Harmonic Analysis of Grid Connected Power Electronic Systems in Low Voltage Distribution Networks

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***Abstract*— The aim of this paper is to analyze the power quality of a low-voltage distribution or a stand-alone network with different grid connected power converter topologies. Passive harmonic mitigation techniques are still attractive solutions in power converters. However, these solutions give different harmonic performances at a system level, where a large numbers of converter units are connected in parallel at a point of common coupling. This is due to harmonic cancellation within parallel converter at the system level, which depends on many different factors. Therefore, in this paper, the harmonic performance of a small grid system has been analyzed with respect to different grid and power electronic parameters. 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. The analysis at the system level has been further extended by including single-phase converters in parallel with the three-phase power converters. A comprehensive modeling and simulation have been carried out in SABER and MATLAB/Simulink to verify the proposed analysis.**

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

I. Introduction

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. The harmonic distortion causes unnecessary heat in the equipment, overloading of neutrals, overheating of transformers, nuisance tripping of circuit breakers, and overstressing of power factor correction capacitors [1], [2]. In addition, these current harmonics, together with grid inductance, lead to voltage harmonics. This results in low power quality of the grid, resonances, and finally, stability issues in the power system.

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. The harmonic mitigation techniques are classified as passive techniques [3]–[5], multipulse rectifier techniques [6], [7], and active harmonic cancellation techniques [8]–[11].

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 recent years, a reduced dc link capacitor used in a three-phase power converter named slim dc link converter is getting more attention as one of the harmonic mitigation techniques [12], [13]. 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 the 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. This paper presents and analyzes the harmonic performances of a power electronic system at a unit and a system level. A mathematical description of a harmonic cancellation mechanism at a system level has been analyzed based on phase angle values of current harmonics.

Harmonic performance of a large number of converters with a slim dc link capacitor connected to a Point of Common Coupling (PCC) has been reported in [14] and [15]. It has been shown that the power converter with a slim dc link capacitor gives the worst harmonic performance compared with the conventional power converter (with ac choke or dc choke) at a system level. However, in [14] and [15] the comparative analysis only includes the magnitude of current harmonics, but information about phase angle values of current harmonics has not been reported so far. There might be an assumption that power converters with a slim dc link capacitor give a better harmonic cancellation when they are connected together with other types of converter topologies. Therefore, 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.

A large number of single-phase non-linear loads may also be connected to a power network such as computers, televisions,

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washing machines, florescent lights, battery chargers, and so on. The influences of the short-circuit ratio, the dc link capacitor and the dc choke inductance on the amplitude, and phase angle of the current harmonics in single-phase converters have been investigated in [16] and [17]. All these investigations have been performed at a unit (product) level with limited information about the variation of phase angle values at a system level. Recently, a few studies have been reported to estimate the harmonic current phase angle [18], [19].

Various studies have already been shown that the phase angle of the fifth current harmonic of a three-phase power converter is almost in counter-phase with the fifth current harmonic of a single-phase converter [20]. However, in [20], a combination of three-phase and single-phase power converter has been analyzed at a unit level. In a real case, there is a possibility of phase angle variation at a system level when a large number of units are connected together. Therefore, this research gap has also been investigated in this paper by implementing a case study where a large number of three-phase converters are combined together with a number of single-phase converters at a PCC. Thus, 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.

II. 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).

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 grid is modeled as an ideal three-phase voltage source (V_s) of 440 V at 60 Hz with a defined grid inductor (L_g). The transformer is modeled as an ideal transformer, with no magnetic saturation and having a series inductor (L_t). Therefore, the system inductor of $L_s = L_g + L_t$ 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 (L_{dc}) and a large dc link capacitor (C_{dc});
2) a three-phase diode rectifier with an ac choke (L_{ac}) and a large dc link capacitor (C_{dc});
3) a three-phase diode rectifier with a slim dc link capacitor (C_{slim}).

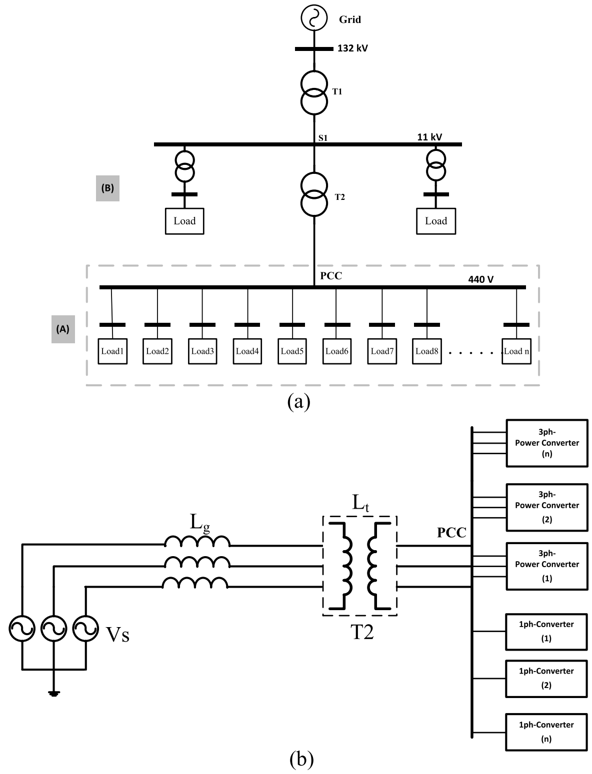


Fig. 1. (a) Line diagram of a distribution network. (b) Detailed line diagram of the low voltage distribution network.

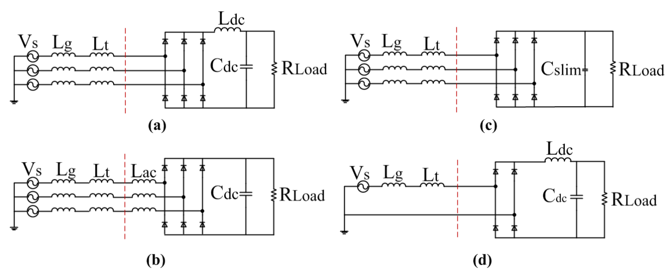


Fig. 2. Power converter topologies, three-phase diode rectifiers. (a) DC choke. (b) AC choke. (c) Slim dc link capacitor. (d) Single-phase diode rectifier with dc choke.

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 (L_{dc}) 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.

Two types of generators and transformers have been considered in this analysis to address a stiff grid with $L_s = 2\ \mu$H (where $L_g = 1\ \mu$H and $L_t = 1\ \mu$H) and a soft grid with $L_s = 130\ \mu$H (where $L_g = 100\ \mu$H and $L_t = 30\ \mu$H). These are typical values for a microgrid generator with 10%–15% base impedance and a transformer with 5%–15% base impedance which give short circuit ratios within the range of 120–230. 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 three-phase power converter operates at 1, 3, and 6 kW power levels. Similarly, the single-phase power converter also operates at 22, 108, and 419 W power levels.

III. 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.

Therefore, in Section III-A the harmonic performance of the three-phase power converter has been analyzed at a unit and a system level. A mathematical expression has been derived to understand the harmonic cancellation of parallel units at a system level.

In Section III-B, the harmonic performance of a single-phase power converter has been analyzed at a unit and a system level.

In Section III-C, a case study has been implemented to show the harmonic cancellation mechanism in a typical industrial network where a large number of three-phase and single-phase power converters are connected at the PCC.

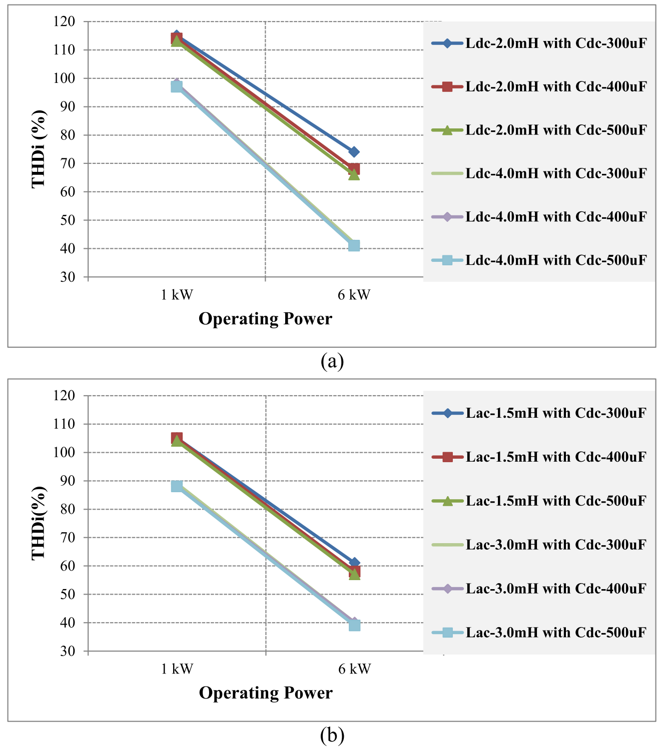


Fig. 3. THD_i (%) of three-phase power converter with (a) dc choke and (b) ac choke.

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.

In order to generalize the finding of this analysis, a sensitivity analysis has been performed at the first stage to analyze the effect of converter's parameters (like ac or dc chokes and dc link capacitor) on the harmonic performance of the three-phase power converter. 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.

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. Current harmonic distortion (THD_i) has been improved by increasing the value of ac or dc choke inductance. However, the proper value of choke's inductor has been calculated based on international regulation of harmonic commission, IEC 61000-3-2 and IEC 61000-3-12. Therefore, the following parameters have been selected for further analysis of power converters with the dc choke and the ac choke:

1) a power converter with a dc choke: $L_{dc} = 2.5$ mH (5% of base impedance) and $C_{dc} = 500$ μF (8 J/kVA);
2) a power converter with an ac choke: $L_{ac} = 1.5$ mH (3% of base impedance) and $C_{dc} = 500$ μF (8 J/kVA);
3) a 30 μF (0.5 J/kVA) dc link capacitor (C_{slim}) has been selected for these power converters, which is the most commonly used capacitor size in these power size converters.

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).

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). 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. The phase angle values of the fifth current harmonics are shown in Fig. 5(c).

According to Fig. 5(b), due to the low system inductor in stiff grid, the THD_v values are almost zero for all three topologies at those power levels. However, it has been shown that the harmonic performances of the power converters with a dc choke and an ac choke are very similar. THD_i, THD_v, and the phase angle values of these two topologies are almost the same at different power levels.

On the other hand, the power converter with the slim dc link capacitor has different phase angle values compared with the other topologies. Many reviewed studies have indicated

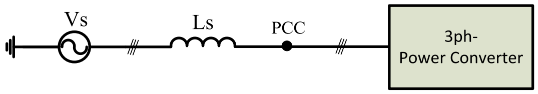


Fig. 4. Line diagram of a grid connected three-phase converter.

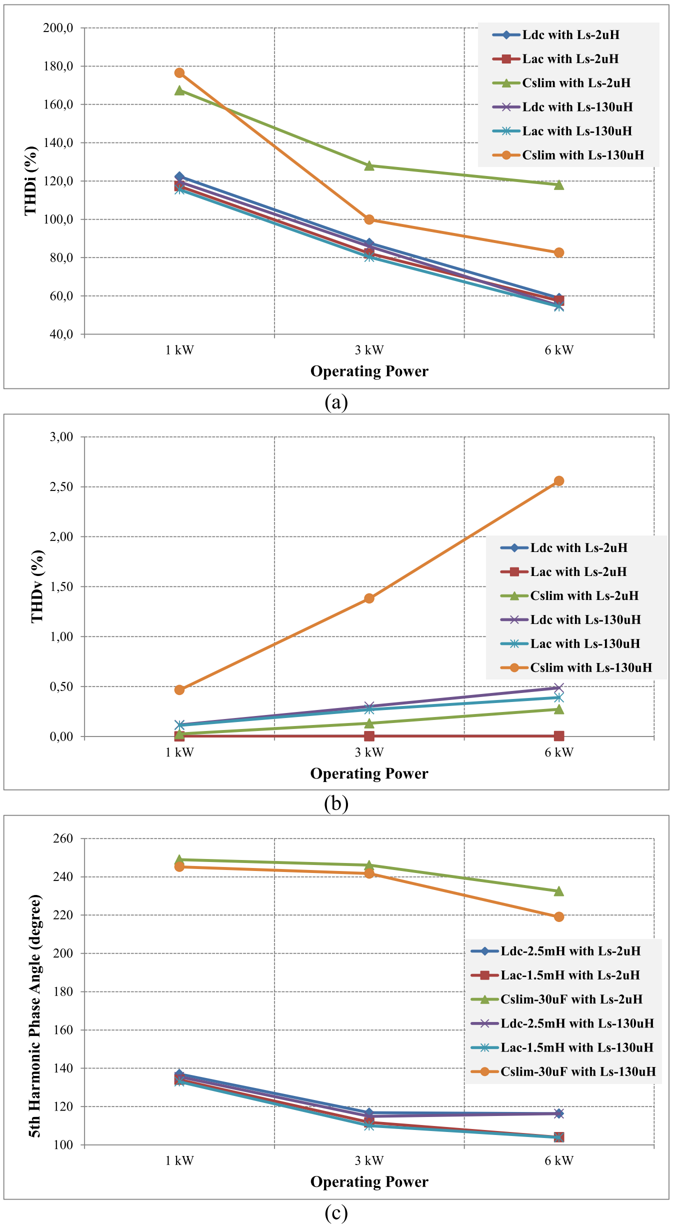


Fig. 5. Harmonic performance of all the three-phase power converter topologies at unit level with 2 and 130 μH system inductor. (a) THD$_i$ (%). (b) THD$_v$ (%). (c) Fifth harmonic current phase angle.

that power converters with a slim dc link capacitor generate low current harmonics at full power [12], [13]. However, the simulation results shown in Fig. 5(a) and (b) indicate that the current and the voltage distortions are higher than the other two topologies. It is expected that the power converters with the slim dc link capacitor generate low current harmonic emission at the fifth and the seventh orders, while the harmonic emission of higher orders are increased. As it was described in [15], the harmonic performance of the power converter with the slim dc link capacitor strongly depends on the system inductor and its power level due to the resonant frequency and the damping ratio of its resonant loop.

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: In order to analyze the harmonic performance of a multiparallel power converter at a system level, it is important to first understand the harmonic cancellation mechanism of parallel power converters at a PCC. Therefore, a mathematical expression has been derived to show the harmonic cancellation mechanism of the parallel converters. Then, a 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 (V_s) with a system inductor (L_s) as shown in Fig. 6. The current harmonics of n number of power converters are defined as $i_{h(1)}, i_{h(2)}, \ldots, i_{h(n)}$, where i is the converter current and h is the order of harmonics

$$\begin{aligned} i_{h(1)}(t) &= I_{h(1)} \sin(\omega_h t + \phi_{h(1)}) \\ i_{h(2)}(t) &= I_{h(2)} \sin(\omega_h t + \phi_{h(2)}) \\ &\ldots \\ i_{h(n)}(t) &= I_{h(n)} \sin(\omega_h t + \phi_{h(n)}) \end{aligned} \tag{1}$$

where $\omega_h = 2\pi h f$ and 'ϕ_h' is the phase angle of harmonics

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

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

$$i_h(t) = i_{h(1)}(t) + i_{h(2)}(t) \tag{3}$$

$$\begin{aligned} i_h(t) &= I_{h(1)} \sin(\omega_h t + \phi_{h(1)}) + I_{h(2)} \sin(\omega_h t + \phi_{h(2)}) \\ i_h(t) &= I_{h(1)} \sin(\omega_h t)\cos(\phi_{h(1)}) + I_{h(1)} \sin(\phi_{h(1)})\cos(\omega_h t) \\ &\quad + I_{h(2)} \sin(\omega_h t)\cos(\phi_{h(2)}) \\ &\quad + I_{h(2)} \sin(\phi_{h(2)})\cos(\omega_h t) \\ i_h(t) &= (I_{h(1)} \cos(\phi_{h(1)}) \\ &\quad + I_{h(2)} \cos(\phi_{h(2)})) \sin(\omega_h t) \\ &\quad + (I_{h(1)} \sin(\phi_{h(1)}) + I_{h(2)} \sin(\phi_{h(2)})) \cos(\omega_h t) \\ i_h(t) &= \sqrt{I_{h(1)}^2 + I_{h(2)}^2 + 2 I_{h(1)} I_{h(2)} \cos(\phi_{h(1)} - \phi_{h(2)})} \end{aligned} \tag{4}$$

$$\begin{aligned} &\text{if } \phi_{h(1)} = \phi_{h(2)} \\ &\text{then } i_h(t) = (I_{h(1)} + I_{h(2)}) \end{aligned} \tag{5}$$

$$\begin{aligned} &\text{if } \phi_{h(2)} = \phi_{h(1)} + 180^\circ \\ &\text{then } i_h = (I_{h(1)} - I_{h(2)}). \end{aligned} \tag{6}$$

This means any difference in the phase angles of the two current harmonics can reduce the total input current with

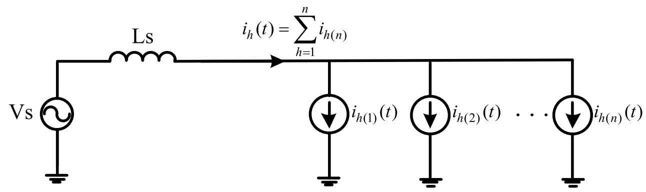


Fig. 6. Simple model of n number of power converters as current harmonic sources.

respect to $I_{h(1)}+I_{h(2)}$ (when the difference between the phase angles is zero or $\phi_{h(1)}=\phi_{h(2)}$).

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

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

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

To simplify the simulation model and reduce the execution time, it has been assumed that all power converters are connected to the PCC through short cables in which their inductance values can be neglected. Nineteen different cases (for each topology) have been considered based on different numbers of power converters at different operating power levels.

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 (THD$_i$), the line voltage distortion (THD$_v$) and the phase angle values of the current 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.

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). This issue can be explained by a resonant frequency of the system inductor and the 90 power converter units. The grid sees a large capacitor at the power converter side due to the fact that the 90 power converters with 30 μF dc link capacitors are connected in parallel. This can change the resonant frequency of the whole system close to 2 kHz, which has a significant impact on THD$_v$.

Fig. 8(c) shows that the phase angle values of the fifth current harmonics of each power converter topology connected to the grid. With soft grid, the phase angle values are

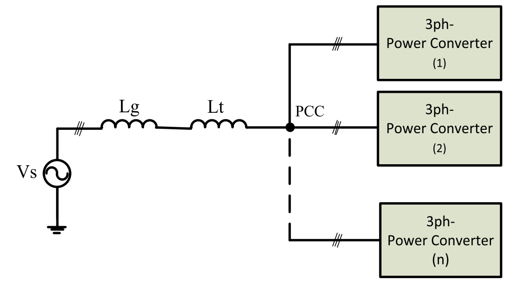


Fig. 7. Several three-phase power converter units are connected in parallel at the PCC.

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

almost the same in all three topologies with a very small variation. This is due to the system inductor effect on the 90 units. The total inductance that each power converter can see toward the grid is approximately 90 times of 130 μH, which is equivalent to 11.7 mH. Therefore, the phase angle values of the current harmonics of the 90 power converters with 2 and 130 μH system inductor are different. This means that the system inductor can be considered as a big ac choke for each power converter and its value depends on the number of units connected in parallel.

This fact can be verified by simulating a case study, where the system inductance is transferred to each power converter connected to the PCC. In Fig. 7, the system inductor (L_s) is transferred to the right-hand side of the PCC and directly connected to each power converter as shown in Fig. 9. The number of power converter units (n) is 90; therefore, a large ac choke inductance of ($90 \times L_s$) has been connected to each power converter.

In order to limit the number of simulations, only three cases (1, 7, and 19) of Table I for a dc choke power converter have been analyzed, and simulation results have been compared with the previous analysis shown in Fig. 8. As given in Table II, the impact of the system inductor (L_s) connected to the 90 power converters is similar to a large ac choke with an inductance of ($90 \times L_s$) connected to each power converter. The line current distortion and phase angles of the fifth current harmonic are almost the same for all three cases. 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

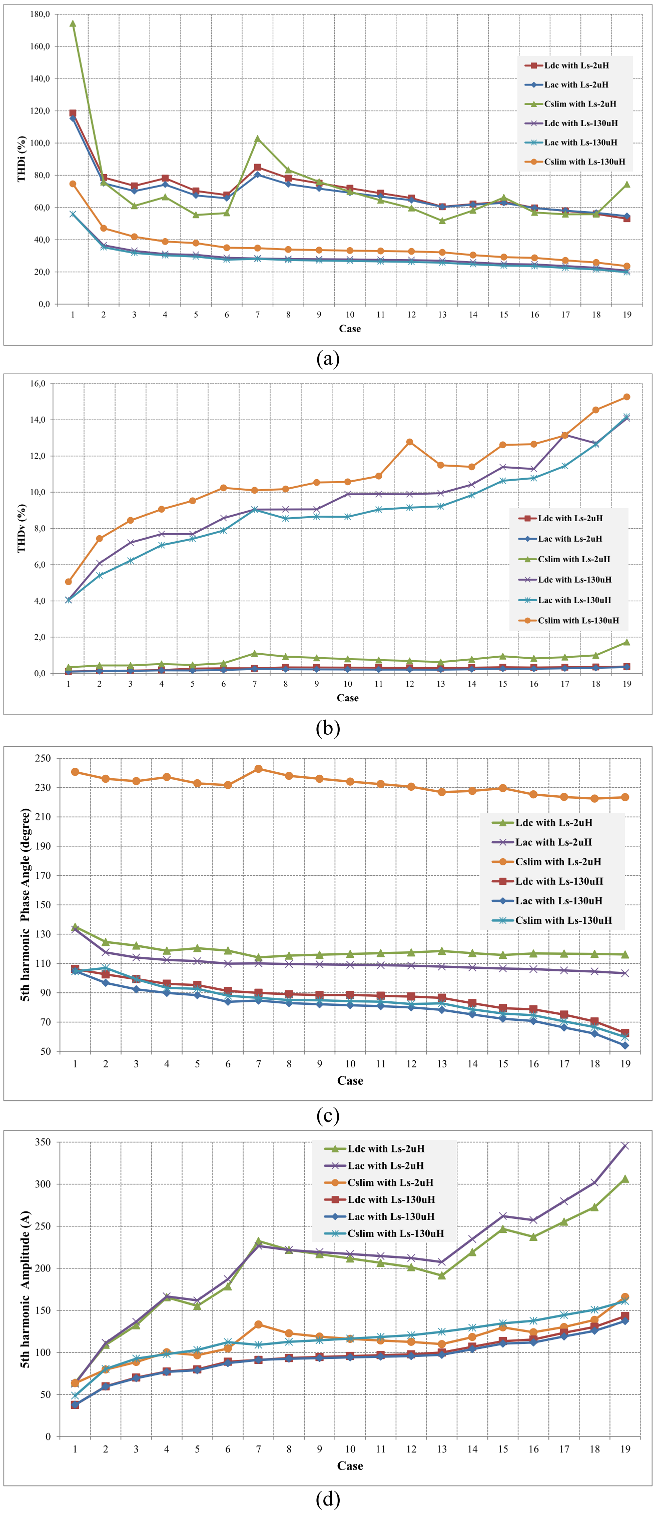


Fig. 8. Harmonic performance of all the three-phase power converter topologies at system level with 2 and 130 μH system inductor. (a) THD$_i$ (%). (b) THD$_v$ (%). (c) and (d) Fifth harmonic current phase angle and fifth harmonic current amplitude.

a phase angle variation (54°–106°) with respect to different power levels. Therefore, the harmonic cancellation due to different phase angle values gives the significant influence on the harmonic performance of a system.

It is also important to highlight that THD$_i$ could be a good indication to measure quality of a converter but it cannot

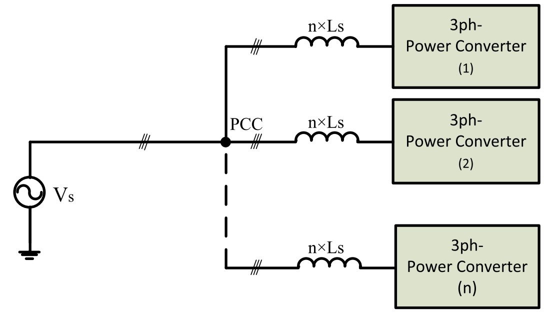


Fig. 9. Simulation model, where system inductor is connected to each converter.

TABLE II

HARMONIC PERFORMANCE OF THREE-PHASE POWER CONVERTERS WITH ONE INDUCTOR (L_s = 130 μH) AT THE GRID SIDE AND WITH 90 INDUCTORS (90 × 130 μH) AT EACH CONVERTER SIDE

Cases	Three-phase units with Ldc: 2.5mH and Ls: 130uH			Three-phase units with Lac: 11.7mH		
	THD$_i$ (%)	5th (deg)	7th (deg)	THD$_i$ (%)	5th (deg)	7th (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

be used to measure THD$_v$. This can be seen in Fig. 8(a), where the power converters with the slim dc link capacitor connected to stiff grid give a better THD$_i$ in most of the cases but at the same time give the worst THD$_v$ compared with other topologies shown in Fig. 8(b). However, with the 130 μH system inductor (soft grid), the power converters with the slim dc link capacitor have the worst THD$_i$, and THD$_v$ performances at the system level compared with other power converter topologies. It is important to highlight that the performance of slim dc link power converter is very sensitive to the system inductor, the load operating power, and the number of units in parallel due to resonance effects.

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) Fig. 8(d) shows that the amplitude of fifth harmonic currents of the converters with the ac and the dc chokes are higher than the converters with the slim dc link while their THD_v values are much lower than the converter with the slim dc link. 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. This analysis shows that the effect of the high-order current harmonics at the system level is on THD_v and the power converters with the slim dc link can affect it significantly.

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 (such as dc choke and dc link capacitor) 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. 10.

The simulation results show that the variation in the dc link capacitor does not give any significant change in the current harmonics. On the other hand, the variation in the dc choke inductance value gives the significant influence on the current harmonics performance. The current harmonic distortion (THD_i) has been improved by increasing the dc choke inductance value. However, the proper inductance value of the choke has been calculated based on international regulation of harmonic commission, IEC 61000-3-2. Therefore, the following parameters have been selected for further analysis of a single-phase converter with: $L_{dc} = 5$ mH and $C_{dc} = 200\ \mu$F.

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. 11.

Harmonic analysis of the single-phase converter with the different grid types have been performed at a unit level (product level). In this analysis, different simulations have been carried out at three different operating power levels.

In the single-phase converter analysis, the main interest is to analyze the variation of phase angles at different operating power levels. The fifth current harmonic phase angles and amplitudes have been captured at three different operating power levels as shown in Fig. 12.

For the single unit analysis, the variation in phase angle with the stiff grid is from (302°–324°) and for the soft grid is from (301°–324°), which is almost the same.

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

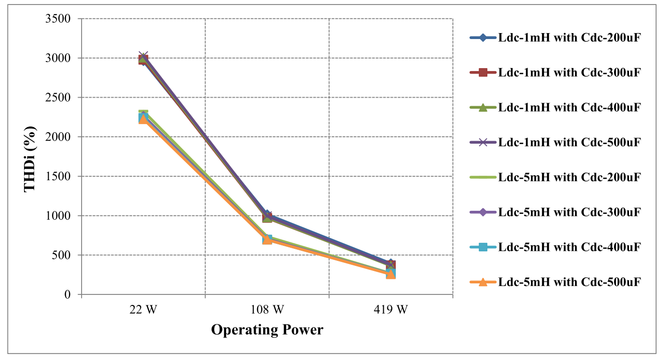


Fig. 10. THD_i (%) of a single-phase power converter with the dc choke.

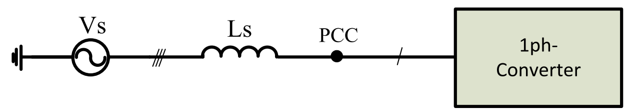


Fig. 11. Line diagram of a grid connected single-phase converter.

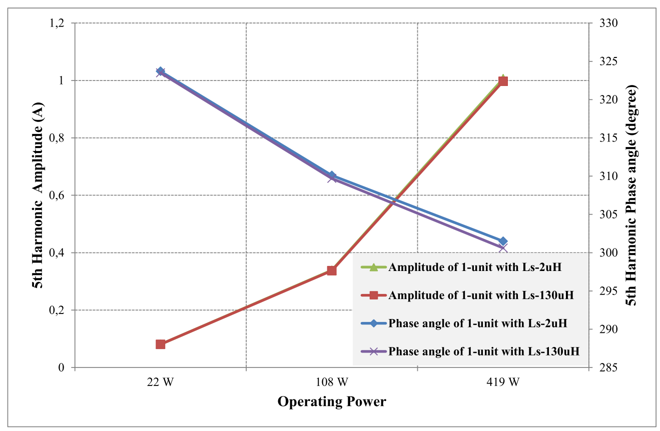


Fig. 12. Fifth harmonic amplitudes and phase angles for single-phase power converter at unit level with 2 and 130 μH system inductor.

analyze the variation of the phase angles at the system level where a large number of single-phase converters are connected at the PCC as shown in Fig. 13.

For this analysis, a simulation model of 90 single-phase converter units operating at three different power levels have been implemented in SABER and MATLAB/Simulink. The fifth current harmonic phase angle values have been captured at the PCC, as shown in Fig. 14.

From the multiunit analysis, the variation in the fifth current harmonic phase angle with stiff grid is from (300°–322°) and for soft grid is from (250°–306°). This is very interesting to note that for single-phase converter system, the fifth current harmonic phase angles variation are close to the single unit system. On the other hand, the phase angle variation for three-phase system is from (54°–106°), which is counterphase to the single-phase converter (as a single unit or as multiunit system). This means that at the system level, there is a possibility of current harmonic cancellation of parallel three-phase and single-phase converter units.

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

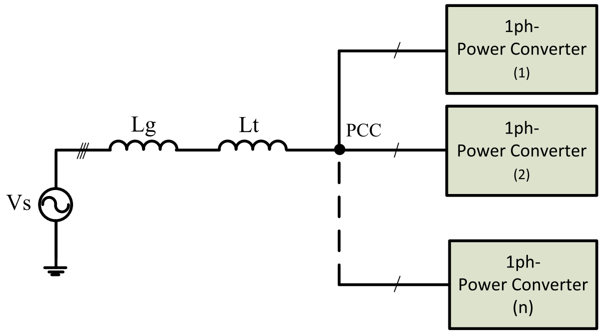


Fig. 13. Several single-phase power converter units are connected in parallel at the PCC.

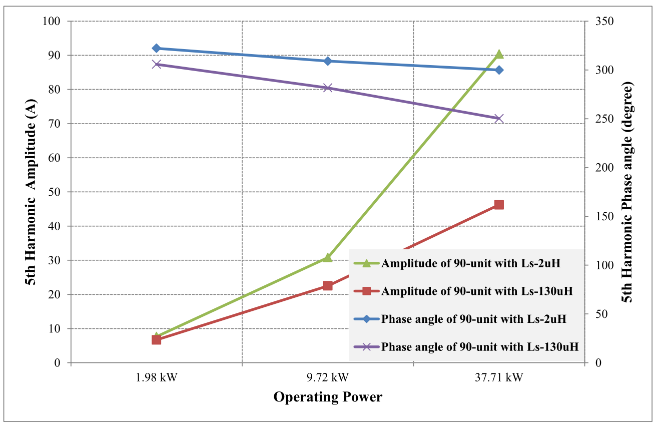


Fig. 14. Fifth harmonic amplitudes and phase angles for single-phase power converter at system level with 2 and 130 μH system inductor.

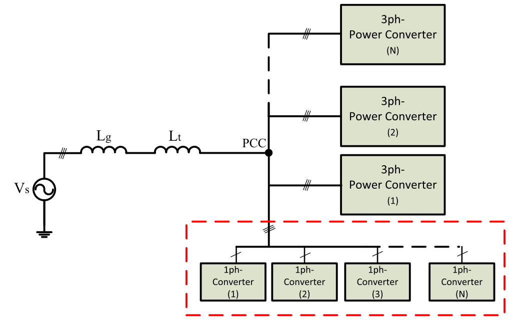
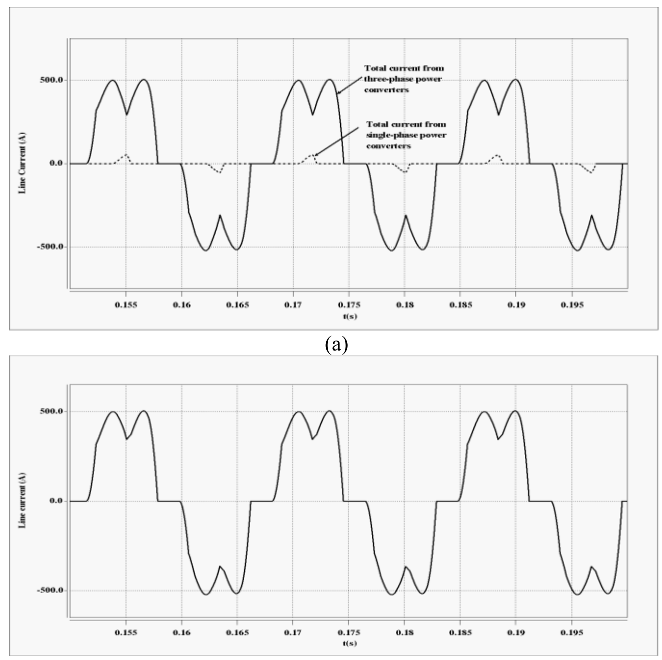


Fig. 15. System with several single-phase and three-phase power converters connected at the PCC.



(a)

(b)

Fig. 16. 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.

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. Therefore, it is important to analyze the harmonic performance of the network with a large number of three-phase and single-phase nonlinear loads connected to a PCC.

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. The simulation model for this case study is shown in Fig. 15, where the supply voltage (V_s) is assumed to a three-phase balanced sinusoidal waveform.

A soft grid condition has been considered for this system. In this analysis a total number of 90 units have been considered and out of them 45 units are single-phase converters, each of them operates at 419 W and the other 45 units are three-phase power converters (with dc choke configuration) each of them operates at 6 kW. All the single-phase units are connected to the three phase system in such a way that 15 single-phase units are connected to each phase of the system to avoid any unbalance situation at the PCC. The system configuration and converter parameters are the same as those used in the pervious analysis.

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. The fifth current harmonic's amplitude and phase angle are captured at the PCC from each simulation model.

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

$$I_{5(3\mathrm{ph})}(t) = 97.93\ \mathrm{A}\angle 94^\circ$$
$$I_{5(1\mathrm{ph})}(t) = 19.03\ \mathrm{A}\angle 282^\circ.$$

Using (7), the total fifth harmonic amplitude at the PCC can be calculated as

$$I_{5(3\text{ph}+1\text{ph})}(t) = \sqrt{I_{5(3\text{ph})}^2 + I_{5(1\text{ph})}^2 + 2I_{5(3\text{ph})}I_{5(1\text{ph})}\cos(\phi_{5(3\text{ph})} - \phi_{5(1\text{ph})})}$$

$$I_{5(3\text{ph}+1\text{ph})}(t) = \sqrt{97.93^2+19.03^2+2 \times 97.93 \times 19.03 \times \cos(94^\circ - 282^\circ)}$$

$$I_{5(3\text{ph}+1\text{ph})}(t) = 79.13 \text{ A}. \tag{8}$$

In order to verify the above mathematical calculation, the value of the fifth current harmonic at the PCC has been captured from the third simulation model (79.20 A). This value is almost the same as the calculated value in (8). Therefore, it is confirmed that the mathematical expression given in (7) can be used to understand the harmonics cancellation mechanism within the parallel connected converter units at the PCC.

The above proposed mathematical expression can be used to estimate the harmonics cancellation in a large system without implementing any extra simulation or measurement. For example, in the above analysis, 45 units of three-phase power converters (dc choke configuration) operate at 6 kW. The total operating power of 45 units is 270 kW. 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.

$$I_{5(3\text{ph})}(t) = 93.41 \text{ A}\angle 89^\circ.$$

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

$$I_{5(1\text{ph})}(t) = 18 \text{ A}\angle 290^\circ.$$

The total fifth harmonics current at the PCC can be calculated using (7) as below

$$I_{5(3\text{ph}+1\text{ph})}(t) = \sqrt{I_{5(3\text{ph})}^2 + I_{5(3\text{ph})}^2 + 2I_{5(3\text{ph})}I_{5(1\text{ph})}\cos(\phi_{5(3\text{ph})} - \phi_{5(1\text{ph})})}$$

$$I_{5(3\text{ph}+1\text{ph})}(t) = 76.87 \text{ A}. \tag{9}$$

The estimated value of the fifth current harmonics in (9) gives ~3% error compare with the simulated value of 79.13 A given in (8).

In order to limit the number of calculation, only fifth harmonic analysis has been consider in this case study, however, similar results are expected for other harmonics order.

IV. Conclusion

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. This study has focused on these passive harmonic mitigation techniques to analyze the harmonic performance of a single unit as well as multiunit converters connected to a soft and a stiff grid. 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.

It has been found that the harmonic performance of a system depends on many factors such as the grid inductor, the transformer parameters, the load profile, the power converter topology, and the number of converters connected together at a PCC.

Finally, a case study has been performed on a typical industrial system network to understand the harmonic cancellation mechanism at the PCC where a large number of three-phase and single-phase converter units are connected together. The results show a significant improvement in harmonic performance can be achieved if there is a big difference in harmonics current phase angle within multiparallel power converter system.

One of the most important power quality issues is to control the voltage and current distortion in a grid. There are a number of passive and active solutions at a system level to mitigate and control harmonic emission and control THD_v below 5%. 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.

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