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Electrical Power Quality Improvement for Renewable Energy Systems Using LCL Filter

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ABSTRACT: Due to the effects of global warming from greenhouse gas released to the atmosphere by combustion of fossil fuels, high prices of fossil fuels and their unsteady supply, researchers are becoming more concerned in the renewable energy sources. This paper presents a method that is used to improve the power quality by filtering harmonics produced by the voltage source inverter (VSI) used for conversion from DC to AC. MATLAB/SIMULINK software is used for simulation and results before and after filtering are compared and conclusions made.

Index terms: Renewable Energy; Power Quality; L-C-L Filter; Harmonics.

1. INTRODUCTION

Renewable energy sources are cheaper, clean and readily available as they can be used again and again without getting diminished. A voltage source inverter is usually used to convert DC power to AC power. The output of this converter has high order harmonics originating from its high switching frequency. These harmonics can affect the operation of electrical equipment connected to the system. In order to reduce the harmonics produced by the inverter, a large input inductance (L filter) can be connected in the system. But a big inductance will be bulky and has low attenuation of the harmonics. Therefore, instead of using just an inductance, a third order LCL filter can be used with good performances in current ripple attenuation even for small inductances [1].

Although LCL filters are good in harmonic attenuation, they bring an undesired resonance effect that generates stability problems. These problems can be solved by using a damping resistor -passive damping [1]. This method has its advantages like reliability and simplicity but it has also disadvantages like increased losses through heat dissipation, which leads to further costs for designing and building a cooling system. This is the reason why active damping methods have been developed [1]. The active damping methods modify the control algorithm, stabilizing the system without increasing the losses.

2. LCL FILTER

The main functions of a filter [5] includes conversion of the voltages from switch devices to current, to reduce high frequency (HF) switching noises and protect the switching devices from transients. As explained in [5] [6] [4] the L-filter and L-C filters has excellent performance in terms of voltage to current conversion but the damping of the HF noise is rather poor. The capacitor to these filters may be exposed to line voltage harmonics that results in large currents. The L-C-L filter has good current ripple attenuation even with small inductance values. [4]

In addition to good voltage-current conversion L-C-L filter damps the HF noises due to its extra inductance. Unlike L and L-C filters, the capacitor in L-C-L filter is not exposed to line voltage distortion [5]. Low grid current distortion and reactive power production and possibility of using

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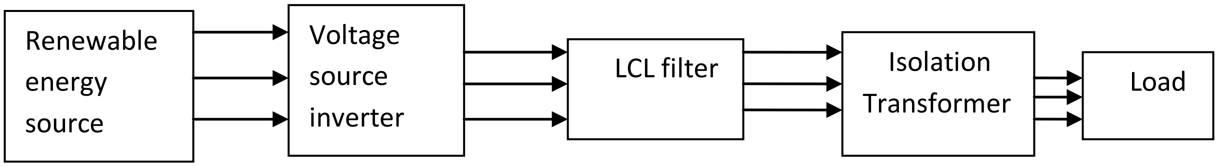


Figure 1: Block diagram for renewable energy connected to a load

a relatively low switching frequency for a given harmonic attenuation are among the advantages of L-C-L filter [4].

L-C-L filter is a third order filter and has attenuation of 60dB/decade for frequencies in excess of the resonance frequency [2] [3] [4]. Though the LCL filter can sometimes cost more than other more simple topologies depicted in Fig. 3.8, its small dependence on the grid parameters is of major importance at high power applications, in order to guarantee a stable power quality level. Furthermore, it provides better attenuation than other filters with the same size and by having an inductive output; it is capable of limiting current inrush problems [42].

On the other side, L-C-L is unstable may cause both dynamic and steady state input current distortion due to resonance [4]. In order to reduce oscillations and unstable states of the

L-C-L filter, the damping resistor is added. This solution is sometimes called “passive damping”. This damping technique is simple and reliable, but it increases the heat losses in the system and it greatly decreases the efficiency of the filter. In general there are four possible places where the resistor can be placed series/parallel to the inverter side inductor or series/parallel to filter capacitor.

These characteristics and advantages of L-C-L filter, over other filter topologies are among the reasons for widespread use of L-C-L filter. This filter is common to voltage source inverters (VSI).

Renewable energy sources such as wind or photovoltaic, are connected through the voltage source inverter to convert DC power to AC power. The output of the VSI is passed through the LCL filter to reduce harmonics i.e to produce a sine wave output out of the square wave output of the VSI. A transformer is used to isolate the generation from the load. As shown in fig. 1.

2.1. Transfer function of the LCL filter

In order to obtain the transfer function of the LCL filter, the single phase electrical diagram in Fig. 2 is considered. The components of the filter on each phase are considered to be identical, so the circuit below is suitable for the other two phases.

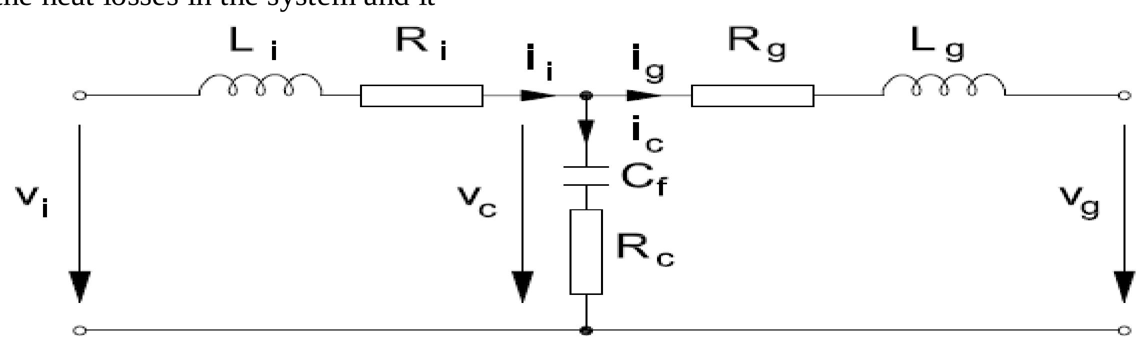


Fig. 2: One phase electrical circuit of an LCL filter.

Using Kirchhoff’s laws, the filter model in s-plane can be written with the following equations:

$$i_i - i_c - i_g = 0 \quad (1)$$

$$v_i - v_c = i_i(sL_i + Ri) \quad (2)$$

$$v_c - v_g = i_g(sL_g + R_g) \quad (3)$$

$$v_c = i_c \frac{1}{sC_f + R_i} \quad (4)$$

The following notations have been made:- v_i- inverter voltage, i_i-inverter current, v_c-voltage drop on filter capacitance, i_c-current across filter capacitance, v_g-grid voltage, i_g-grid current, L_i- filter inductance on inverter side, R_i- inverter side parasitic resistance, C_f- filter capacitance, R_c- parasitic resistance of filter capacitance, L_g- filter inductance in grid side, R_g- grid side parasitic resistance

The transfer function of the filter is expressed by:

In order to compute the transfer function of the filter, some

$$H_{LCL} = \frac{i_g}{v_i} \quad (5)$$

mathematical calculations have to be made. The grid voltage is assumed to be an ideal voltage source and it represents a short circuit for harmonic frequencies, and for the filter analysis it is set to zero: $v_g = 0$.

$$v_i = v_c + i_i(sL_i + R_i)$$

From the equations (3) and (4), the following relation can be written

$$i_g(sL_g + R_g) = i_c(1/sC_f + R_c) \quad (6)$$

Hence;

(7)

Equation (2) can be written as:

$$i_c = i_g(s^2 C_f L_g + sC_f R_g)/sC_f R_c + 1) \quad (8)$$

By introducing (3), (1) and (6) into the above relation, the inverter voltage can be written as (9):

$$v_i = i_g(sL_g + R_g) + (i_g + i_c)(sL_i + R_i) = i_g(sL_g + R_g) + (i_g + i_g \frac{s^2 C_f L_g + sC_f R_g}{sC_f R_c + 1})(sL_i + R_i) \quad (9)$$

Hence;

$$v_i = i_g(sL_g + R_g + sL_i + R_i + \frac{(sL_i + R_i)(s^2 C_f L_g + sC_f R_g)}{sC_f R_c + 1} \quad (10)$$

So, considering (5), the transfer function of the filter can be calculated as (11):

$$H = \frac{sR_cC_f + 1}{s^3L_gL_iC_f + s^2C_f\,(L_g(R_c + R_i) + L_i(R_c + R_g)) + s(L_g + L_i + C_f\,(R_cR_g + R_cR_i + R_gR_i)) + R_g + R_i} \qquad (11)$$

3. SIMULATION AND DISCUSSION

The parameters used for simulation are shown in Table 1.

Fig. 3 shows the SIMULINK block diagram for the designed system. Renewable energy source is represented by a DC source of 870V and a three level voltage source inverter is used for conversion from DC to AC. Filtering of harmonics is done by use of LCL filter. The voltages and currents were measured before filtering and after filtering for comparison.

Table 1: Summarized parameters.

Grid line to line voltage (V_{LL})	415V
Switching frequency (f_s)	6000Hz
Inverter side filter inductor (L_1)	1.23mH
Grid side filter inductor (L_2)	469µH
Filter capacitor (C_f)	92µF
Filter resonant frequency f_{res}	936Hz
Equivalent series resistances for L_1 andL_2	0.03 ohms
Equivalent series resistor for the capacitor C_f	0.1 ohms

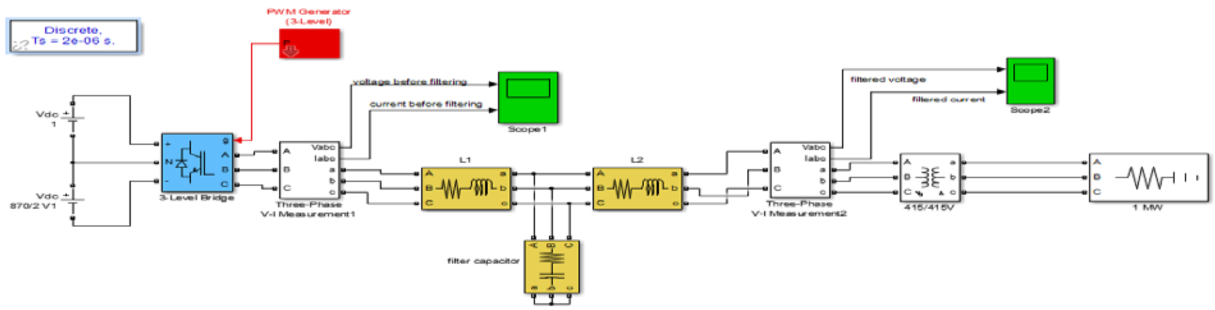
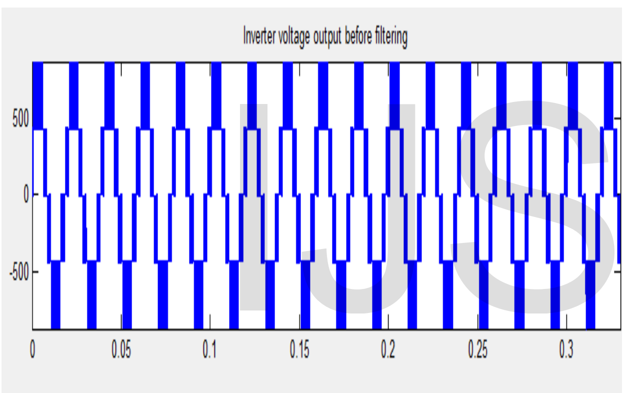


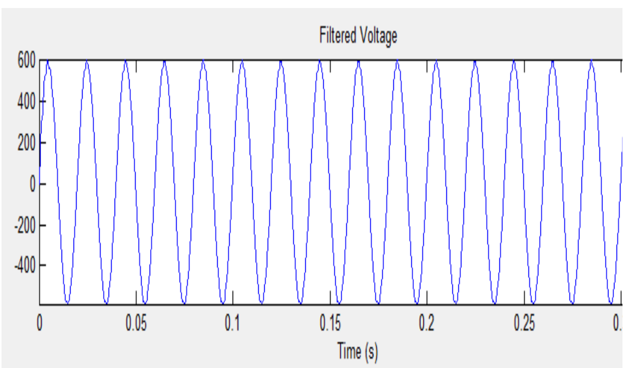
Fig. 3: MATLAB/SIMULINK model of the unsynchronized inverter system

The results for the Voltage before and after filtering are presented fig. 4 (a) and (b):

i) Voltage waveform comparison



(a)



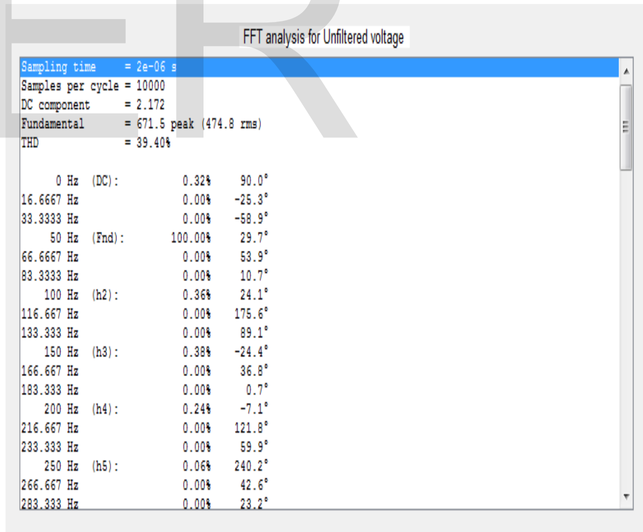
(b)

Fig 4: Voltage waveform (a) before filtering and (b) after filtering

The FFT analysis for voltage and current waveform harmonics was done and the results presented as fig. 5 (a) and (b).

ii) Voltage FFT analysis

(a) FFT analysis for Voltage before filtering



(a)

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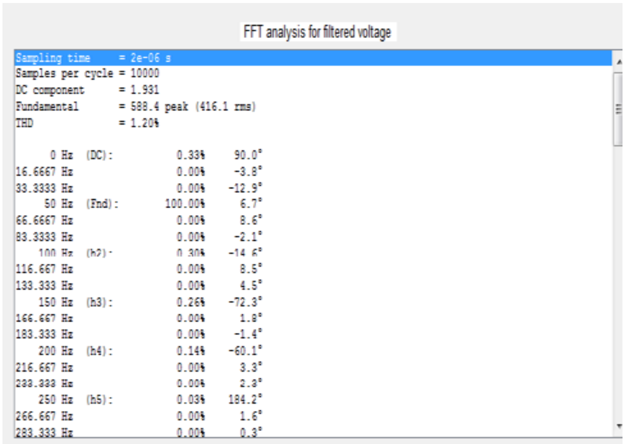
(b) FFT analysis for voltage after filtering


FFT analysis for filtered voltage

Sampling time = 2e-06 s
Samples per cycle = 10000
DC component = 1.931
Fundamental = 588.4 peak (416.1 rms)
THD = 1.20%

0 Hz	(DC):	0.33%	90.0°
16.6667 Hz		0.00%	-3.8°
33.3333 Hz		0.00%	-12.9°
50 Hz	(Fnd):	100.00%	6.7°
66.6667 Hz		0.00%	8.6°
83.3333 Hz		0.00%	-2.1°
100 Hz	(h2):	0.30%	-14.6°
116.667 Hz		0.00%	8.5°
133.333 Hz		0.00%	4.5°
150 Hz	(h3):	0.26%	-72.3°
166.667 Hz		0.00%	1.8°
183.333 Hz		0.00%	-1.4°
200 Hz	(h4):	0.14%	-60.1°
216.667 Hz		0.00%	3.3°
233.333 Hz		0.00%	2.3°
250 Hz	(h5):	0.03%	184.2°
266.667 Hz		0.00%	1.6°
283.333 Hz		0.00%	0.3°

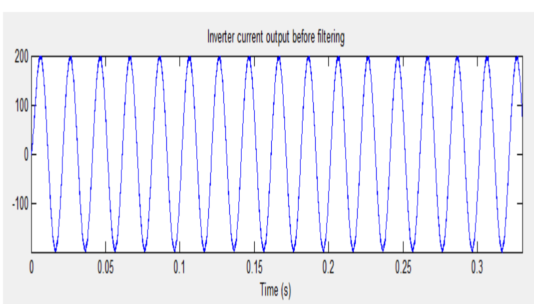
(b)

Fig 5: Inverter voltage output FFT analysis (a) before filtering and (b) after filtering.

As can be seen from fig.4 (a) (b), voltage harmonics have been reduced. The FFT analysis presented in fig. 5 (a) and (b) shows that the voltage harmonics have been reduced from a THD of 39.40% to 1.20%.

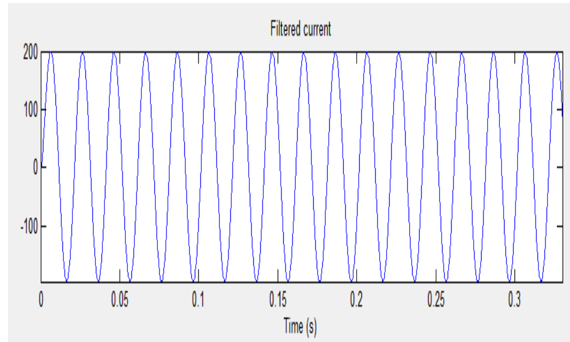
iii) Inverter current waveforms before and after filtering

(a) Current waveform before filtering



(a)

(b) Current waveform after filtering

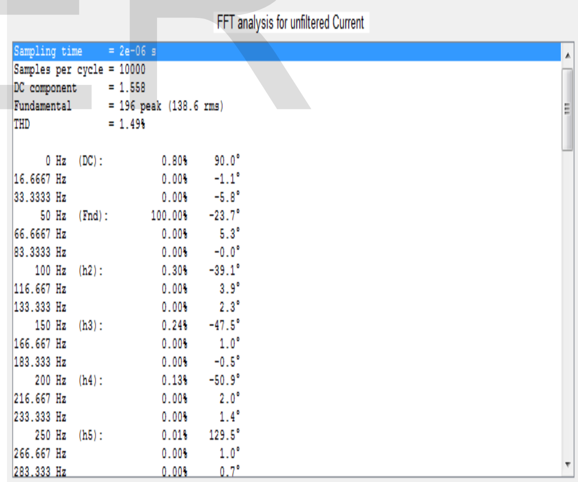


(b)

Fig 6: Comparison of current waveforms (a) before and (b) after filtering.

iv) Current FFT analysis

(a) FFT analysis for current outputs before filtering

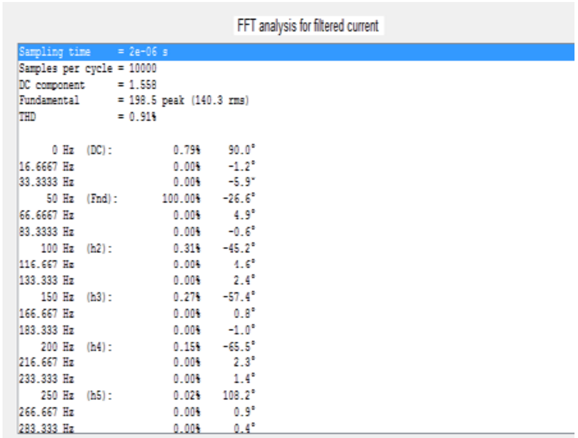

FFT analysis for unfiltered Current

Sampling time = 2e-06 s
Samples per cycle = 10000
DC component = 1.558
Fundamental = 196 peak (138.6 rms)
THD = 1.49%

0 Hz	(DC):	0.80%	90.0°
16.6667 Hz		0.00%	-1.1°
33.3333 Hz		0.00%	-5.8°
50 Hz	(Fnd):	100.00%	-23.7°
66.6667 Hz		0.00%	5.3°
83.3333 Hz		0.00%	-0.0°
100 Hz	(h2):	0.30%	-39.1°
116.667 Hz		0.00%	3.9°
133.333 Hz		0.00%	2.3°
150 Hz	(h3):	0.24%	-47.5°
166.667 Hz		0.00%	1.0°
183.333 Hz		0.00%	-0.5°
200 Hz	(h4):	0.13%	-50.9°
216.667 Hz		0.00%	2.0°
233.333 Hz		0.00%	1.4°
250 Hz	(h5):	0.01%	129.5°
266.667 Hz		0.00%	1.0°
283.333 Hz		0.00%	0.7°

(a)

(b) FFT analysis for current output after filtering



(b)

Fig. 7: Inverter current waveform harmonics (a) before filtering and (b) after filtering

From fig 6 and fig 7, current harmonics have been reduced by the LCL filter from THD of 1.49% to 0.91% .

CONCLUSION

From the results presented above, the output of the VSI has high harmonics. The LCL filter used reduces the harmonics hence it was concluded that the power from the renewable energy sources has been improved by reduction of the harmonics produced by the VSI.

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