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HARMONIC ANALYSIS OF LOW VOLTAGE GRID CONNECTED POWER ELECTRONIC SYSTEMS WITH LCL FILTERS

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ABSTRACT- The harmonic performance of a small grid system has been analyzed in comparison with different grids and is proposed in this paper. By increasing number of power electronics based systems and loads, coupled harmonic as well as non-characteristic harmonics are generated.The main function of the LCL filter is to reduce high-order harmonics on the output side. The power quality of a low-voltage distribution or a stand-alone network with different grid connected power converter topologies are proposed in this paper. This paper presents and analyzes the harmonic performances of a power electronic system at a unit and a system level. The main aim of LCL filter is to reduce high-order harmonics and doesgood current ripple attenuation even with small inductance values.Passive harmonic mitigation techniques are still attractive solutions in power converters. This is due to harmonic cancellation within parallel converter at the system level, which depends on many different factors. This paper also elaborates the importance of phase angle values of current harmonics in order to analyze the power quality of a grid. Harmonic performances of different three-phase power converter topologies have been compared individually. By using the simulation results we can analyze the proposed method.

Index Terms—Harmonic mitigation, inductor, microgrid,power quality, LCL filter, power system, total harmonic distortion.

INTRODUCTION

In this paper, the phase angle variations of the current harmonics from a single unit to a multiunit configuration with different grid conditions have been analyzed and compared for each individual topology.Increasing the use of nonlinear industrial and commercial loads, such as power converters and variable speed motor drives, in various industrial pumps, air-conditioning, and reefer compressor creates high harmonic distortion in distribution networks[1]. Therefore, the harmonic mitigation techniques are very important to improve the quality of grids. There are various harmonics mitigation techniques at unit (product) and at system levels to improve grid current and voltage waveforms. In many low-power industrial applications, the passive techniques like ac and dc chokes are still preferred solutions due to their cost-effectiveness, simplicity, and reliability advantages. In these drives, a large electrolytic capacitor is replaced by a small film capacitor. Therefore, this paper focuses on the most common passive harmonic solutions such as ac choke, dc choke, and slim dc link capacitor used in three-phase power converters.

Normally, it is assumed that the harmonic performance of a power converter is same at both a unit (product) and a system level. Therefore, it is expected to predict and solve the current harmonic problems at a system level by incorporating the harmonic mitigation techniques at a unit level. However, there are possibilities to cancel current harmonics for parallel converter units at a system level due to phase angle differences. These depend on many factors such as grid inductance, transformer parameters, system configuration, load profiles, and topologies. A mathematical description of a harmonic cancellation mechanism at a system level has been analyzed based on phase angle values of current harmonics.

The LCL filter has good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter. In the technical literature we can find many articles on the design of the LCL filters. Important parameter of the filter is its cut-off frequency. The main function of the LCL filter is to reduce high-order harmonics on the output side; however poor design may cause a distortion increase. Therefore, the filter must be designed correctly and reasonably.

A large number of single-phase non-linear loads may also be connected to a power network such as computers, televisions, washing machines, florescent lights, battery chargers, and so on. All these investigations have been performed at a unit

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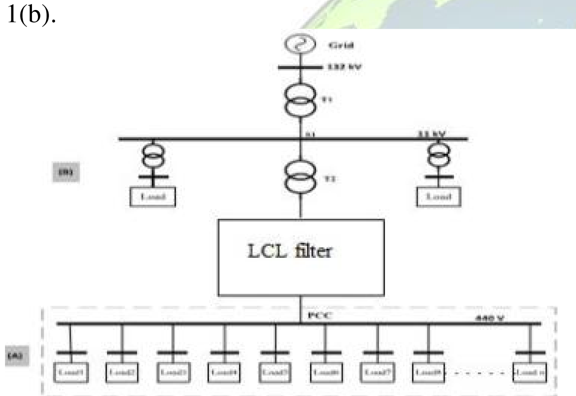
(product) level with limited information about the variation of phase angle values at a system level.

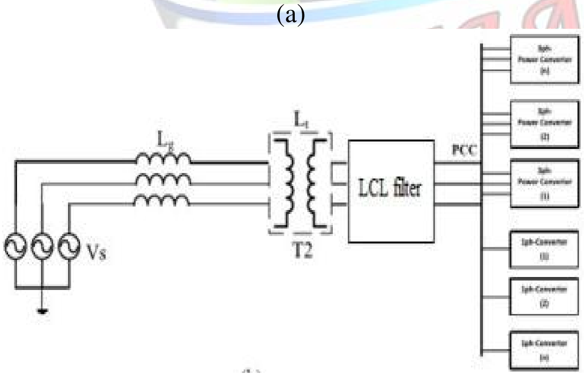
There is a possibility of phase angle variation at a system level when a large number of units are connected together. In this paper, the current harmonic cancellations of a combined parallel single-phase and different three-phase topologies have been investigated with respect to different load profiles.

SYSTEM DESCRIPTION

A typical industrial system network consists of a large number of nonlinear loads connected at different locations via various step-down transformers as shown in Fig. 1(a). The whole system network is divided into two parts: low and medium voltage networks (A) and (B). More details about the low voltage distribution network are shown in Fig. 1(b).



(a)



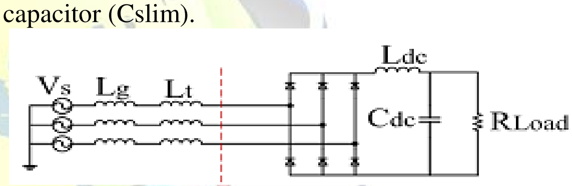
(b)

Fig. 1. (a) Line diagram of a distribution network. (b) Detailed line diagram of the low voltage distribution network.

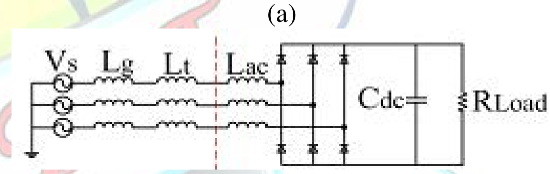
Low voltage distribution networks and microgrids are considered under this study, where a number of power electronic systems are connected in parallel at the secondary side of the step-down transformer as shown in Fig. 1(b). These power electronic systems could be three-phase and single-phase systems. The system inductance consists of the grid and the transformer inductances. The transformer is modeled as an ideal transformer, with no magnetic saturation and having a series inductor (Lt). Therefore, the system inductor of L s = Lg + Lt is a combination of the grid and the transformer inductances.

For low voltage applications, the six-pulse diode bridge rectifiers are the most commonly used in three-phase converters. Therefore, in this paper, the following three most popular configurations have been considered for three-phase diode rectifiers. The topologies and configurations are shown in Fig. 2(a)–(c):

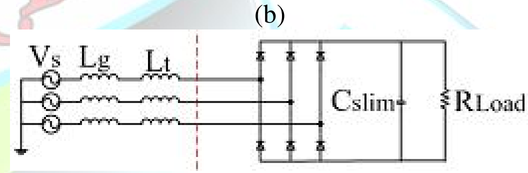
1) A three-phase diode rectifier with a dc choke (Ldc) and a large dc link capacitor (Cdc);
2) A three-phase diode rectifier with an ac choke (Lac) and a large dc link capacitor (Cdc);
3) A three-phase diode rectifier with a slim dc link capacitor (Cslim).



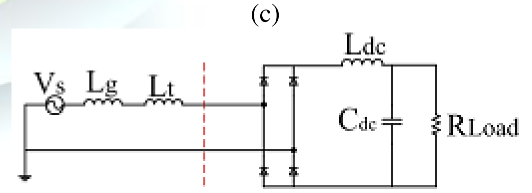
(a)



(b)



(c)



(d)

Fig. 2. Power converter topologies, three-phase diode rectifiers. (a) DC choke. (b) AC choke. (c) Slim dc link capacitor. (d) Single-phase diode rectifier with dc choke.

There are various applications, where the single-phase converter topologies have been used. To mitigate the line current harmonics of single-phase diode rectifier, ac or dc chokes can be used. However, in this paper, only the dc choke (Ldc)

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configuration of single-phase rectifier has been considered as shown in Fig. 2(d). This can help to analyze the low-order harmonic effects of the single-phase converters at a system level.

The low voltage distribution system shown in Fig. 1(b) has a number of three-phase and single-phase power converter units connected to the same PCC.

The following important conclusions have been drawn from this analysis.

1) This analysis has verified that the grid type (system inductance) has a big influence on performance and phase angle values of the current harmonics. Therefore, the harmonic performance of a unit (product) can be different at a system level and depends on many factors such as system inductance, the number of power converters, operating power levels, and the power converter topology.

2) In the stiff grid, the converters with the ac and the dc choke have almost the same current harmonic phase angles, but are significantly different compared with the converters with the slim dc link. Therefore, a stiff grid has a better possibility to cancel current harmonics when power converters with slim dc link are connected in combination of other converters with the ac and/or the dc choke.

3) In a soft grid all three topologies have almost the same current harmonic phase angles. Therefore, there is less possibilities of harmonic cancellation in a soft grid with different converter topologies.

4) This shows that the low and the high-order current harmonics generated by the power converters are different at the system level.

5) Two significant low-order current harmonics (fifth and seventh) can influence the system efficiency and quality.

HARMONIC ANALYSIS OF A LOW VOLTAGE DISTRIBUTION NETWORK

The main aim of this paper is to analyze the effect of the grid system parameters on individual three-phase and single-phase power converter and then comparatively analyze their harmonic performances at the system level based on phase angle variation of the current harmonics.

A mathematical expression has been derived to understand the harmonic cancellation of parallel units at a system level.

A. Harmonic Analysis of the Three-Phase Power Converter

In this analysis, the most common three-phase diode rectifier configurations (ac choke, dc choke, and slim dc link capacitor) have been used to analyze their harmonic performances at a unit and at a system level.

Several simulations have been carried out to compare the total harmonic distortion (THD) of line current with different values of ac or dc choke and dc link capacitor at different operating powers for a soft grid condition as shown in Fig. 3.

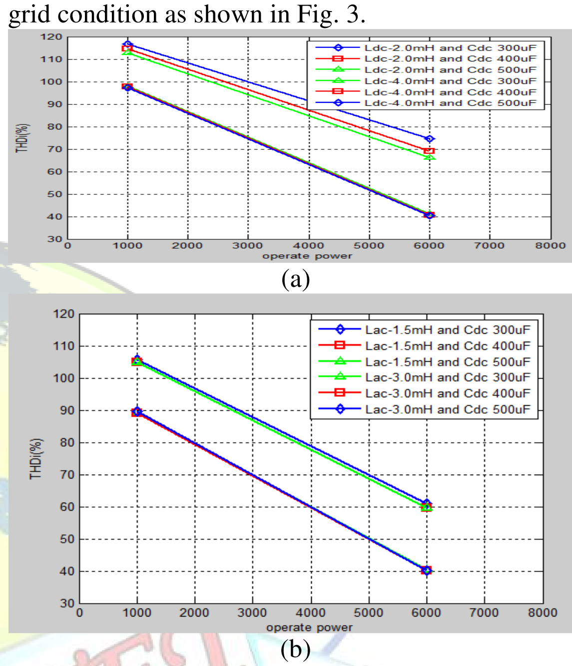

Fig. 3. THDi (%) of three-phase power converter with (a) dc choke and (b) ac choke.

The simulation results show that the variation in the dc link capacitor does not give any significant change in current harmonics. This is because a large dc link capacitor used in power converter will not significantly vary the resonance frequency of the system. On the other hand, the ac or dc choke gives the significant influence on current harmonic performance.

1) Harmonic Analysis of a Three-Phase Power Converter at a Unit Level:

In this analysis, it is assumed that only one three-phase power converter is connected at the PCC as shown in Fig. 4. This three-phase power converter could be one of the above mentioned topologies—ac choke, dc choke, and slim dc link capacitor as shown in Fig. 2(a)–(c).

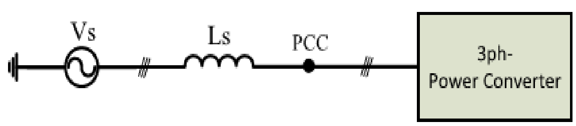

Fig. 4. Line diagram of a grid connected three-phase converter.

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Harmonic analysis of all three power converter topologies with two grid types has been performed at a unit level (product level). In this analysis, different simulations have been carried out at different operating power levels. Line current and grid voltage harmonic distortions have been captured at the primary side of transformer for each converter topology as shown in Fig. 5(a) and (b).

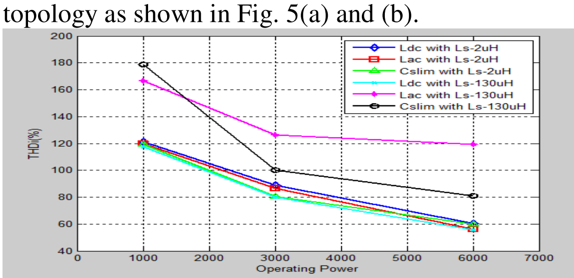

Fig. 5. Harmonic performance of all the three-phase power converter topologies at unit level with 2 and 130 μH system inductor. (a) THDi (%).

To limit the number of data, only the fifth current harmonics have been considered in this paper. However, a similar conclusion is expected for other harmonics also. [5] discussed about Improved Particle Swarm Optimization. The fuzzy filter based on particle swarm optimization is used to remove the high density image impulse noise, which occur during the transmission, data acquisition and processing. The proposed system has a fuzzy filter which has the parallel fuzzy inference mechanism, fuzzy mean process, and a fuzzy composition process. In particular, by using no-reference Q metric, the particle swarm optimization learning is sufficient to optimize the parameter necessitated by the particle swarm optimization based fuzzy filter, therefore the proposed fuzzy filter can cope with particle situation where the assumption of existence of "ground-truth" reference does not hold. The merging of the particle swarm optimization with the fuzzy filter helps to build an auto tuning mechanism for the fuzzy filter without any prior knowledge regarding the noise and the true image. Thus the reference measures are not need for removing the noise and in restoring the image. The final output image (Restored image) confirm that the fuzzy filter based on particle swarm optimization attain the excellent quality of restored images in term of peak signal-to-noise ratio, mean absolute error and mean square error even when the noise rate is above 0.5 and without having any reference measures.

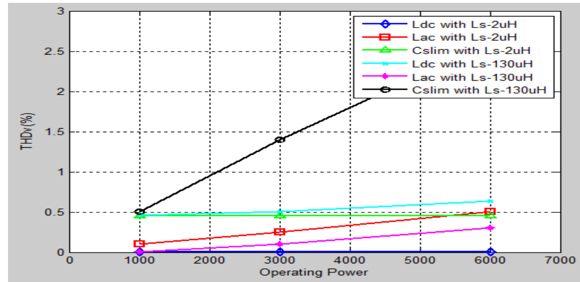

Fig. 5. Harmonic performance of all the three-phase power converter topologies at unit level with 2 and 130 μH system inductor. (b) THDv (%).

According to Fig. 5(b), due to the low system inductor in stiff grid, the THDv values are almost zero for all three topologies at those power levels. THDi, THDv, and the phase angle values of these two topologies are almost the same at different power levels.The phase angle values of the fifth current harmonics are shown in Fig. 5(c).

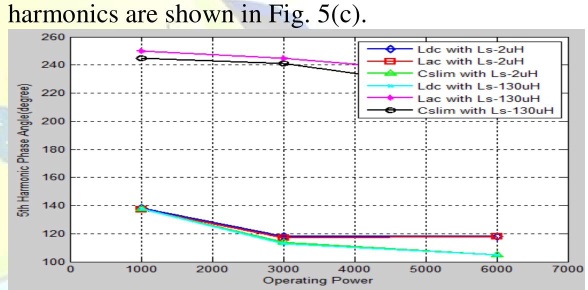

Fig. 5. Harmonic performance of all the three-phase power converter topologies at unit level with 2 and 130 μH system inductor. ((c) Fifth harmonic current phase angle.

The power converter with the slim dc link capacitor has different phase angle values compared with the other topologies. In short, the following important conclusions have been drawn from this analysis:

1) at the unit (product) level, the phase angle values of the fifth current harmonic are not changed with respect to the grid types (stiff and soft) for each topology;

2) harmonic performance and phase angle values of the converters with the ac and the dc choke are almost the same, but are different from those of the converter with the slim dc link.

2) Harmonic Analysis of a Three-Phase Power Converter at a System Level:

Number of simulations have been carried out to analyze the harmonic cancellation at the system level. For this, n number of power converters are connected to a balanced and a sinusoidal voltage source (Vs) with a system inductor (Ls) as shown in Fig. 6.

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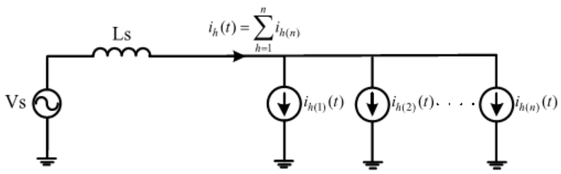

Fig. 6. Simple model of n number of power converters as current harmonic sources.

The current harmonics of n number of power converters are defined as ih(1), ih(2), . . . , ih(n), where i is the converter current and h is the order of harmonics

$$i_{h(1)}(t) = I_{h(1)} \sin\left(\omega_h t + \emptyset_{h(1)}\right)$$
$$i_{h(2)}(t) = I_{h(2)} \sin\left(\omega_h t + \emptyset_{h(2)}\right)$$
$$\cdots$$
$$i_{h(n)}(t) = I_{h(n)} \sin\left(\omega_h t + \emptyset_{h(n)}\right) \quad (1)$$

where ωh = 2πh f and 'φh' is the phase angle of harmonics

$$i_h(t) = \sum_{h=1}^{n} i_{h(n)}(t) = i_{h(1)}(t) + i_{h(2)}(t) + \cdots i_{h(n)}(t) \quad (2)$$

If only two converters are considered, then the total harmonic current ih(t) will be

$$i_h(t) = I_{h(1)}(t) + I_{h(2)}(t) \quad (3)$$
$$i_h(t) = I_{h(1)} \sin\left(\omega_h t + \emptyset_{h(1)}\right) + I_{h(2)} \sin\left(\omega_h t + \emptyset_{h(2)}\right)$$
$$i_h(t) = I_{h(1)} \sin\left(\omega_h t + \emptyset_{h(1)}\right) + I_{h(1)} \sin\left(\omega_h t + \emptyset_{h(2)}\right) + I_{h(2)} \sin(\omega_h t) \cos\left(\emptyset_{h(1)}\right) + I_{h(2)} \sin\left(\emptyset_{h(1)}\right) \cos(\omega_h t)$$
$$i_h(t) = \left(I_{h(1)} \cos\left(\emptyset_{h(1)}\right) + I_{h(1)} \cos\left(\emptyset_{h(2)}\right)\right) \sin(\omega_h t) + \left(I_{h(1)} \sin\left(\emptyset_{h(1)}\right) + I_{h(1)} \sin\left(\emptyset_{h(2)}\right)\right) \cos(\omega_h t)$$
$$i_h(t) = \sqrt{I_{h(1)}^2 + I_{h(2)}^2 + 2 I_{h(1)} I_{h(1)} \cos\left(\emptyset_{h(1)} - \emptyset_{h(1)}\right)} \quad (4)$$
$$if\, \emptyset_{h(1)} = \emptyset_{h(2)} then\; i_h(t) = \left(I_{h(1)} + I_{h(2)}\right) \quad (5)$$
$$if\, \emptyset_{h(2)} = \emptyset_{h(1)} + 180^0\; then i_h(t) = \left(I_{h(1)} - I_{h(2)}\right) \quad (6)$$

This means any difference in the phase angles of the two current harmonics can reduce the total input current with respect to Ih(1) + Ih(2) (when the difference between the phase angles is zero or φh(1) = φh(2)). Equation (4) gives the total harmonic current for two power converters. However, it can be generalized for n number of power converter to calculate the total harmonic current for any particular harmonic order as below

$$\sum_{h=1}^{n} i_{h(n)}(t) = \sqrt{\sum_{i=1}^{n}\left(\sum_{i=1}^{n} i_{h(i)}(t)\, I_{h(j)}(t) \cos\left(\emptyset_{h(i)} - \emptyset_{h(j)}\right)\right)} \quad (7)$$

From this expression, it can be understood that the total current at the PCC is the vector summation of current harmonics. This means the phase angle values of the current harmonics are very important factor to analyze the harmonic performance of a multiconverter at system level. In order to analyze the harmonic performance of power converter topologies at a system level, simulation models of the multiconverter units have been implemented in SABER and MATLAB/Simulink as shown in Fig. 7.

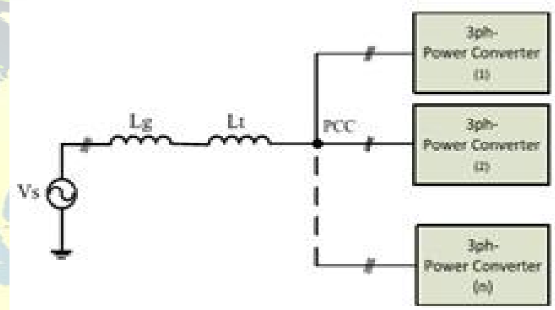

Fig. 7. Several three-phase power converter units are connected in parallel at the PCC.

The total number of power converters used in these simulations is 90, which are classified in different load profiles as indicated in Table I.

Table I
Different Load Profiles For A System Analysis

Load Profile : Number of units at different power levels				
Cases	Low Power Units	Medium Power Units	High Power Units	Power (kW)
1	90	0	0	59
2	70	10	10	135
3	60	15	15	174
4	40	40	10	204
5	50	20	20	213
6	40	25	25	253
7	0	90	0	263
8	10	70	10	273
9	15	60	15	278
10	20	50	20	283
11	25	40	25	288
12	30	30	30	293
13	40	10	40	303
14	25	25	40	339
15	10	40	40	374
16	20	20	50	384
17	15	15	60	431
18	10	10	70	478
19	0	0	90	574

The purpose of this analysis is to analyze the influence of different load profiles, system parameters, and power converter topologies on overall harmonic performance of the system. The line current distortion (THDi), the line voltage distortion (THDv) and the phase angle values of the current

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harmonics have been captured at the primary side of the transformer for two systems: 1) a stiff and 2) a soft grid, as shown in Fig. 8.

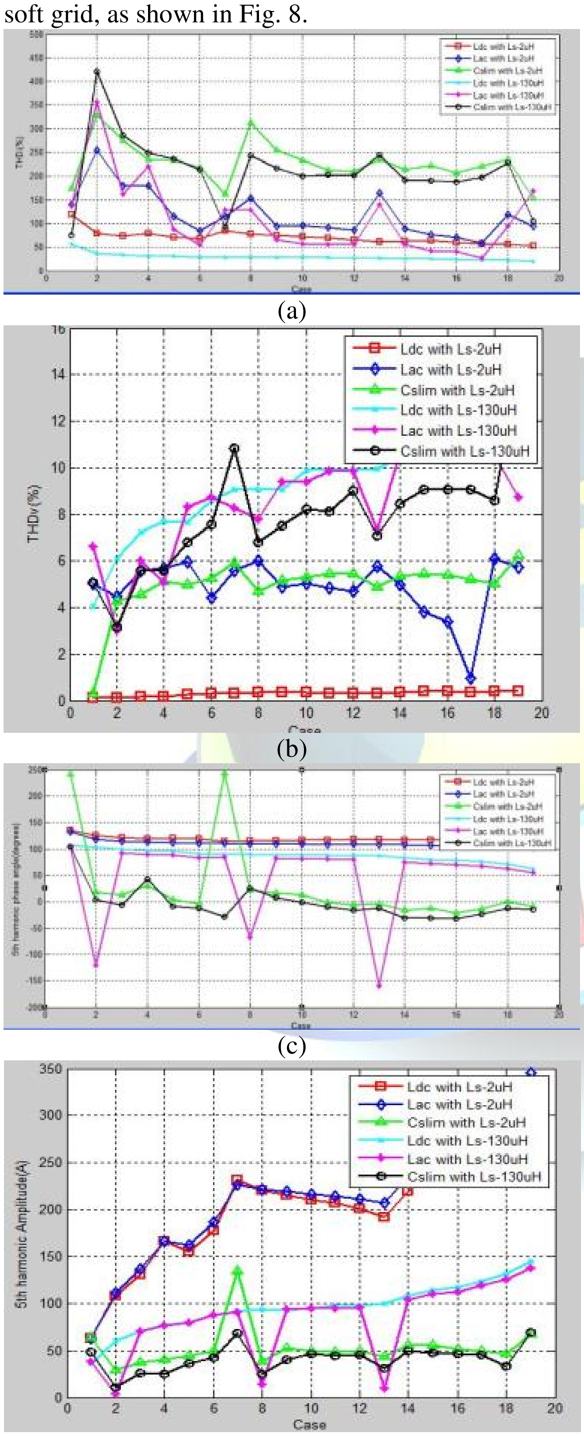

Fig. 8. Harmonic performance of all the three-phase power converter topologies at system level with 2 and 130 μH system inductor. (a) THDi (%). (b) THDv (%). (c) and (d) Fifth harmonic current phase angle and fifth harmonic current amplitude.

The power converters with the slim dc link capacitor have the worst THD v compare with other two topologies, as shown in Fig. 8(b). Fig. 8(c) shows that the phase angle values of the fifth current harmonics of each power converter topology connected to the grid.

This fact can be verified by simulating a case study, where the system inductance is transferred to each power converter connected to the PCC. The system inductor (Ls) is transferred to the right-hand side of the PCC and directly connected to each power converter as shown in Fig. 9.

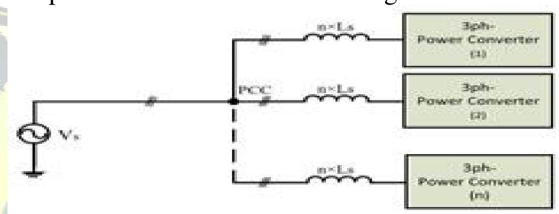

Fig. 9. Simulation model, where system inductor is connected to each converter.

The influence of the system inductance can be confirmed by comparing the phase angle of the fifth current harmonic variation shown in Fig. 8(c), where the 90 units connected to the soft grid have a phase angle variation (54°–106°) with respect to different power levels.

Table II
Harmonic Performance Of Three-Phase Power Converters With One Inductor (Ls = 130 Mh) At The Grid Side And With 90 Inductors (90 × 130 Mh) At Each Converter Side

Cases	Three-phase units with Ldc: 2.5mH and Ls: 130uH			Three-phase units with Lac: 11.7mH		
	THD_i (%)	5^{th} (deg)	7^{th} (deg)	THD_i (%)	5^{th} (deg)	7^{th} (deg)
1	55.8	106	236	55.2	106	234
7	28.4	90	127	28.3	87	124
19	20.8	63	55	20.7	57	49

It is also important to highlight that THDi could be a good indication to measure quality of a converter but it cannot be used to measure THD v. This can be seen in Fig. 8(a).

LCL FILTER

The output filter reduces the harmonics in generated current caused by semiconductor switching. There are several types of filters. The simplest variant is filter inductor connected to the inverter's output. But also combinations with capacitors like LC or LCL can be used.

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The LCL filter has good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter. In the technical literature we can find many articles on the design of the LCL filters. Important parameter of the filter is its cut-off frequency.

The cut-off frequency of the filter must be minimally one half of the switching frequency of the converter, because the filter must have enough attenuation in the range of the converter's switching frequency. The cut-off frequency must have a sufficient distance from the grid frequency, too. The cut-off frequency of the LCL filter can be calculated as,

$$f_{res} = \frac{1}{2\pi} * \sqrt{\frac{L_i+L_g}{L_i*L_g*C_f}} \qquad (8)$$

The LCL filter will be vulnerable to oscillations too and it will magnify frequencies around its cut-off frequency. Therefore the filter is added with damping. The simplest way is to add damping resistor. 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.

The main function of the LCL filter is to reduce high-order harmonics on the output side; however poor design may cause a distortion increase. Therefore, the filter must be designed correctly and reasonably.

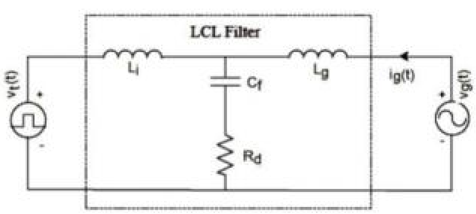

Fig.10.L-C-L filter and components

B. Harmonic Analysis of the Single-Phase Power Converter

In this analysis, the most common configuration of single-phase diode rectifier with dc choke has been considered as shown in Fig. 2(d).

Similar to three-phase power converter, a sensitivity analysis has been performed to analyze the effect of converter's parameters on the harmonic performance of the single-phase power converter. Several simulations have been carried out to compare the THD of line current with different values of dc choke inductances and dc link capacitors as shown in Fig. 11.

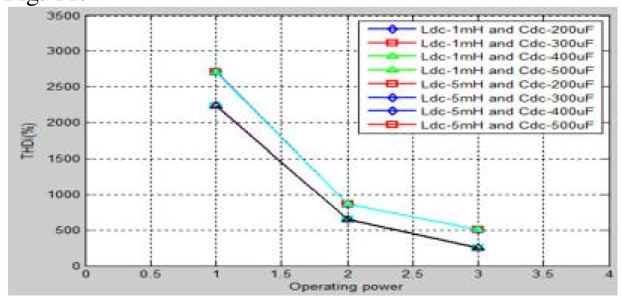

Fig. 11. THDi (%) of a single-phase power converter with the dc choke.

The simulation results show that the variation in the dc link capacitor does not give any significant change in the current harmonics

1) Harmonic Analysis of a Single-Phase Power Converter at Unit Level:

In this analysis, it is assumed that only one single-phase power converter is connected at the PCC as shown in Fig. 12. The fifth current harmonic phase angles and amplitudes have been captured at three different operating power levels as shown in Fig. 12.

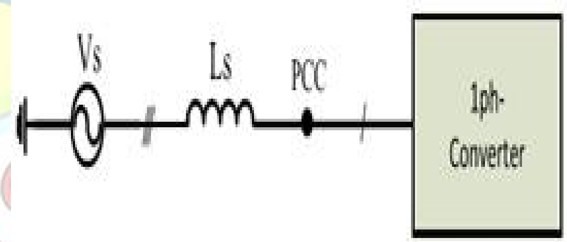

Fig. 12. Line diagram of a grid connected single-phase converter.

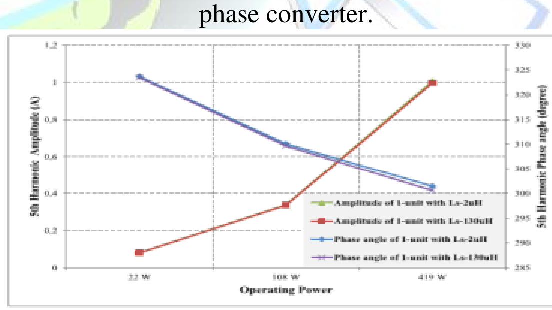

Fig. 13. Fifth harmonic amplitudes and phase angles for single-phase power converter at unit level with 2 and 130 μH system inductor.

2) Harmonic Analysis of a Single-Phase Power Converter at System Level:

Similar to the previous analysis of the three-phase power converters, here it is also important to analyze the variation of the phase angles at the system level where a large number of single-phase

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converters are connected at the PCC as shown in Fig. 14.

This means that at the system level, there is a possibility of current harmonic cancellation of parallel three-phase and single-phase converter units.

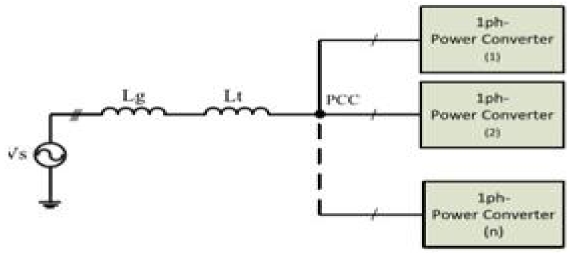


Fig. 14. Several single-phase power converter units are connected in parallel at the PCC.

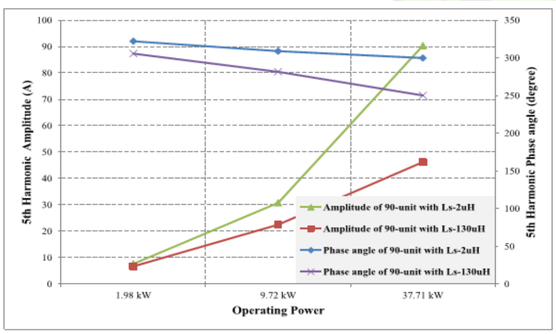


Fig. 15. Fifth harmonic amplitudes and phase angles for single-phase power converter at system level with 2 and 130 µH system inductor.

In order to verify this conclusion a case study has been implemented in Section III-C.

C. Harmonic Analysis of Parallel Three-Phase and Single-Phase Power Converters at a System Level—A Case Study

In a typical industrial distribution network, a large number of single-phase nonlinear loads, such as computers, televisions, and other domestic systems are also connected to a power network together with the three-phase nonlinear loads.

In order to verify the above conclusion and to validate the harmonics cancellation mechanism shown in Fig. 6, a case study has been performed for a large office building, where few three-phase nonlinear loads like Adjustable Speed Drives for heating and ventilation and many single-phase nonlinear loads like computers, laptops, and florescent lights are connected to the same PCC.

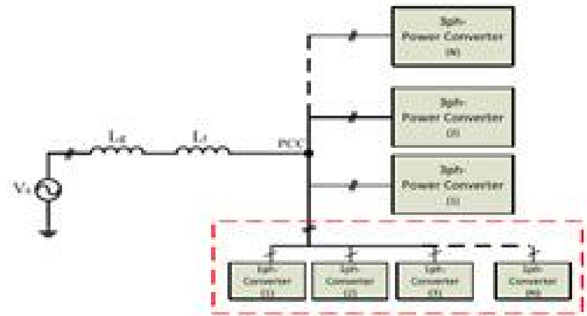
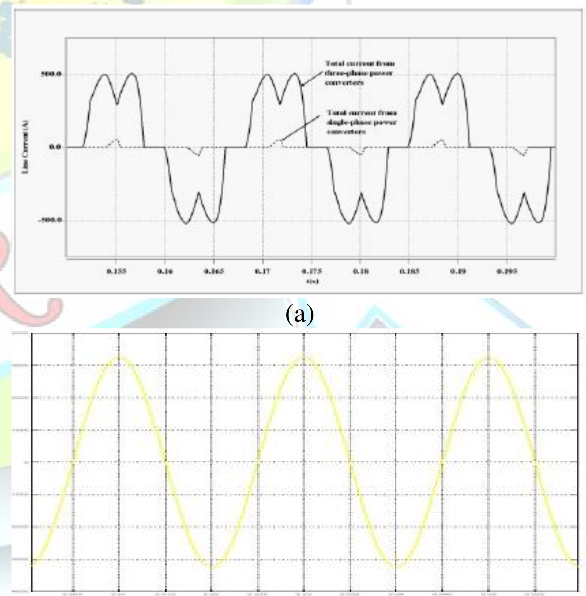


Fig. 16. System with several single-phase and three-phase power converters connected at the PCC.

In order to understand the harmonics cancellation mechanism, three simulation has been implemented in SABER: 1) for 45 units of three-phase power converter; 2) for 45 units of single-phase converter; and 3) for 90 units as a combination of three-phase and single-phase converters. The current waveforms for all the three simulations are shown in Fig. 16.



(a)

(b)

Fig. 17. Current waveforms for (a) 45 units of three-phase power converter (solid line) and the 45 units of single-phase power converter (dotted line) and (b) 90 units as a combination of three-phase and single-phase converters.

The fifth current harmonics for three-phase and single-phase power converter units from the first and the second simulation are

$$I_{5(3ph)}(t) = 97.93A\angle 94^0 \qquad (9)$$

$$I_{5(1ph)}(t) = 19.03A\angle 282^0 \qquad (10)$$

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This total power is close to 90 units system mentioned in case-8 (273 kW) given in Table I. Another approach for estimating the power quality of a system is based on drive performances. For example, instead of implementing a separate simulation model or measurement, we purpose to use the amplitude and phase angle of the fifth harmonics for case-8 which can be estimated from the graphs shown in Fig. 8.

$$I_5(3ph)(t) = 93.41A\angle 89^0 \quad (12)$$

Similarly, 15 units of single-phase converter (per phase) operated at 419 W gives the total power of 6.28 kW. For this case, the amplitude and phase angle of the fifth current harmonic can be estimated from the graph shown in Fig. 14, which is

$$I_{5(1ph)}(t) = 18A\angle 290^0 \quad (13)$$

CONCLUSION

In this paper, the importance of the phase angle values of current harmonics has been addressed to predict the harmonic cancellation of a large system including several different nonlinear power electronics based loads.This paper presents and analyzes the harmonic performances of a power electronic system at a unit and a system level. Therefore the main aim of LCL filter is to reduce high-order harmonics and it also good current ripple attenuation even with small inductance values. In various industrial applications, the traditional harmonic mitigation techniques such as ac choke, dc choke, and slim dc link capacitor are more attractive solutions in low power applications due to their cost effectiveness, simplicity, and reliability advantages.The main function of the LCL filter is to reduce high-order harmonics on the output side. This analysis shows that current harmonic mitigations are possible at system level where a large number of single and three phase power converters are connected to a grid but the harmonic mitigation depends on several factors, such as grid configuration and condition, load types, and their profiles. By using the simulation results we can analyze the proposed method.

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