FILTER DESIGN AND PERFORMANCE ANALYSIS FOR GRID CONNECTED AND STAND-ALONE SYSTEM

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Abstract

The power electronic sources are of great importance in order to maximize the power transfer capacity form various distributed as well as renewable energy sources, such as solar, wind, hydrogen based fuel cell to the utility grid. To interconnect the inverter to the utility grid an LCL filter is often used in order to filter the harmonics produced by the inverter. There is a lot of literature available describing LCL filter and its design methodology. There has been gap in providing systematic design methodology, and also lack of a state-space mathematical modelling approach. This paper describes a design methodology of an LCL filter for grid connected system as well as stand- alone system along with detailed study of how to mitigate harmonics. The procedure and techniques described in this paper are often used for small scale as well as medium and large scale renewable energy conversion systems

Index Terms: filter, harmonics, inverter, power quality, renewable energy sources, utility grid.

I. INTRODUCTION

A filter is an electrical network that alters amplitude and phase characteristics of signal with respect to frequency. Ideally, a filter will not add new frequencies to the input signal nor will change the component frequencies of that signal, but it will change the relative amplitudes of the various frequency components and their phase relationships. Filters are mainly used in large power application of electrical drives from simple first order inductor to more complex high order filters. They are also used for grid interconnection of renewable energy sources. This paper proposes filter design guideline for LCL filter topology with IGBT based inverter. This filter cancels most of the harmonics and almost pure sinusoidal output voltage is obtained. A passive filter used to reduce adverse effects of PWM inverters used in this system. Voltage source inverters (VSI's) are used for energy conversion from various renewable energy sources such as PV module whose output is in DC form, to an ac output both in stand- alone as well as grid connected system. Commonly high order LCL filter are used in place of conventional L filter for smoothing the output current as well as voltage harmonics from VSI [1], [2]. LCL filter have advantages over conventional L filter such as, high attenuation along with cost saving, overall weight and size reduction of components. LCL filter minimizes amount of current distortion injected into the utility grid [3]. The higher harmonic attenuation of the LCL filter allows the use of lower switching frequencies to meet the harmonic constraints defined by standards such as IEEE-519 and IEEE- 1547 [5][6]. In order to design an effective LCL filter, it is necessary to have an appropriate mathematical model of the filter.

II. SYSTEM MODELLING

A. Per - phase equivalent model of an LCL filter

The LCL filter model is shown in fig. 1, where L1 is the inverter side inductor, L2 is the grid-side inductor, Cf is a capacitor with series

Rf damping resistor, R1 and r2 are inductors resistances, and voltages vi and Vg are the input and output voltages.

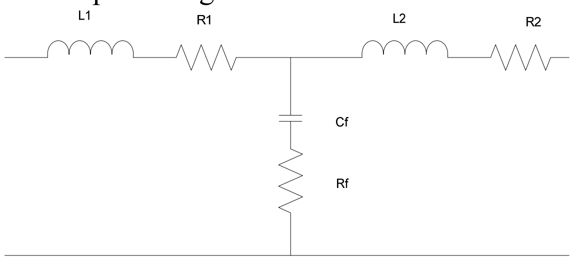

Fig.1 LCL filter per phase model

A functional block diagram for the grid connected inverter using this LCL filter is shown in fig. 2.

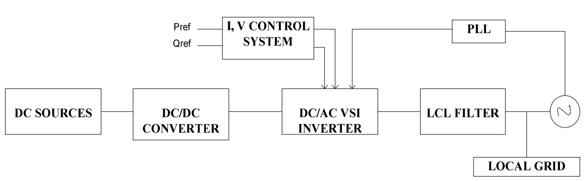

Fig.2 Functional block diagram of grid connected inverter

B. Wye connected capacitors

The above mentioned LCL filter [fig.1] has some superior characteristics and accuracy in case of mitigation of harmonics. It is called as 3rd order because of having 3 active elements in it and hence we get S^3 calculating the transfer functions. As the system has 2 inputs and 2 outputs it is an MIMO system and hence the differential equation comes as follows, the equation shows no cross coupling terms as indicated by the matrix expression:

$$\begin{bmatrix} \frac{di_i}{dt} \\ \frac{di_g}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_1+R_f}{L_1} & \frac{R_f}{L_1} & \frac{-1}{L_1} \\ \frac{R_f}{L_2} & \frac{-R_2+R_d}{L_2} & \frac{1}{L_2} \\ \frac{1}{C_f} & \frac{-1}{C_f} & 0 \end{bmatrix} \begin{bmatrix} i_i \\ i_g \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 \\ 0 & \frac{-1}{L_2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_i \\ v_g \end{bmatrix}$$

From the above equations three inputs can be given to the filter and three outputs can be obtained.

The transfer function of LCL filter with damping resistance will become –

$$Hd_{LCL}(s) = \frac{C_f R_f s + 1}{L_1 C_f L_2 s^3 + C_f (L_1 + L_2) R_f s^2 + (L_1 + L_2) s}$$

Design of Filter procedure is described with respect to flowchart in detail –

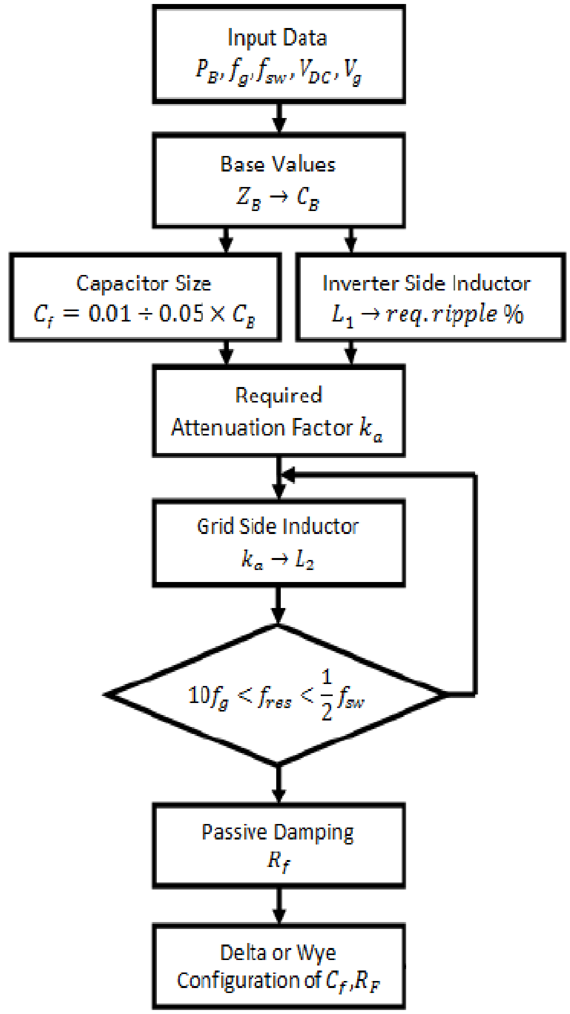

Fig.3 LCL filter design algorithm

C. Calculation of values for LCL filter

For designing LCL filter following parameters need to be considered,

f_g =Grid frequency, f_{sw} =switching frequency, V_{DC} = DC Link voltage, V_g =Grid voltage

After assumptions base impedance and base capacitances are evaluated because filter values are referred in percentage base values, then filter capacitance is calculated by assuming 5% maximum power factor variation by the grid. By assuming current ripples inverter side inductor value is evaluated. Grid side inductor is calculated by assuming attenuation factor 20%.

Resonant frequency is calculated by using the values of inductors and capacitors which must be in between 10 times grid frequency and half of switching frequency. Then passive damping resistor value is calculated. As per the requirement LCL filter is connected in delta or wye configuration.

The specifications used for calculation of various parameters related to LCL filter are,

$E_n = 120\sqrt{3}\,V$, line to line RMS voltage; P_s=P_n=5KW,rated active power; V_{DC}= 400V, dc-link voltage; ω_g = 2π60, grid angular frequency; ω_{SW} = 15kHz, switching frequency; x= 0.05, maximum power factor variation seen by the grid; k_a = 0.2(20%), attenuation factor

Now,

$$Z_b = \frac{E_n^2}{P_n} = \frac{(120\sqrt{3})^2}{5*10^3} = 8.64\Omega\text{, base impedance}$$

$$c_B = \frac{1}{\omega g * Z_b} = \frac{1}{(2\pi 60)(8.64)} = 307\mu F\text{, base capacitance}$$

$$c_f = 0.05 * c_B = 0.05 * 307 = 15\mu F\text{, filter capacitance}$$

$$I_{max} = \frac{P_n\sqrt{2}}{3V_{ph}} = \frac{5*10^3*\sqrt{2}}{3*120} = 19.64A$$

$$\Delta I_{max} = 0.1 * I_{max} = 0.1 * 19.64 = 1.964A$$

$$L_1 = \frac{V_{dc}}{6*f_{sw}*\Delta I_{max}} = \frac{400}{6*15*10^3*1.964} = 2.33mH\text{, inverter side inductor}$$

$$L_2 = \frac{1+\sqrt{\frac{1}{k_a^2}}}{C_f*(\omega_{sw})^2} = \frac{1+\sqrt{\frac{1}{(0.2)^2}}}{15*(10)^{-6}*(2\pi*15*(10)^3)^2} = 0.045mH\text{, grid side inductor}$$

D. Frequency response of LCL filter

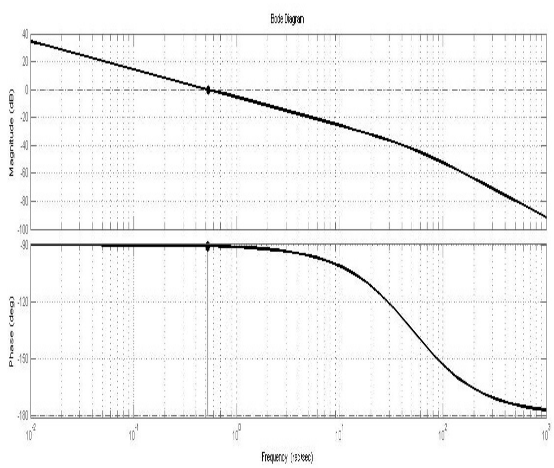

Fig.4 Frequency response of LCL filter

Above figure shows the frequency response of the evaluated transfer function of the LCL filter. By which the gain and phase margin can be observed which decides whether system is stable or not and if it is unstable then system would get damage.

III. SIMULATION RESULTS

A. Grid connected system

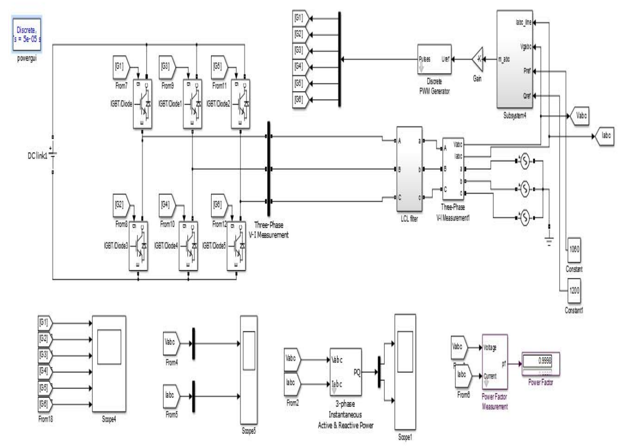

Fig.5 Simulation of grid connected LCL filter

The performance of the simulated system analyzed in MATLAB/SIMULATION as shown in fig.5. The system was tested considering following parameters,

Table 1

Parameter	Symbol	Value
Inverter side inductor	L_i	2.432 mH
Grid side inductor	L_g	0.085 mH
Capacitor/phase	C_f	9.564 µF
Resistor/phase	R_f	0.987 Ω
Output phase voltage	V_{rms}	230 V
Output capacity	P_{cap}	10KWp

The output at the utility terminals has been analyzed for THD with and without LCL filter. The THD analysis is performed by means of FFT analysis tool in MATLAB. For system without LCL filter the THD is around 97%. The output waveforms at utility level after connecting LCL filter is as follows,

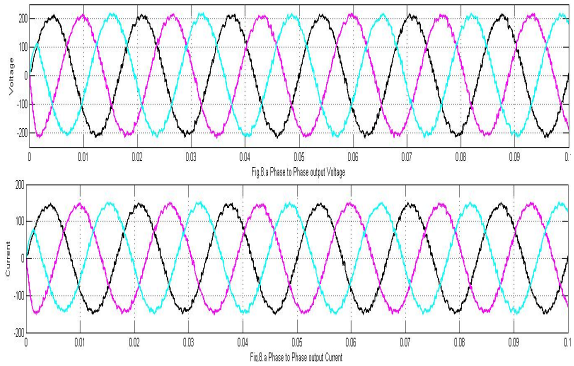

Fig.6 Output waveforms at utility grid

Hence to mitigate the harmonics in the system we need to connect specially designed LCL filter in series with the system. After connecting LCL filter the THD is found to be 3.43% in FFT analysis of MATLAB.

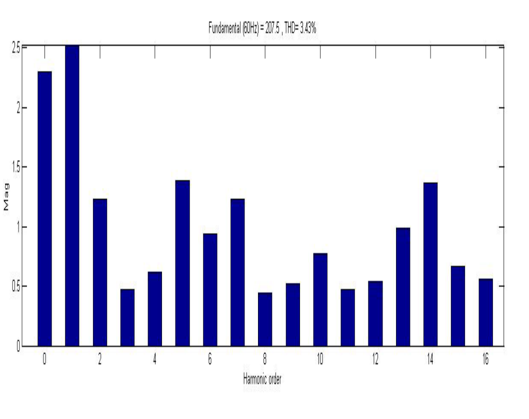

Fig.7 THD analysis at utility grid

B. Stand-alone system

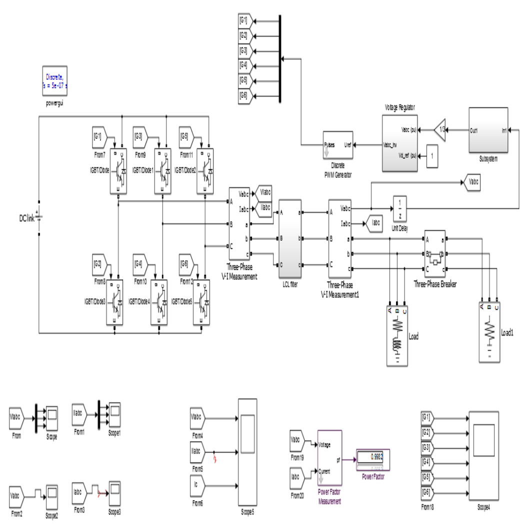

Fig.8 Simulation of stand-alone system

The output at the utility terminals has been analyzed for THD with and without LCL filter. The THD analysis is performed by means of FFT analysis tool in MATLAB. For system without LCL filter the THD is around 12.52%. The output waveforms at utility level after connecting LCL filter is as follows,

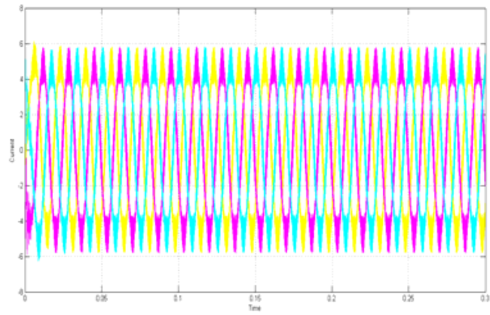

Fig.9 Output current at load terminal

Hence to mitigate the harmonics in the system we need to connect specially designed LCL filter in series with the system. After connecting LCL filter the THD is found to be 0.72% in FFT analysis of MATLAB.

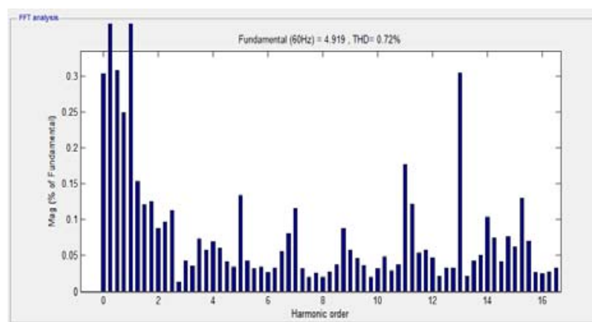

Fig.10 THD analysis at utility

IV. CONCLUSION

This paper proposes the systematic LCL design methodology for grid connected as well as stand-alone inverter system. The LCL filter reduces the switching frequency ripple and helps in coupling with current-like performance to the utility grid as well as for stand-alone system. This paper describes a comprehensive and detailed design procedure for LCL filter design. It is found that the proposed model meets industrial standards and allows a THD within a prescribed range. The theoretical design procedure has explained in detail for determining the various parameters used in LCL filter along with the calculations. The design procedure is applicable to the small and medium scale distributed power sources.

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