



Article Impact of Grid-Connected Inverter Parameters on the Supraharmonic Emissions in Distributed Power Generation Systems

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Abstract: In this paper, a mathematical analysis is presented to show the effect of grid-connected inverter (GCI) parameters on its emissions in the supraharmonic range. This analysis is extended to explain the effect of asymmetry on the emissions of parallel-connected GCIs on distributed power generation systems. The switching harmonics of a GCI appear as bands around the switching frequency and its multiples. A MATLAB/Simulink model is built to perform two studies. In the first study, we use one GCI to examine the effect of the parameters on the emissions, while in the second study, we examine the effect of the asymmetry of two parallel-connected GCIs on the total emission toward the grid. An actual setup is built to verify the results of the mathematical analysis and the simulation study. It is found that the SHs of single-phase GCI amplitude are strongly dependent on the DC-link voltage and the coupling inductor, while the phases of the sideband harmonics only change with changing the injected power. The variation of the injected power does not have any tangible effect on the carrier harmonics.

Keywords: supraharmonics; switching harmonics; grid-connected inverters; distributed power generation systems

1. Introduction

Distributed power generation systems (DPGSs) are becoming gradually more crucial to integrate renewable energy sources in the grid [1,2]. In these systems, numerous grid-connected inverters (GCIs) are connected in parallel at the point of common coupling (PCC). These GCIs work as switching harmonics sources which inject harmonics lying between 2 and 150 kHz, which was recently named as the supraharmonic (SH) range [3,4].

Research efforts have been intensified to identify the problems associated with supraharmonics and to convince the standardization committees to include the SH within the power quality standards. It is reported that the presence of supraharmonics leads to equipment malfunctioning, unintentional switching, audible noise, electrical thermal stress, and reduction in lifetime [5,6]. In [6,7], it is reported that the electronic control unit of LED lamps can interfere with the SHs, causing operation failure. The study in [7] comes to a conclusion that both supraharmonics and modulation of the test profiles, described in IEC 61000-4-19 [8], can reveal light flicker. Multiple studies are conducted to study the interferences between smart meters, touch dimmer lamps and inverters [8,9]. Interferences in AC–DC LED drivers exposed to voltage disturbances in the considered frequency range were presented in [10]. It is concluded from [10] that there are three phenomena that affect the light intensity: earlier conduction/later blocking caused by SH voltage, intermittent conduction depending on the SH impedance of the LED driver, and the reverse-recovery current of the diodes at higher frequency. Further studies show that SHs may interfere



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). with the grid-connected converters, resulting in injecting additional interharmonics below 2 kHz into the grid [11].

The single-phase GCI is considered one of multiple SH emission sources [12]. In [13], the SH emissions of ten low power photovoltaic (PV) GCIs for single-phase and three phase applications are studied experimentally. The study concludes that the-maximum power point tracker as well as the injected power affect the SH emissions. The SH propagation in a system, consisting of a GCI in parallel with LED lamps, is investigated in [14]; the authors found that the lengths of the cables that connect GCI and LED lamps to the PCC as well as the cable that connects the PCC to the grid affect the emissions of each piece of equipment as well as the interferences between both switching devices. A comparative study between the simulation and experimental results of the GCI emissions in the SH range is evaluated in [15]. Selecting a suitable modelling approach, building experimental setups and achieving a compromise between the simplicity and the accuracy of the GCI for SH emissions is discussed in [16].

One of the utmost significant aspects that has attracted the attention of the scientific society to study SHs is that SHs act differently from the harmonics and interharmonics below 2 kHz. The first difference is that while the harmonics below 2 kHz are linked to the grid frequency, the SHs are associated with both the switching frequency and the grid frequency. The second difference is the propagation behavior. The (inter)harmonics below 2 kHz tend to propagate through the grid, while the SHs head for propagating among the neighboring devices as well as the grid. The intensity of the currents is based on the ratio between the input impedance of neighboring devices and the grid impedances. The study performed in [17] is carried out to investigate the effect of the cable impedances of a PV GCI in parallel with LED lamps on the SH propagations among the grid and the components of the system. Moreover, the study performed in [18] gives an analysis of the Bergeron model of transmissions lines in the SH range in order to study the SH propagation and penetration. It is found in [18] that the Bergeron model of transmission lines cannot be used in its current form to study the SH propagation. This is because the transmission line resistances are modeled as lumped in the model instead of being distributed. As a result, the model cannot calculate the impedance of the line accurately around the even-ordered resonances of the transmission line impedance.

As SHs propagate among grid-connected devices as well toward the upstream grid, SH emissions are divided into two categories, i.e., the primary and secondary emissions. The primary emissions of any switching converter are defined as the emissions in the SH range depending on the switching behavior of the converter itself. The secondary emissions are defined as the SH emissions appearing at the converter terminals generated by neighboring converters based on the impedance relation between the converter and the grid [19]. Moreover, the background distortion in the SH range at the PCC may cause additional emissions in that range of the AC–DC converters connected to the same PCC [20].

For the purpose of mitigating the switching harmonics, two solutions are provided in the literature. The first solution is associated with the design of the passive filter that connect the GCI to the grid [21]. This solution is limited to eliminate a specific number of switching bands by designing the passive filter with a specific number of series resonances provided by its impedance. This solution has many drawbacks. When the number of series resonances increase, the complexity of the filter increases, the transient response of the GCI deteriorates and the control parameter selection becomes more challenging. In addition to that, the associated parallel resonances of the filter threaten the system's stability. Moreover, the filter design depends on the grid impedance, which decreases the design robustness.

The second solution is restricted to parallel-connected GCIs in DPGSs. The mechanism of this solution depends on generating one central carrier signal, and then the carrier signal is distributed among the parallel-connected GCIs with equal phase shifts [22]. This solution is effective only when the parallel-connected GCIs are symmetric. For the asymmetry GCIs, many studies calculate the optimum phase shift to reduce the total switching harmonics injected to the grid [23]. However, the control algorithm becomes much more complicated

due to the need to add optimal carrier phase spacing techniques that minimize a particular cost function to the control algorithm. So, this paper is presented in order to determine exactly the parameters that affect the emissions in order to have a deep understanding of the impact of these parameters. This can lead in the future to an efficient solution to lower the emissions of parallel-connected GCIs.

This paper provides an insightful exploration into the parameters that affect the highfrequency emissions in the SH range of single-phase GCIs. The main parameters found are the DC-link voltage, the coupling filter and the injected power. Since the aforementioned parameters affect the SH emissions of the GCIs, the carrier-phase shift asymmetry in parallel GCIs in DPGSs reduces the filtering behavior of the system.

The main contributions of this paper follow:

- Giving mathematical expressions that present the parameters that affect the SH emissions of GCIs;
- Studying the effect of some of the parameters on the emissions of GCIs mathematically by simulation and by experimental studies;
- Studying the effect of parameters' symmetry and asymmetry of parallel-connected GCIs on the total emissions to the grid;
- Giving a corner stone for studying the propagations and penetration of SH emissions of GCIs in single-phase installations in addition to filtering them out and preventing them from flowing into the grid.

It is found from the study that the carrier harmonics, which occur exactly at the switching frequency and its integer multiples, are independent of the variations on the injected power from the GCI into the grid. The variation of the power affects only the phase of the sideband harmonics, while the amplitude of all switching harmonics in the SH range is independent of the active power variations. The amplitude of the switching harmonics is affected by the variations of the DC-link voltage and by the coupling filter inductance. The amplitude of these harmonics has a non-linear relationship with the DC-link voltage, while the relationship between these harmonics and the coupling filter inductance is an inverse one. The main findings in the mathematical analysis are supported by a MATLAB/Simulink simulation and validated through an experimental study on a laboratory setup.

The remainder of the paper is organized as follows. The emissions of a single-phase GCI are presented in Section 2. Sections 3 and 4 give an analysis of the parameter effect on the SH emissions of the GCI and the effect of that on parallel-connected GCIs, respectively. Simulation and experimental studies are provided in Sections 5 and 6, respectively.

2. SH Emissions of Single-Phase GCI

Figure 1 shows the structure of a single-phase GCI. It consists of a DC-link, H-bridge single-phase inverter and a coupling inductor as a filter. For any stand-alone single-phase inverter driven by the sinusoidal-triangle Pulse Width Modulation (PWM) scheme illustrated in Figure 2, the output voltage of the inverter can be fully described by the following equation [24]:

$$v_{i} = V_{dc}Mcos(\omega_{g}t + \theta_{g}) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\frac{1}{m} \cdot J_{o}\left(\frac{m\pi M}{2}\right)sin(m\frac{\pi}{2})cos(m[\omega_{c}t + \theta_{c}]) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\n\neq 0}}^{\infty}\frac{1}{m} \cdot J_{n}\left(\frac{m\pi M}{2}\right)sin((m+n)\frac{\pi}{2})cos(m[\omega_{c}t + \theta_{c}] + n[\omega_{g}t + \theta_{g}])$$

$$(1)$$



Figure 1. Single-phase GCI structure. Here, V_{dc} is the DC-link voltage; S_1 , S_2 , S_3 and S_4 are the switches of the inverter; i_{GCI} is the instantaneous value of the GCI current; L_f is the coupling filter inductance, v_i is the instantaneous value of the inverter output voltage between points A and B; r_g and L_g are the grid resistance and inductance, respectively; and v_g is the instantaneous value of the grid voltage.



Figure 2. Sine-triangle modulation for driving the semiconductor switches of the single-phase GCI. Here, *M* is the modulation index; ω_g is the reference signal angular frequency; θ_g is the control signal phase; ω_c is the carrier signal angular frequency.

Here, v_i is the inverter output voltage; V_{dc} is the DC-link voltage; $m \in \mathbb{N}_0$ is the order of harmonics generated from the carrier signal; $n \in \mathbb{N}_0$ is the order of harmonics generated by the reference signal within each carrier sideband harmonic; J is the Bessel function of the first kind; θ_g is the phase shift of the reference signal, which also is the phase shift of the fundamental component of the output voltage; θ_c is the carrier phase shift; M is the modulation index; ω_c is the angular frequency of the carrier signal, which represents the switching angular frequency; and ω_g is the angular frequency of the reference signal, which represents the power frequency.

Consider the grid voltage as ideal sinusoidal:

$$v_g = V_{amp} \cdot \cos(\omega_g t) \tag{2}$$

Here, v_g is the instantaneous value of the grid voltage and V_{amp} is the amplitude. Then, Equation (1) becomes:

$$v_{i} = V_{dc}Mcos(\omega_{g}t + \delta) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\frac{1}{m} \cdot J_{o}\left(\frac{m\pi M}{2}\right)sin(m\frac{\pi}{2})cos(m[\omega_{c}t + \theta_{c}]) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\n\neq 0}}^{\infty}\frac{1}{m} \cdot J_{n}\left(\frac{m\pi M}{2}\right)sin((m+n)\frac{\pi}{2})cos(m[\omega_{c}t + \theta_{c}] + n[\omega_{g}t + \delta])$$
(3)

Here, δ is the load angle. Appendix A provides the definition of the load angle in power systems. For the purpose of simplifying the analysis, since $\omega_c \gg \omega_g$, consider $m\omega_c + n\omega_g \approx m\omega_c$. Also, let $\theta_c = 0$. So, Equation (2) is modified as:

$$v_{i} = V_{dc}Mcos(\omega_{g}t + \delta) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\frac{1}{m} \cdot J_{o}\left(\frac{m\pi M}{2}\right)sin(m\frac{\pi}{2})cos(m[\omega_{c}t]) + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\n\neq 0}}^{\infty}\frac{1}{m} \cdot J_{n}\left(\frac{m\pi M}{2}\right)sin((m+n)\frac{\pi}{2})cos(m\omega_{c}t + n\delta)$$

$$(4)$$

Due to the load angle δ in the fundamental component of Equation (4), the inverter injects active current to the grid. Unfortunately, the harmonic components in the inverter voltage inject high-frequency (HF) current harmonics, which are power dependent. To reduce the harmonic content injected into the grid, a passive filter is connected between the inverter and the grid. Applying the superposition theorem determines the current injected to the grid by the inverter voltage:

$$i_g = i_{gf} + i_{gs} + i_{gsb} \tag{5}$$

Here, i_g is the current injected to the grid; i_{gf} is the fundamental current of the GCI current; i_{gs} is the carrier switching harmonics in the SH range of the GCI current, and i_{gsb} is the sideband current switching harmonics in the SH range of the GCI current. The three current equations are as follows:

$$i_{gf} = \frac{V_{dc}Mcos(\omega_g t + \delta - \theta_0) - V_{amp}\cos(\omega_g t - \theta_0)}{\sqrt{\left(r^2 + \left(\omega_g L\right)^2}\right)}$$
(6)

$$i_{gs} = \frac{4V_{dc}}{\pi} \sum_{m=1}^{\infty} \left[\frac{1}{\sqrt{\left(r^2 + \left(m\omega_c L\right)^2} \cdot \frac{1}{m} \cdot J_o\left(\frac{m\pi M}{2}\right) \sin\left(m\frac{\pi}{2}\right) \cos\left(m\omega_c t - \theta_m\right)} \right]$$
(7)

$$i_{gsb} = \frac{4V_{dc}}{\pi} \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \sum_{m=-\infty}^{\infty} \left[\frac{1}{\sqrt{\left(r^2 + \left(m\omega_c L\right)^2} \frac{1}{m} \cdot J_n\left(\frac{m\pi M}{2}\right) \sin\left(\left(m+n\right)\frac{\pi}{2}\right) \cos\left(m\omega_c t + n\delta - \theta_m\right)} \right]$$
(8)

where $\theta_0 = \tan^{-1}\left(\frac{\omega_g L}{r}\right)$, $\theta_m = \tan^{-1}\left(\frac{m\omega_c L}{r}\right)$, and $L = L_f + L_g$, L_f , L_g are the filter and grid inductances, respectively, and r is the grid resistance. Neglecting the value of r with respect to $m\omega_c L$ for the high-frequency components of the current, Equations (7) and (8) yield:

$$i_{gs} = \frac{4V_{dc}}{\pi} \sum_{m=1}^{\infty} \left[\frac{1}{m^2 \omega_c L} \cdot J_o\left(\frac{m\pi M}{2}\right) \sin\left(m\frac{\pi}{2}\right) \cos\left(m\omega_c t - \theta_m\right) \right]$$
(9)

$$i_{gsb} = \frac{4V_{dc}}{\pi} \sum_{m=1}^{\infty} \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \left[\frac{1}{m^2 \omega_c L} \cdot J_n\left(\frac{m\pi M}{2}\right) \sin\left((m+n)\frac{\pi}{2}\right) \cos\left(m\omega_c t + n\delta - \frac{\pi}{2}\right) \right]$$
(10)

For the currents in Equations (9) and (10), the term $m^2 \omega_c L$ increases linearly with the frequency, which in turn highlights the importance of the coupling filter in mitigating the flow of the SHs from GCIs into the grid. Figure 3 gives a graphical representation of the GCI current introduced by Equations (5), (6), (9) and (10).



Figure 3. GCI current spectrum based on sine-triangle modulation.

3. GCI Parameter Effect on the High Frequency Emissions

In case no reactive power is injected into the grid and only active power is generated from the GCI, from power flow rules and from Equation (6), the following is deduced:

$$V_{dc}M = V_{amp} \tag{11}$$

Since *M* is less than one for under modulation, V_{dc} is greater than V_{amp} . As far as V_{dc} is kept constant, *M* is constant. Inversely, *M* changes only when V_{dc} changes under the condition of no reactive power generation.

From Equations (9) and (10), it is clear that the high-frequency harmonic components of the current, located in the SH range, depend on the DC-link voltage, coupling filter inductance and the active power injected represented by the load angle δ in the equations. The carrier harmonics and the sideband harmonics amplitudes in (9) and (10) are affected by the DC-link voltage. Since *M* is also a function of the DC-link voltage as stated in (11), the relationship between the harmonics amplitude and the DC-link voltage is a non-linear one. This means the amplitude of the harmonics may increase or decrease when the DC-link voltage increases based on the combined effect of the DC-link voltage and the modulation index. But from Equations (9) and (10), there is no effect of the DC-link voltage on the phases of these harmonics.

The effect of the coupling inductance on the amplitude is clearly obvious from Equations (9) and (10). The amplitude of the harmonics and the inductance value are with an inverse relation. The effect of the inductance on the phases of the harmonics is neglected as the filter resistance is neglected with respect to the filter inductance in the SH range.

The active power has no effect on the amplitudes of the harmonics as well as the phases of the carrier harmonics. The only effect of the active power is seen on the phases of the sideband harmonics, as it adds a positive phase shift to the right sideband harmonics (i.e., with positive order n) and a negative phase shift to the left sideband harmonics (i.e., with negative order n).

4. Carrier Phase-Shift Concept to Reduce the Total SH Emissions of Parallel GCIs in DPGSs

In DPGSs, multiple GCIs are connected in parallel to the same PCC to integrate renewable energy sources in the grid (Figure 4). The aggregated SH emissions injected to the grid by means of the parallel GCIs represent one of the main problems of such systems.



Figure 4. Parallel GCIs in a DPGS.

The phases of the carrier and sideband harmonics depend mainly on the carrier phase. Then, the switching harmonics phases of the parallel-connected GCIs can be controlled to cancel out each other at the PCC. As a result, the SHs generated from the GCIs flow among the GCIs instead of flowing to the grid. Let N be the number of GCIs connected in parallel to the same PCC, as shown in Figure 4. In order to cancel out N-1 consecutive switching bands and their multiples, the same centralized carrier generator should provide all the GCI controllers with the same carrier but with a phase shift of $\frac{360^{\circ}}{N}$ distributed among them. The concept is effective for the scenario of having symmetric parallel-connected GCIs. In other words, they must have the same value of the DC-link voltage, coupling inductor inductance and injected power. If any of the aforementioned parameters are not the same, the mitigation of the harmonics is not optimal, as discussed in Section 2.

5. Simulation Studies

5.1. GCI Model

The study of the parameters' effects on the emissions of GCIs in the SH range and their effects on the total emissions of parallel-connected GCIs are studied through two simulations. The simulation studies are carried out through MATLAB/Simulink. The first simulation contains the system shown by Figure 1; the simulation parameters are as listed in Table 1. The controller of the GCI is built using a proportional–resonance (PR) controller to control the current of the GCI. The second simulation contains two parallel GCIs connected to the same PCC. The second simulation is used to study the effect of the parameters symmetry and asymmetry on the total emissions to the grid. The base parameters for both GCIs are listed in Table 1.

Table 1. Simulation parameters.

Parameter	Value
DC-link voltage	600 V
Switching frequency	16 kHz
Coupling filter inductance	1 Ω, 10 mH
Injected active power	1.6263 kW
Grid impedance	$r_g = 0.01 \Omega$, $L_g = 0.1 mH$
Grid voltage and frequency	230 V _{rms} , 50 Hz

5.2. Simulation with One GCI

The simulated current of the GCI in both time and frequency domains under the base parameters is demonstrated in Figure 5. The emissions appear as bands around the switching frequency and its multiples. The current in the time domain is rising and falling linearly with time during the ON and OFF periods, respectively. This in turn confirms the assumption made in the mathematical analysis by neglecting the effect of the inductor and the grid resistances with respect to the coupling filter reactance in the high-frequency range. The value of the resistor is negligible with respect to the inductive reactance in the SH range. The FFT analysis of the GCI current shows that the GCI current contains multiple HF emissions in the SH range. These emissions are divided into the carrier harmonics, which are located at exactly the switching frequency and its odd integer multiple. The remaining HF emissions are located at frequencies affected by both the switching frequency and the grid frequency. These emissions are deduced mathematically by Equations (5), (9) and (10). For purpose of comparison, the harmonics at the 16 kHz switching frequency, 15.9 kHz and 16.1 kHz as sideband harmonics, are taken as examples to monitor while the parameters change.



Figure 5. GCI current (a) in the time domain, (b) in the frequency domain.

The impact of the DC-link voltage on the harmonics amplitudes is illustrated in Figure 6. It is clear that the sideband harmonics decrease and the carrier harmonics increase as the DC-link voltage increases. This can be explained by the effect of the modulation index



on the Bessel function of the first kind found in the equations of the sideband harmonics and carrier harmonics.

Figure 6. Effect of the DC-link voltage on the amplitude of the chosen harmonic examples.

Figure 7 illustrates the effect of the inductance on the chosen harmonics amplitudes. It is obvious from the figure that as the inductance increases, the harmonic amplitudes decrease. The relationship between the inductance and the harmonic amplitudes is an inverse relationship. This is exactly what is concluded by Equations (9) and (10).



Figure 7. Effect of the coupling filter inductance on the amplitude of the harmonics.

The effect of the active power injected into the grid on both the amplitude and the phase of the chosen harmonics is clarified in Figures 8 and 9, respectively. The active power does not have any effect on the amplitudes of the switching harmonics and on the phase of the carrier harmonics. However, the change in the active power affects the phase of the sideband harmonics by adding a positive phase shift for the sideband harmonics with the positive order n and a negative phase shift to the ones with the negative order n.



Figure 8. Effect of the active power on the amplitude of the chosen harmonic examples.





The following can be concluded from the simulation study.

- The amplitude of the SH emissions of single-phase GCIs depends on the DC-link voltage and the coupling filter inductance.
- The relationship between the DC-link voltage and SH emissions amplitudes of GCIs is non-linear.
- The amplitudes of the SH emissions of GCIs are in an inverse relationship with the coupling filter inductance.
- The amplitude of the SH emissions of single-phase GCIs are independent of the active power variation.
- The phase of the carrier harmonics is independent of the active power variations
- The active power variation affects only the phase of the sideband harmonics.

5.3. Simulation with Two Parallel GCIs

Two parallel GCIs are now connected to the grid via the same PCC, i.e., N = 2. The carrier is generated centrally and distributed among the two GCIs with a phase shift of 180^0 between them. Each GCI current and the total current injected into the grid is shown in Figures 10 and 11. In Figure 10, the GCIs are under symmetrical condition (1st scenario). This means the DC-link voltages are equal. It is clear that the first switching harmonics band and its odd multiples have been totally cancelled. Only the switching harmonics band around the even multiples of the switching frequency appear in the total grid current. Although the switching frequencies are present in each inverter, the switching frequency and sidebands that are present in the grid are at double switching frequency.

For the asymmetrical scenario (2nd scenario), V_{dc2} is changed from 600 to 500 V. The result of this scenario is illustrated in Figure 11. It is clear that the asymmetry in the DC-link voltage leads to an SH emissions asymmetry between the GCIs. This in turn increases the emission to the grid of Scenario 2 when it is compared with Scenario 1.

To study the effect of asymmetry between the parallel-connected GCIs on the total emissions, the weighted total harmonic distortion (WTHD) is used, as introduced in [24]. It is similar to the total harmonic distortion defined in [25] with the assumption that the coupling inductor resistance is neglected with respect to its reactance. The WTHD can be calculated as shown below:

$$WTHD = \frac{\sqrt{\sum_{k=2}^{\infty} \left(\frac{V_k}{k}\right)^2}}{V_1}$$
(12)

Here, V_1 and V_k are the root mean square (RMS) values of fundamental and *n*-order harmonic components, respectively.

The impact of the DC-link voltage is presented in Figure 12 when the filters inductances and the injected active power are the same. It is apparent that the lower WTHD in the total current occurs only when the two parallel-connected GCIs are symmetric. Moreover, as the asymmetry increases, the WTHD increases.



Figure 10. GCIs and the total grid currents under symmetry scenario (a) in time and (b) in frequency.



Figure 11. GCIs and the total grid currents under asymmetry scenario (a) in time and (b) in frequency.



Figure 12. Effect of changing GCI2 DC-link voltage value on the grid current WTHD.

The effect of changing the coupling filter inductance of the second GCI is presented in Figure 13, keeping the DC-link voltages and active powers symmetric. It is obvious that the lower WTHD occurs only for the symmetric coupling filter. The WTHD increases with the increase in the coupling filter inductance asymmetry.



Figure 13. Effect of changing GCI2 inductance value on the grid current WTHD.

6. Experimental Verifications

6.1. System Description

Two experimental setups were built to validate the results of the two simulations (Figure 14). The first model consists of a Taraz inverter with a DC-link energized from a power rectifier. The DC-link capacitor is 470 μ F. A coupling inductor with a base value of 20 mH is used to connect the inverter to the grid. The DC-link of the inverter is energized with 325 V from the same grid. Since the grid voltage peak must be lower than the DC-link voltage, a grid-connected transformer is used to reduce the grid voltage on the inverter side and to provide the isolation function between the DC-link and the grid. The grid voltage on the inverter side is 66 Vrms. The voltages and currents are measured by a Taraz VI measurement module with 200 kHz and 100 kHz bandwidths for the current sensors and voltage sensors, respectively. The control algorithm is built using dSPACE rti1102 MicroLabBox. The switching frequency used is 5 kHz. The results are captured by a PicoScope 4000 series with 20 MHz bandwidth. Then, the results are analyzed by MATLAB 2021b software. The second system is a duplicate of the first system except that there are two GCIs connected in parallel.



Figure 14. Cont.



Figure 14. Experimental setup. (a) Study 1, and (b) Study 2.

6.2. Study 1: One GCI

The GCI switches are driven by 5 kHz pulses generated from a sine-triangle modulation. The results in time and frequency domains are illustrated in Figure 15. It is clear that the switching harmonic bands around the odd multiple of the switching frequency contain the carrier harmonic side by side with the sideband harmonics, while only sideband harmonics exist in the switching harmonics bands around the even multiple of the switching frequency. To study the effect of the parameters on the switching harmonics in the SH range, three harmonic examples are taken into account: 5 kHz as a carrier harmonic and 5.1 kHz and 4.9 kHz as sideband harmonics.



Figure 15. Measured GCI current (a) in time domain and (b) in frequency domain.

The first parameter under investigation is the impact of the inductor value. The base value is 20 mH; different values are then chosen. The impact on the harmonics is depicted in Figure 16. It is noticeable that as the inductance value increases, the amplitude

of the harmonics decreases. The second parameter is the injected power generated by the GCI. The base value is 198 W. The results are presented in Figure 17. It is clear that the amplitudes of the harmonics are almost constant, and they are independent of the injected active power. The results obtained by simulation and experimental studies meet what is concluded by the mathematical analysis. This in turn confirms the possibility of applying the four assumptions made in the mathematical analysis.



Figure 16. Effect of changing the coupling inductance on the amplitude of the chosen harmonic examples.



Figure 17. Effect of changing the active power on the amplitude of the chosen harmonic examples.

6.3. Study 2: Two Parallel GCIs

Study 2 is carried out by connecting two GCIs in parallel. The GCIs are symmetric in Scenario 1 with $L_{f1} = L_{f2} = 20$ mH. The measured results in both the time and frequency domain are introduced by Figure 18. The carrier harmonic is not totally eliminated due to some small timing differences between the control signals and the response time of the system. But overall, the filtering performance is good with approximately -11.8335 dB. As more GCIs are connected in parallel, lower emissions in the SH range are attained.

Scenario 2 considers two asymmetrical GCIs connected in parallel. This is completed by changing the inductance value of the coupling filter of the second GCI to be 10 mH, while 20 mH inductance is used for the first GCI. The variation of the DC-link voltage is omitted from the experimental study due to some practical limitations. The measured result is shown in Figure 19. It is obvious that the filtering performance has deteriorated, and this can be seen clearly in both the time and frequency domains.



Figure 18. The results of two symmetric parallel-connected GCIs (**a**) as a function of time and (**b**) as a function of frequency.



Figure 19. The results of two asymmetric parallel-connected GCI (**a**) as a function of time and (**b**) as a function of frequency.

7. Conclusions and Future Work

In this paper, a comprehensive analysis of the high-frequency emissions of GCIs in the SH range has been presented. A mathematical analysis has been carried out in order to investigate the parameters that affect the SH amplitudes as well as their phases. It has been concluded that three main factors affect the emissions: the DC-link voltage, the coupling inductance value and the amount of active power injected. The following conclusions have been found:

- The amplitude of the SH emissions of single-phase GCIs depends on the DC-link voltage and the coupling filter inductance.
- The amplitude of the SH emissions of single-phase GCIs is independent of the active power variation.
- The phase of the carrier harmonics is independent of the active power variations
- The active power variation affects only the phase of the sideband harmonics.

Furthermore, as an application of that, the effect of the parameters has been studied for parallel-connected GCIs in DPGSs with equal carrier phase shift. The mathematical analysis has been confirmed through simulation and experimental studies. It is worth mentioning that this study is applicable for GCIs with different sizes and ratings, GCIs based on PWM, and GCIs in DPGSs where the inverters are geographically nearby. Meanwhile, this study is applicable for GCIs based on hysteresis controlling and GCIs that are geographically far apart. Knowing the behavior of these harmonics would help in future research scope, which includes the following:

- Studying deeply the propagations and penetrations of SH of single-phase GCIs in low-voltage grids.
- Studying the interference between single-phase GCIs and any other switching converter, such as switched-mode power supplies and LED lamps, at any residential installation.
- Developing active filters to mitigate the emissions of GCIs in the SH range.

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Abbreviations

The following abbreviations are used in this manuscript:

DPGS	Distributed power generation system
GCI	Grid-connected inverters
PCC	Point of common coupling
SH	Supraharmonic
PV	Photovoltaic
PWM	Pulse width modulation
HF	High frequency
PR	Proportional resonance
WTHD	Weighted total harmonic distortion

Variables

The following variables are used in this manuscript:

- v_i Inverter output voltage
- V_{dc} DC-link voltage
- ω_g Grid angular frequency—reference signal angular frequency
- θ_g Grid phase—reference signal phase
- ω_c Carrier angular frequency
- θ_c Carrier phase
- *M* Modulation index
- *J* Bessel function of the first kind
- v_g Instantaneous value of the grid voltage
- V_{amp} The amplitude of the grid voltage
- δ The load angle
- i_g The instantaneous current injected to the grid
- i_{gf} The instantaneous fundamental current
- *i*_{gs} The instantaneous carrier switching harmonics
- i_{gsb} The instantaneous sideband current switching harmonics
- *L_f* The coupling filter inductance
- L'_g The grid inductance
- r_f The coupling filter resistance
- r_g The grid resistance
- RMS Root mean square
- *V*₁ RMS values of fundamental
- V_k RMS values of n-order harmonic components

Appendix A. Load Angle Definition in Power Systems

This appendix is added to explain the definition of the load angle mentioned in Equation (3). Let a two bus system be connected through an inductive reactance X_l . The phasor voltage of the first bus is $V_1 \angle \delta_1$, while the phasor voltage of the second bus is $V_2 \angle \delta_2$. The conditions needed to have only an active power, flowing from bus 1 to bus 2:

$$V_1 = V_2 \tag{A1}$$

$$\delta_1 > \delta_2 \tag{A2}$$

In this case, the load angle is defined as the phase difference between the δ_1 and δ_2 as:

δ

$$=\delta_1 - \delta_2 \tag{A3}$$



Figure A1. Two-bus power system.

For the mathematical analysis in Section 2, the inverter output voltage is considered as bus 1, while the grid voltage is considered as bus 2, and the coupling filter works as inductance that connects the two buses. As the power flows from the GCI into the grid, then the fundamental voltage of v_i leads the grid voltage by the load angle δ .

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