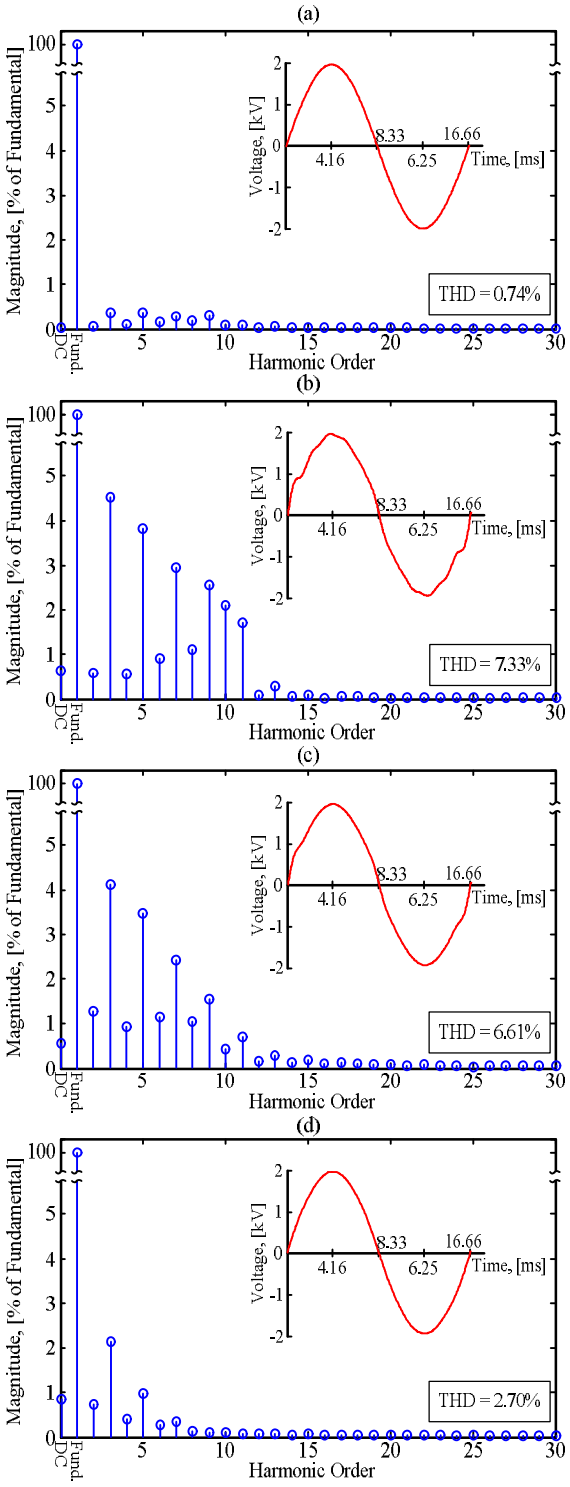


Fig. 14. Harmonic distortion of (a) LC filter, (b) LCL filter, (c) LCL with series damping filter and (d) LCL with parallel damping filter

Fig.15 indicates the effects of changing resistor value on the total harmonic distortion. As it shown, THD for voltage and current at grid-connected will increase by increasing the resistor value for parallel damping LCL filter. It must be mentioned the filter power loss for smaller damping resistor is less. In series damping LCL filters, the voltage and current harmonics will decrease by increasing the resistor value.

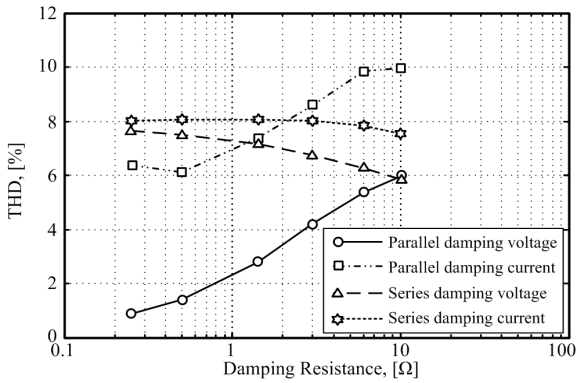


Fig. 15. Total harmonic Distortion for Parallel Damped LCL Filter with Different Resistors

CONCLUSION

A 20 kW three-phase grid-connected inverter with a PI tuned controller is implemented to validate the designed LC, LCL and damped LCL filters and compared their performance. Based on the simulation results, it can been seen with the same resistor value, the parallel resistor damped LCL filter has better action at resonance frequency compare with series damped LCL filter. And, the voltage and current of the grid show less harmonic distortion for this damped filter. In fact, the parallel damped LCL filter has the best design to filter the harmonics for grid-connected renewable energy systems.

RERFERENCES

[1] Y. Tang, P. Loh, P. Wang, F. Choo, F. Gao, and F. Blaabjerg, "Generalized design of high performance shunt active power filter with output LCL-filter," IEEE Trans. 1 nd. Electron., vol. 59, no. 3, pp. 1443–1452, Mar. 2012.

[2] Y. Tang, P. Loh, P. Wang, F. Choo, and F. Gao, "Exploring inherent damping characteristic of LCL-filters for three-phase grid-connected voltage source inverters," IEEE Trans. Power Electron., vol. 27, no. 3, pp. 1433– 1443, Mar. 2012.

[3] J. Dannehl, M. Liserre, and F. W. Fuchs, "Filter-based active damping of voltage source converters with LCL filter," IEEE Trans. I nd. Electron., vol. 58, no. 8, pp. 3623–3633, Aug. 2011.

[4] A. Cagnano, E. De Tuglie, M. Liserre, and R. A. Mastromauro, "Online optimal reactive power control strategy of PV inverters," IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4549–4558, Oct. 2011.

[5] T. C. Y. Wang, Z. Ye, G. Sinha, and X. Yuan, "Output filter design for a grid-interconnected three-phase inverter," in Proc. PESC , Acapulco, NM, Jun. 15–19, 2003, pp. 779–784.

[6] R. Turner, S. Walton, and R. Duke, "Stability and bandwidth implications of digitally controlled grid-connected parallel inverters," IEEE Trans. Power Electron., vol. 57, no. 11, pp. 3685–3694, Nov. 2010.

[7] A. A. Rockhill, M. Liserre, R. Teodorescu, and P. Rodriguez, "Grid-filter design for a multimegawatt medium-voltage voltage-source inverter," IEEE Trans. I nd. Electron., vol. 58, no. 4, pp. 1205–1217, Apr. 2011.

[8] P. Channegowda and V. John, "Filter optimization for grid interactive voltage source inverters," IEEE Trans. I nd. Electron., vol. 57, no. 12, pp. 4106–4114, Dec. 2010.

[9] M. Hojabri, A. Toudeshki," Power quality consideration for off-grid renewable energy systems," Energy and Power Engineering, doi:10.4236/epe, vol.5, no.5, 377-383, 2013.

[10] F. L. M. Antunes S. V. Araujo, "LCL filter design for grid-connected npc inverters in offshore wind turbines," The 7th International Conference in Power Electronics, 1:1133–1138, 22-26 October, 2007 / EXCO, Daegu, Korea.

[11] V. Blasko and V. Kaura, "A novel control to actively damp resonance in input lc filter of a three-phase voltage source converter," IEEE Trans. Ind. Appl., vol. 33, no. 2, pp. 542–550, Mar./Apr. 1997.

[12] H. M. Kojabadi et al., "A Novel DSP-based current-controlled PWM strategy for single phase grid connected inverters," IEEE Transactions on Power Electronics, vol. 21, no. 4, pp. 985-993, July 2006.

[13] H. Kim and S.K Sul, "A novel filter design for output LC filters of PWM inverters," Journal of Power Electronics., vol. 11, no.1, pp. 74-81,2011.

[14] K. H. Ahmed et al, "Passive filter design for three phase inverter interfacing in distributed generation," Electric Power Quality and Utilization, vol. XIII, no. 2, pp. 49-58, 2007.

[15] X. Renzhong, X. Lie, Z. Junjun, and D. Jie ,„Design and research on the LCL filter in three-phase PV grid-connected inverters, International Journal of Computer and Electrical Engineering, vol. 5, no. 3, June 2013.

[16] Z.Ye, G. Sinha, X.Yuan and T. C.Wang, Output filter design for a grid-interconnected three-phase inverter, IEEE Annual Conf, 2003.

[17] F.Liu1, X. Zha1, Y. Zhou, S.Duan, Design and research on parameter of LCL filter in three-phase grid-connected inverter, IEEE Annual Conf, 2009.

[18] H. Cha and T.K Vu, Comparative analysis of low-pass output filter for single-phase grid-connected photovoltaic inverter, IEEE Annual Conf, 2010.

[19] Standard IEEE-519, IEEE recommended practices and requirements for harmonic control in electric power systems, 1992.

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