European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Impact of Multiple Inverter Based Distributed Generation Units on Harmonic Resonance

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Abstract. With the growing concerns over environmental impacts and rebate programs offered by governments, small renewable technology based distributed generation (DG) units are increasingly being used in commercial and domestic electric power production. However, a large number of DG units in a distribution system may sometimes contribute to high levels of harmonic distortion even though the emission level of individual DG units comply with the current harmonic standards. In addition, the incorporation of a passive filter within these DG units also has a negative effect due to the resonance phenomenon. Thus, this paper aims to analyse the impact of multiple inverter based DG units on resonance and harmonic distortion. Furthermore, the effect of simplifying DG model by bundling the realistic model of multiple and small DG units into a single unit were investigated. The analysis was performed for an inverter based DG system connected to the IEEE 13 bus distribution test system. To investigate resonance phenomenon, frequency scan was conducted while the fast Fourier transform analysis was carried out to measure the voltage and current distortion at the point of the common coupling and the DG connected buses. The test system was simulated using MATLAB/SimPowerSystems. The result shows that a simplified model of multiple DG units can be used as a DG model for harmonic distortion and resonance phenomenon study.

Key words

Distributed Generation, Harmonic, Resonance, Inverter, Passive Filter.

1. Introduction

In recent years, many power utilities promote interconnection of renewable energy sources into the distribution system. However, the insertion of DG into the distribution system will have either a positive or negative impact that depends on the distribution network operating characteristics and the DG characteristics. DG can be advantageous if, at minimum, it meets the basic requirements of the systems operating philosophy and feeder design [1]. Current research has studied the impact of DG on the systems power quality. It was noted that the effect of DG on power quality depends on type of DG, its interfaces with the utility system, size of the DG unit, total capacity relative to the system, size of generation relative to a load at the interconnection point and feeder voltage regulation practice [2].

DG connected to a distribution system may contribute to harmonic distortion in the system depending on the type of DG unit and the power converter technology. There are two types of DG namely, inverter based DG and non-inverter based DG [3]. Examples of inverter based DG include photovoltaic systems, wind turbine generators, fuel cells, and micro turbines which use power converters as interfacing devices to the grid. The mini-hydro synchronous generator and induction generator are considered as non-inverter based DG units.

Harmonic resonance related to the integration of DG into the grid is becoming a critical issue in power systems due to the increasing quantity of renewable energy and other distributed generation resources. This harmonic resonance can occur at the interconnection point of individual or multiple DG units to the grid. It typically results from an impedance mismatch between the grid and the inverters. Moreover, there has been an increase in additional harmonic producing equipment, such as adjustable speed drives (ASD), which may lead to a greater propagation of the harmonics through the system, increase losses and possibly decrease the equipment life time. Besides, the equipment can be damaged by overcurrents or overvoltages that are created due to the resonance [4]. Dynamic interaction between grid and inverter output impedance can lead to additional resonance in grid current and/or voltage. These can occur at certain frequencies that are not characteristic of the grid network impedance or produced by the inverter alone or when connected to an ideal grid. The effect of this resonance not only presents a severe power quality problem but it can also trip protection devices and cause damage to sensitive equipment [5].

A research related to harmonic interaction between multiple DGs and a distributed network was conducted in [6]. It was reported that the higher penetration of PV inverters, associated with LC filters, under certain circumstances would affect the system in terms of nuisance tripping. This increases harmonic emission significantly even though the PV inverters individually satisfy the harmonic limits. In [6]-[7], it was reported that the parallel and series resonance phenomena between the network and PV inverters were found to be responsible for unexpected high current and voltage distortion levels in the PV network. In a similar work [8], the effect of resonance and harmonic distortion due to wind based DG connections was reported. The aim was to analyse the impact of wind turbine generation (WTG) on resonant modes of system impedance and total harmonic distortion in the network. The WTG use a power factor correction capacitor bank at their terminal in order to improve the power factor. It was concluded that the combination of different WTGs, feeder capacitors and cable lengths might cause system resonance frequencies closely aligned with injected harmonic current frequencies. Additionally, it could potentially increase the total harmonic distortion (THD) to unacceptably high values that violate the IEEE 519 limits. However, this study did not consider the effect of a passive filtering of the WTG in the resonance analysis.

This paper aim to observe the effect of harmonics on the interaction between a distribution system and the inverter based DG associated with a passive LCL filter. The maximum allowable penetration level of DG units connected to the grid was assumed as 40% of the total connected load [9]-[10]. It is based on the violating limits of the standard voltage harmonic distortion. Many researchers use simplified DG model as a single DG unit [11]-[15] in similar studied without highlighting the reason for the adaptation of simplified model. In reality, the size of a single DG unit is small, in the range of 1kW to 100kW, which may contribute more than 34GW [16] of power due to the rise in DG installation in the distribution system. Therefore, this study also analyse the effect of the multiple DG on harmonic penetration and resonance and compare the results when the DG is modelled a single large DG unit on resonance and harmonic distortion at the specific penetration level.

2. Modelling of Inverter Based DG Units

Most of the non-conventional DG units require specific power electronic converters to convert the generated power into useful power in the grid system. Depending on the nature of the DG sources, different configurations of power electronic converters are required. However for harmonic analysis, the DG is typically modelled by assuming that the DC voltage is constant. This assumption can be justified by the large capacitance in the DC circuit and by the DC voltage controller that keeps the voltage at near nominal values. Using this assumption, DG can now be represented by a voltage source inverter (VSI) fed by a constant DC source [10]. Fig. 1 illustrates the general components of the voltage source inverter. This system consists of a DC source, an inverter, a P-Q controller and an LCL passive filter.

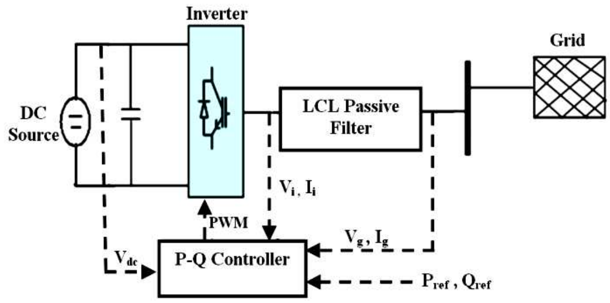

Fig. 1. Voltage source inverter

The function of the inverter is to convert DC to AC voltage. This inverter uses pulse width modulation (PWM) to generate a sinusoidal output current by switching the IGBTs switching element in the inverter. In order to interface the VSI to the grid, an LCL passive filter is required to eliminate the current harmonics created by the PWM switching inverter.

A. *Mathematical modelling of voltage source inverter*

The modelling of a VSI connected to the grid is depicted in Fig. 2. The inverter controller is used to control the DGs DC link voltage, reactive power and power factor. The inverter control loop can be derived from the relationship between the inverter and grid voltage behind its grid impedance [17].

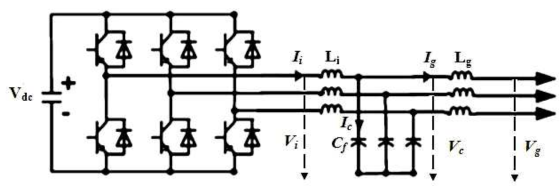

Fig. 2. VSI connected to grid through LCL filter

The LCL passive filter model can be derived in the stationary reference frame by using the Kirchhoff's Laws as follows [10] and [17]:

$$I_i - I_c - I_g = 0 \tag{1}$$

$$V_i - V_c = L_i \frac{dI_i}{dt} \tag{2}$$

$$V_c - V_g = L_g \frac{dI_g}{dt} \tag{3}$$

The relationship between inverter output voltage (V_i) and grid voltage (V_g) was established by taking into consideration the voltage drop at the LCL filter. This can be written as:

$$V_i = V_g + L_g \frac{dI_g}{dt} + L_i \frac{dI_i}{dt} \tag{4}$$

After transforming to the rotating reference frame in the positive direction of grid voltage, Eq. (5) is obtained:

$$V_{id} = V_{gd} + L_g \frac{dI_{gd}}{dt} - \omega L_g I_{gd} + L_i \frac{dI_{id}}{dt} - \omega L_i I_{iq} \qquad (5)$$

where the imaginary component can be expressed as

$$V_{iq} = V_{gq} + L_g \frac{dI_{gq}}{dt} + \omega L_g I_{gd} + L_i \frac{dI_{iq}}{dt} + \omega L_i I_{id} \qquad (6)$$

In the rotating voltage oriented reference frame, $V_{gd} = |V_{gd}|$ and $V_{gq}=0$. Although $V_{gq}=0$, it is not eliminated from the equations to aid the derivation of the controller equation.

For controller derivation, the voltage drops across LCL filter are treated as an output for the PI controllers:

$$L_g \frac{dI_{gd}}{dt} + L_i \frac{dI_{id}}{dt} = K_p\left(1+\frac{1}{sT_1}\right)\left(I_{id\_ref} - I_{id}\right) \qquad (7)$$

$$L_g \frac{dI_{gq}}{dt} + Li \frac{dI_{iq}}{dt} = K_p\left(1+\frac{1}{sT_1}\right)\left(I_{iq\_ref} - I_{iq}\right) \qquad (8)$$

Substituting Eq. (7) into Eq. (5) and Eq.(8) into Eq. (6), the inverter voltage reference can be obtained as:

$$V_{id\_ref} = K_p\left(1+\frac{1}{sT_1}\right)\left(I_{id\_ref} - I_{id}\right) + V_{gd} - \omega L_g I_{gq} - \omega L_i I_{iq} \quad (9)$$

$$V_{iq\_ref} = K_p\left(1+\frac{1}{sT_1}\right)\left(I_{iq\_ref} - I_{iq}\right) + V_{gq} + \omega L_g I_{gd} + \omega L_i I_{id} \quad (10)$$

The inner current loops for the inverter controller can be derived from Eq. (9) and (10) as depicted in Fig. 3. [10] and [17].

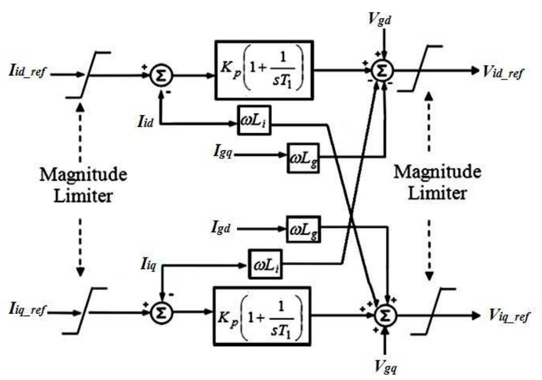

Fig. 3. Inverter inner control loop

In the voltage oriented reference frame, $\boldsymbol{I_{id}}$ is equal to the active current and $\boldsymbol{I_{iq}}$ is equal to the negative of the reactive power. The active current is calculated from the control loop that controls DC-link voltage for the d-component. The reactive current is generated by the loop that controls AC output voltage for the q-component.

Fig. 4 shows the inverters outer control loop. In the outer DC voltage control loop, active current from the DG source is fed forward to enhance the performance of the controller. The loop is based on a P-Q control scheme that allows the execution of active and reactive power outputs to be independently controlled. These two control loops are the general structure of the controller for the DG model [10] and [17].

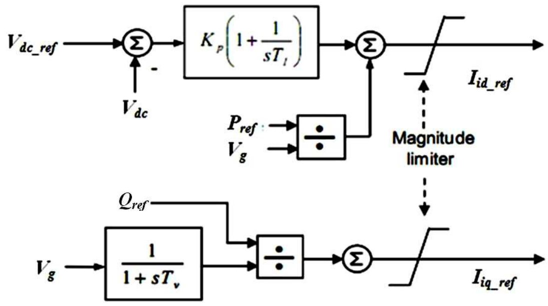

Fig. 4. Inverter outer control loop

B. Simulation model for inverter based DG

Fig. 5 shows the modelled inverter based DG in the MATLAB/SimPowerSystems software. It is based on the block diagram depicted in Fig.1 and the aforementioned control methods. The IEEE 13 bus system is located in the grid subsystem block.

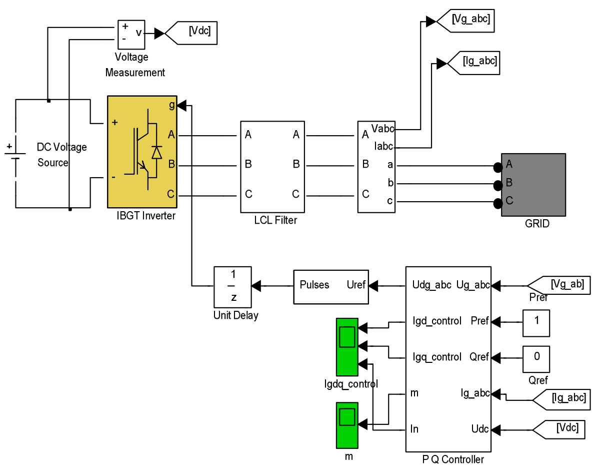

Fig. 5. Modelling of inverter based DG in MATLAB/ SimPowerSystems

3. Test Case with the IEEE 13 Bus System

IEEE 13 Node Test Feeder [18], as depicted in Fig. 6, is used for this study. The system is unbalanced and serves as a benchmark system for unbalanced harmonic propagation studies. For this study, the original IEEE 13 bus system is modified by adding a non-linear load (adjustable speed drive, ASD) at bus 680 and the inverter based DG units at the specific buses. A power factor correction capacitor (PFCC) and additional loads are placed in the same manner as they would be in the original IEEE 13 Node Test System. The current spectrum for the ASD model is referred in [4]. The PFCC and other loads are modelled as a static capacitor and static load respectively. In this study, the impact of multiple DG units at different location has been analysed. The total connected load of this system is 3.2 MW. The overall size of the DG units is 40% of the total connected load, which is 1280 kW.

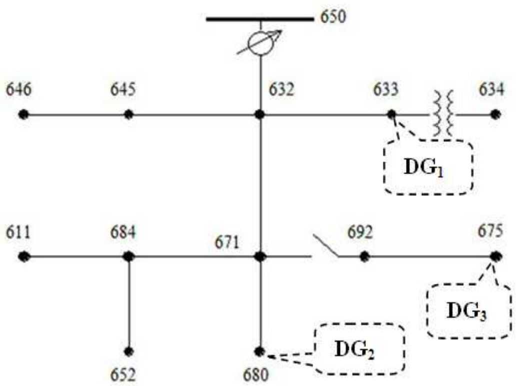

Fig. 6. IEEE 13 Node Test Feeders

4. Results and Discussion

This study aims to analyse the impact of multiple DG unit in distribution system on the network resonance and harmonic distortion. The system resonance frequency at the PCC can significantly change when the network resonance gets closer to the harmonic frequencies injected by DG in the system. As mentioned in Section III, the DG unit is located at the specific buses while the PFCC and the ASD are located at Bus 675 and 680 respectively as shown in Fig. 6.

Two simulation scenarios are created to analyse the effect of multiple DG units at different buses and the effect of multiple DG units at the same bus respectively. The first scenarios was divided into four cases, namely system with no DG, one DG unit (DG_1) connected at Bus 633, two DG units (DG_1 and DG_2) connected at Bus 633 and 680, and three DG units (DG_1, DG_2 and DG_3) connected at Bus 633, 680 and 675. The second scenarios also involves four cases namely system with no DG, one DG unit connected at Bus 633, two DG units connected at Bus 633, and three DG units connected at Bus 633. It should also be noted that the overall DG size is kept constant at 40% of total load in all the cases even the number of DG is increased.

Fig. 7 shows the frequency scan obtained at PCC for each phase when the multiple DG units are installed at the different buses. From the frequency scan illustrated in Fig. 7, it is observed that only a single peak resonance has occurred with the absence of inverter based DG which is due to the present of PFCC. However, when the DGs are installed in the system, the two resonance frequencies were observed which indicates that the inverter based DG associated with the LCL filter has a significant influence on the resonance phenomenon in the power system. By increasing the number of DG units in the system, the pattern of resonance shape also changes. However, only a small difference on the resonance shape was noted when two and three DG units were connected to the grid. The detailed results of the frequency scan in Fig. 7 (the peak value of parallel and series resonance) are shown in Tables I and II.

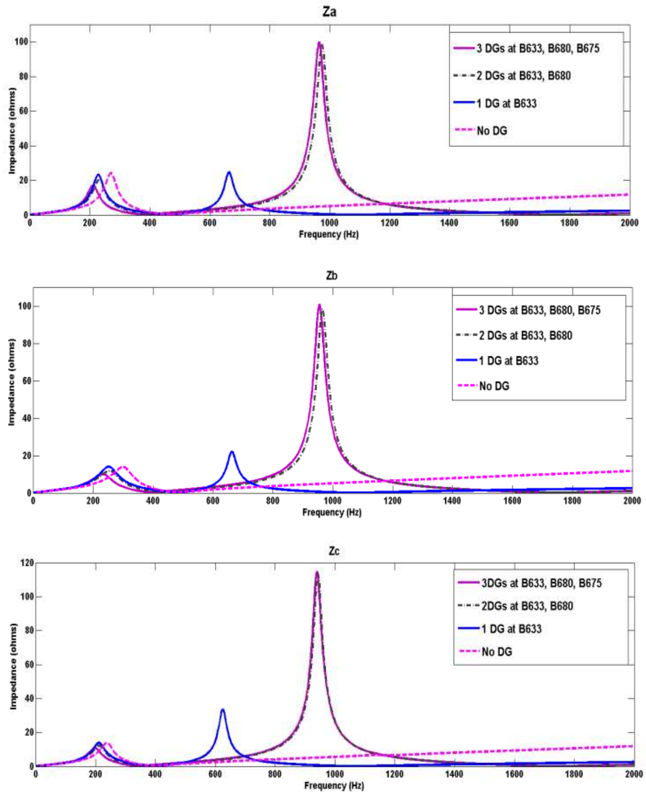

Fig. 7. Three phase frequencies scan plots for IEEE 13 bus test system with multiple DGs at different buses

Table I. Peak resonance frequency for parallel resonance with multiple DGs at different buses

DG numbers	First peak (n^{th} harmonic)			Second peak (n^{th} harmonic)		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
No DG	**304 (5^{th})**	264 (4^{th})	238 (4^{th})	-	-	-
1 DG unit at Bus 633	262 (4^{th})	232 (4^{th})	216 (4^{th})	740 (12^{th})	730 (12^{th})	710 (12^{th})
2 DG units at Bus 633 and 680	230 (4^{th})	256 (4^{th})	212 (4^{th})	974 (16^{th})	966 (16^{th})	944 (16^{th})
3 DG units at Bus 633, 680 and 675	210 (4^{th})	226 (4^{th})	**198 (3^{rd})**	964 (16^{th})	956 (16^{th})	940 (16^{th})

Table II. Peak resonance frequency for series resonance with multiple DGs at different buses

DG numbers	First peak (n^{th} harmonic)			Second peak (n^{th} harmonic)		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
No DG	489 (8^{th})	460 (8^{th})	382 (6^{th})	-	-	-
1 DG unit at Bus 633	489 (8^{th})	460 (8^{th})	382 (6^{th})	1220 (20^{th})	1214 (20^{th})	1203 (20^{th})
2 DG units at Bus 633 and 680	**424 (7^{th})**	**436 (7^{th})**	372 (6^{th})	**1764 (29^{th})**	**1750 (29^{th})**	**1736 (29^{th})**
3 DG units at Bus 633, 680 and 675	**394 (7^{th})**	**404 (7^{th})**	350 (6^{th})	**1764 (29^{th})**	**1750 (29^{th})**	**1736 (29^{th})**

Fig. 8 shows the frequency scan result obtained at PCC for three phases when the multiple DG units are installed at the same bus. From the frequency scan illustrated in Fig. 8, only one peak resonance is noted with the absence of inverter based DG which is due to the present of PFCC. However, when the DG are installed in the system, the two noticeable resonate frequencies appear in the system. The figure showed that the inverter based DG associated with the LCL filter has a significant influence on the resonance phenomenon in the power system. The pattern of resonance shape also different compared to the previous scenario. The detailed results including the peak value of parallel and series resonance of the frequency scan in Fig. 9 are shown in Tables III and IV.

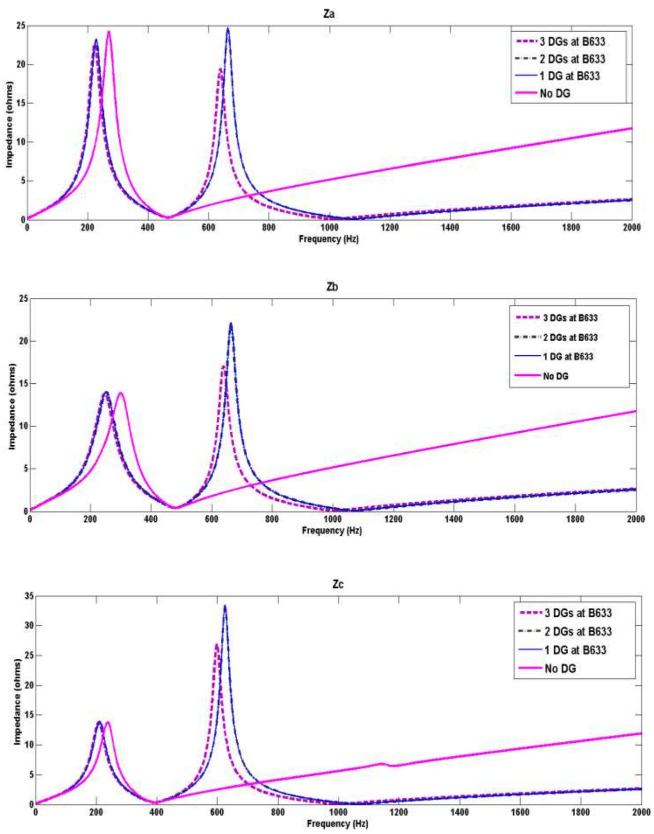

Fig. 8. Frequencies scan for IEEE 13 bus test system for each phase for multiple DGs at the same bus

The total harmonic distortion for voltage and current (THDv and THDi) for bus 632 (PCC) for the first scenario are shows in Table V. The THDv and THDi are obtained through a fast Fourier Transform (FFT) analysis. From the result, it can be seen that with the absence of the inverter based DG in the system, the parallel resonance occurs in the system and some voltage and current distortion appear due to the presence of ASD at bus 680. The resonance frequency is fairly close to the harmonic frequency at phase a, so it can be noted that the THDv is high which is close to the harmonic limit (5%). However, phase b and phase c are not affected since the resonance occurs farther away from the harmonic frequency.

Table III. Frequency at peak resonance for parallel resonance for multiple DGs at the same bus

DG numbers	First peak (n^{th} harmonic)			Second peak (n^{th} harmonic)		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
No DG	**304 (5^{th})**	264 (4^{th})	238 (4^{th})	-	-	-
1 DG unit at Bus 633	262 (4^{th})	232 (4^{th})	216 (4^{th})	740 (12^{th})	730 (12^{th})	710 (12^{th})
2 DG units at Bus 633	228 (4^{th})	252 (4^{th})	212 (4^{th})	**664 (11^{th})**	**664 (11^{th})**	**626 (11^{th})**
3 DG units at Bus 633	224 (4^{th})	246 (4^{th})	208 (4^{th})	**638 (11^{th})**	**640 (11^{th})**	598 (10^{th})

Table IV. Frequency at peak resonance for series resonance for multiple DGs at the same bus

DG numbers	First peak (n^{th} harmonic)			Second peak (n^{th} harmonic)		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
No DG	489 (8^{th})	460 (8^{th})	382 (6^{th})	-	-	-
1 DG unit at Bus 633	489 (8^{th})	460 (8^{th})	382 (6^{th})	1220 (20^{th})	1214 (20^{th})	1203 (20^{th})
2 DG units at Bus 633	466 (8^{th})	482 (8^{th})	**418 (7^{th})**	1086 (18^{th})	1078 (18^{th})	1068 (18^{th})
3 DG units at Bus 633	456 (8^{th})	482 (8^{th})	418 (8^{th})	**1018 (17^{th})**	**1024 (17^{th})**	986 (16^{th})

On the other hand, when one DG unit is connected to the grid, series resonance occurred in the system is close to the harmonic frequency, resulting in the uptick of distortion current at the PCC. Next, with two DG units was injected to the system, series resonance still occurs in the system. The THDi is slightly increased but the THDv is within the limits. When three DG units connected to the grid, the parallel resonance occurred the phase c, and the series resonance remained as previous cases. The THDv is increased but not violating the limit, while the current distortion occurred in the system.

Table **V**. THD_v and THD_i measured at Bus 632 for multiple DGs at the different bus

DG numbers	V_a (%)	I_a (%)	V_b (%)	I_b (%)	V_c (%)	I_c (%)
No DG	4.76	3.17	3.65	3.00	2.23	0.90
1 DG unit at Bus 633	2.20	3.83	2.98	2.44	1.68	1.36
2 DG units at Bus 633 and 680	2.32	6.5	2.97	6.28	1.51	4.78
3 DG units at Bus 633, 680 and 675	2.18	6.71	2.83	6.23	3.29	4.24

The total harmonic distortion for voltage and current (THDv and THDi) for bus 632 (PCC) for the second scenario are shows in Table VI. From the result, the first two cases are same with the previous scenario. On the other hand, when two DG units are connected to the same bus which is Bus 633, parallel resonance occurred in the system close to the harmonic frequency, resulting distortion voltage at the PCC. But the THDv did not exceed the limits. The current distortion occurs at phase c because the series resonance exists in the phase c. Next, when three DG units were connected to the system, parallel and series resonance still occurs in the system.

The THDv and THDi are slightly increased but did not exceed the limits.

Table VI. THD_v and THD_i measured at Bus 632 for multiple DGs at the same bus

DG numbers	V_a (%)	I_a (%)	V_b (%)	I_b (%)	V_c (%)	I_c (%)
No DG	4.76	3.17	3.65	3.00	2.23	0.90
1 DG unit at Bus 633	2.20	3.83	2.98	2.44	1.68	1.36
2 DG units at Bus 633	4.03	1.54	4.69	2.08	4.16	5.31
3 DG units at Bus 633	4.74	5.65	4.01	5.44	2.23	1.33

5. Conclusion

The resonance phenomenon and harmonic distortion between the distribution system and the multiple DG units are presented with a frequency scan and FFT analysis through the use of computer simulation. The simulation results show that with DG, multiple, parallel and series harmonic resonances occur in the system due to the interaction of the inverter based DG associated with LCL passive filter and the PFCC and grid impedance. When resonance occurs close to the harmonic frequency, it dramatically increases the distortion. The results also demonstrated that the impact of THD is nearly similar for both DG models which are the simplified model of single unit and the realistic model of multiple small DG units. The 40% penetration level of DG in the test distribution system proved that the THD is not violating the harmonic limit even DG units are model in different ways. This study concludes that it is satisfactory to model the DG as a simplified model because the THD values are not significantly affected.

Acknowledgements

This work was supported by Universiti Teknikal Malaysia Melaka, Universiti Kebangsaan Malaysia, and Ministry of Higher Education of Malaysia.

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