Impact of Reactive Current Injection by Islanding Detection Techniques on the Voltage Quality of Distributed Generation

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***Abstract*—Many active islanding detection techniques uses current injection through q-axis current controller of grid side converter (GSC) for islanding detection of distributed generation (DG). This paper studies the impact of injection of current on voltage quality of DG. The voltage quality of the DG is investigated by measuring the total harmonic distortion (THD) of voltage at the point of common coupling (PCC). The THD curves are plotted to suggest and help in selecting the amplitude and frequency of q-axis injection current for designing the q-axis injection current based islanding detection technique (IDT). The studies are carried out on a partial converter based small wind energy system on per unit basis to have generalized conclusions. Computer simulations are carried out in MATLAB.**

***Index Terms*—Distributed generation (DG), grid side converter (GSC), islanding detection technique (IDT), power quality (PQ), total harmonic distortion (THD) and voltage quality (VQ).**

I. Introduction

Power electronic converter (PEC) based DG generally distort the voltage by injecting harmonics in the system [1-3]. Beside AC/DC and DC/AC conversion, the PECs are expected to perform many other functions, for example maximum power point tracking (MPPT), output active and reactive power control etc [4-9]. Current literature recommends that the modern PECs should be equipped with IDT[10-15]. Current injection based IDTs are recommended for islanding detection when the power mismatch is very low [10-15]. Thus, the DGs are recommended to have a converter with injection current feature either from d–axis [14] or q–axis current controllers [10-13] [15]. Active voltage and frequency change [14]-[16]; cross correlation index based scheme [12]; average absolute frequency deviation value (AFDVavg) based active IDT [11], active ROCOF [15] are based on injection of current either through d-axis or q-axis of current controllers of GSC. The injection current can seriously pollute voltage and current if chosen a high value. For such IDT the estimation of THD is essential before its implementation.

This paper investigates the impact of reactive current injection on the voltage quality of DG. The load is kept linear so that only the effect of injection current on THD may be studied and need for segregation of effect of non-linear load on THD may be avoided. The injection of current is taken as periodic as recommended in [10, 11] [15]. The investigation plots the THD curves of voltage versus reactive current amplitude, injection current frequency and the GSC filter quality factor. Section II discusses the GSC's current controllers and measurement of THD. Section III discusses the test system. Section IV presents the results and section V concludes the paper.

II. GSC Current Controllers and Measurement of Total Harmonic Distortion

The output power of PEC based DG is controlled with the help of internal control loop of GSC [17]. This is done with help of d-q transformation based control scheme to control active and reactive power. Fig. 1 shows the d-axis and q-axis based current controllers of GSC. A proportional plus integral controller (PI) regulate the q-axis component of PCC voltage (v_q) to zero. The output active power (P) and reactive power (Q) of DG is expressed in [17] as (1) and (2),

$$P = \frac{3}{2} v_d i_d \tag{1}$$

$$Q = \frac{3}{2} v_d i_q \tag{2}$$

where i_d,i_q, v_d and v_q are the GSC 's output currents and voltages respectively. Thus, with the help i_d and i_q , the DG output active power and reactive power may be independently controlled. The decoupling of the d and q–axis current may be done easily as reported in [10-12] [17]. The GSC 's current controllers are now equipped with islanding detection algorithms with the help of injection of current either through d–axis[14] [16] or q–axis [10-12] which is as shown in Fig. 1 which is evident from the current injection feature in Fig.1. The injection current may be selected as in (3) and (4), respectively.

$$i_{di} = I_d cos \omega_d t \tag{3}$$

$$i_{qi} = I_q cos \omega_q t \tag{4}$$

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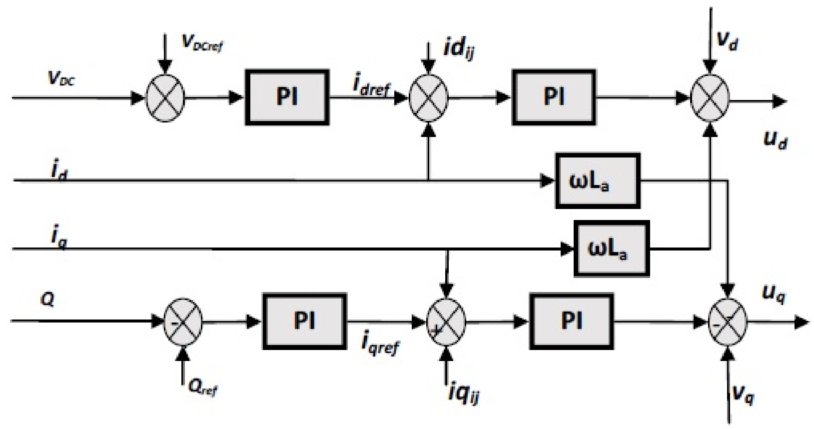

Fig. 1. Block diagram of GSC's current controllers

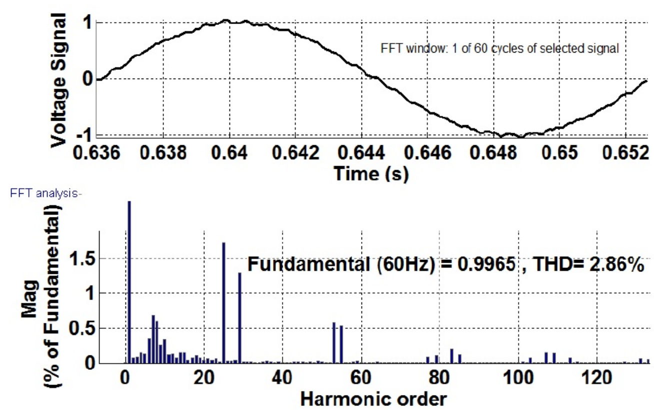

Fig. 2. FFT Analysis of converter output voltage waveform for GSC filter quality factor of 50 without any injection current

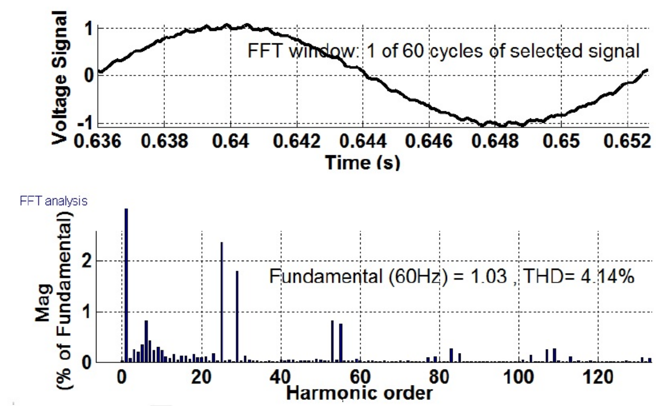

Fig. 3. FFT Analysis of converter output voltage for GSC filter quality factor of 50 with I_q= 5% to rated DG capacity and f_q=30Hz

where I_d and I_q are amplitude and ω_d and ω_q are frequency of injection current through d–axis and q–axis current controllers, respectively. The injection current frequencies ω_d and ω_q may be selected different from grid frequency (60Hz) preferably lower than 60Hz and the magnitude of current is chosen to very small value to cause a very less power quality deterioration. This generates two currents with sideband frequencies (i.e. 60+ ω_q, 60- ω_q, if injection is done from q–axis) along with current at grid frequency.

During grid connected mode these current does not show any significant deviation, however during islanding the current at side–band frequencies causes a noticeable deviation in the frequency of island [10-12]. This is because the injection current is now forced to flow in the load due to the grid disconnection. On the other hand the d–axis injection deviate the output voltage [10-12] [14] [16]. Thus, islanding may be detected locally at DG site by monitoring the PCC voltage or frequency. Since these methods deteriorate the power quality, the THD analysis is important. In this paper we have investigated the THD introduced by q-axis injection method, however for d–axis injection method similar approach may be used. The harmonic emission by the inverters are investigated on the basis of the IEC Standard 61000-4-7 [18] and 61400-21[19]. THD is an important measure of power quality which helps in quantifying the level of pollution i.e. harmonics present in voltage and current waveform. It is defined as the measure of total harmonic components present in the signal with respect to the fundamental component [20]. For example voltage THD for a given signal can be expressed as (5),

$$THD_v = \frac{\sqrt{(\sum_{n=2}^{\inf} V_n^2)}}{V_1} \tag{5}$$

where V_n are the amplitude of the n^{th} harmonic component and V_1 is the amplitude of the fundamental component of the voltage signal. The FFT analysis of DG output voltage without and with current injection is shown in Fig. 2 and Fig. 3 respectively. The FFT analysis is done only for one cycle of the signal, keeping a high Q_{fg} as 50 for both the cases. However, for all the simulation reported in this paper, the FFT analysis is done for 30 cycles of the signal to achieve more accuracy.

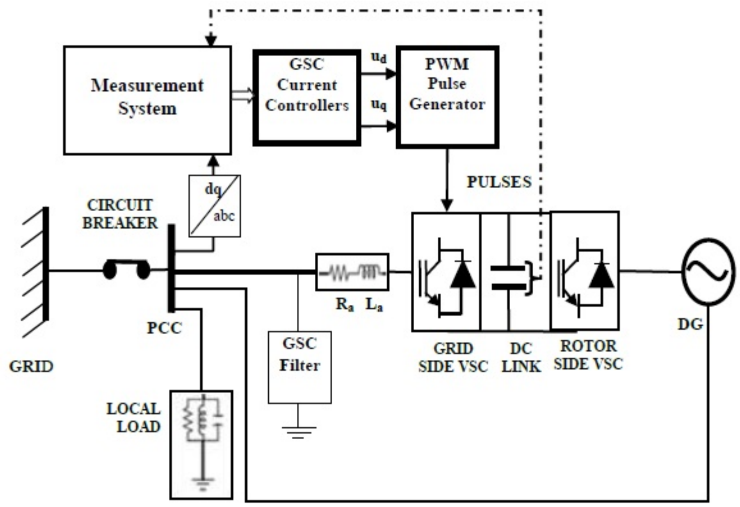

Fig. 4. Single line diagram of the test system

TABLE I
TEST SYSTEM PARAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
V_{abc} (L-L)	575V	f	60Hz	R_L	0.069
I_a (L-L)	6.8kA	R_a	5.95mΩ	L_L	182μH
S_{DG}	4.8MW	L_a	11.75μH	C_L	38.5mF
VDC	1200V	f(PWM)	1620Hz	Q_{fL}	1

III. Test System Description

Fig.4 shows the single line diagram of a grid connected distributed generation interfaced to grid through modern PECs. The circuit breaker connects the distributed generation to grid and a three phase phase-locked loop module (PLL) synchronizes the DG to grid. Table I shows the parameters of test system. A parallel RLC local load (R_L, L_L, C_L) is made to consume active power equal to rated generation by DG at a resonant frequency of 60 Hz. The Q_{fg} of the GSC filter can be set as per (1),

$$Q_{fg} = \frac{1}{\omega_0 CR} \tag{6}$$

where ω_0 is the fundamental frequency.

The converter is controlled with the help of d–q current controllers and a pulse width modulation (PWM), which generates switching pulses. The output voltage and frequency is basically dependent upon the PWM pulse generator. The switching frequency of the PWM is 1620 Hz. The DC link voltage of converter is maintained to 1200 V. The test system satisfies the IEEE standard 1547.1 [21] condition for testing islanding and is taken from [11]. The quality factor (Q_{fL}) of the load is taken as 1, as recommended in [21].

IV. Results and Discussions

This section analyzes the increase in THD, when the q–axis current injection is done for islanding detection of DG. The simulation model of the test system as shown in Fig. 4 is run for 1 s and 60 cycles of the corresponding voltage and current waveform is generated. It is observed that the Simulink transients settle down within a time span of 0.5 s i.e. within first 30 cycles. Thus the THD is obtained with the help of FFT analysis of the voltage and current waveform for last 30 cycles i.e. after 0.5 s when the Simulink transients settle down. The number of cycles is chosen as 30 so as to achieve accuracy in the measured value of THD. The following subsection discusses the effect of injection current effect on the THD. The local load is kept linear and constant in all the cases having a value of 500 kW, 0 kVAr.

A. PCC Voltage THD vs GSC Filter Quality Factor

This section plots the curve between PCC voltage THD (THD_v) and GSC quality factor (Q_{fg}). The Q_{fg} is varied from 10 to 50 and THD_v is measured with the help of FFT analysis of 30 cycles of the voltage signal. Two scenarios are taken (a) First the injection current amplitude is kept variable and the injection current frequency is kept constant; (b) Later the injection current frequency is kept variable and injection current amplitude is kept constant. The simulation model of the test system is run for 1 s every time by injecting a periodic current signal of variable amplitude (1% to 5% of the rated DG capacity) and constant frequency of 30 Hz from q–axis current controller of GSC. The PCC voltage THD is measured by FFT analyses of the voltage waveform for a set value of quality factor of the GSC filter. The obtained values of THD_v with respect to Q_{fg} and I_q are tabulated in Table II. Later, the injection current amplitude is kept constant to 5% of the rated DG capacity and injection current frequency is varied from 10Hz to 50Hz. The THD_v is again measured for a set value of the GSC filter quality factor. The obtained values of THD_v with respect to GSC filter quality factor and f_q are tabulated in Table III. The corresponding THD_v vs Q_{fg} curves are plotted for both the scenarios as in Fig.5 and Fig.6 respectively. This is done to observe the injection current amplitude and frequency

TABLE II
THD_i (FOR VARIABLE INJECTION CURRENT AMPLITUDE)

GSC Filter Quality Factor(Q_{fg})	THD_i Without injection Current	THD_i for Variable q-axis Injection Current Amplitude [in%] and constant frequency (f_q)=30Hz				
		1	2	3	4	5
1	14.01	14.26	15.49	16.23	17.41	17.92
10	4.77	4.53	5.14	5.53	5.92	6.51
20	3.98	4.11	4.36	4.75	5.17	5.22
30	3.40	3.98	4.31	4.61	4.96	5.13
40	3.13	3.37	4.04	4.27	4.65	4.96
50	2.97	3.15	3.59	3.92	4.29	4.77

TABLE III
THD_i (FOR VARIABLE INJECTION CURRENT FREQUENCY)

GSC Filter Quality Factor(Q_{fg})	THD_i Without injection Current	THD_i for Variable q-axis Injection Current Frequency (Hz) and constant amplitude (I_q)=5%				
		10	20	30	40	50
1	14.01	17.98	17.87	17.41	16.96	15.87
10	4.77	8.12	7.11	6.51	5.66	5.25
20	3.98	6.01	5.73	5.22	4.93	4.65
30	3.40	5.43	5.21	5.13	4.77	4.31
40	3.13	5.21	5.03	476	4.35	4.19
50	2.97	5.19	4.86	4.47	4.22	3.97

TABLE IV
THD_v (FOR VARIABLE INJECTION CURRENT AMPLITUDE)

GSC Filter Quality Factor(Q_{fg})	THD_v Without injection Current	THD_v for Variable q-axis Injection Current Amplitude [in%] and constant frequency (f_q)=30Hz				
		1	2	3	4	5
1	15.75	15.95	15.97	16.05	16.18	16.8
10	6.49	4.21	4.44	4.62	5.18	5.37
20	4.12	3.67	3.85	4.44	4.63	5.21
30	3.36	3.46	3.68	4.31	4.52	5.02
40	3.03	3.07	3.44	3.95	4.19	4.37
50	2.85	3.03	3.30	3.62	4.09	4.22

TABLE V
THD_v (FOR VARIABLE INJECTION CURRENT FREQUENCY)

GSC Filter Quality Factor(Q_{fg})	THD_v Without injection Current	THD_v for Variable q-axis Injection Current Frequency (Hz) and constant amplitude (I_q)=5%				
		10	20	30	40	50
1	15.75	16.98	16.87	16.8	15.96	15.87
10	6.49	6.23	5.96	5.37	5.21	4.91
20	4.12	5.56	5.38	5.16	4.92	4.57
30	3.36	5.37	5.25	4.92	4.57	4.32
40	3.03	5.22	5.10	4.57	4.25	4.04
50	2.85	5.08	4.57	4.12	3.96	3.34

effect on the PCC voltage THD when varied individually. It can be seen from Fig.5 and Fig.6 that GSC filter has very important role in controlling the power quality, the THD_v is very high at lower value of filter quality factor. A Q_{fg} below 20 is not acceptable as there is a chance of THD_v crossing its permissible limit of 5%. Injection current effects the THD_v to a great extent. It can be seen from Table II and Fig.5 that more is the amplitude of injection current, the higher is THD_v. The injection current amplitude of 5% deteriorates the voltage waveform and has a high THD_v of around 4-5%, even at a high filter quality factor of 50.

Increasing the amplitude of injection current, the THD_v also increases and thus injection current amplitude should be kept as low as possible. However, it can be concluded from Table II that if the GSC filter quality factor is kept above 20 then the injection current amplitude of up to 5% of the rated DG capacity is acceptable for an injection current frequency of 30Hz. But it is always preferable to keep the injection current amplitude as low as possible. From Table III and Fig.6, it can be seen that an f_q=10Hz is not acceptable even for Q_{fg} as high as 50, because of THD_v crossing the acceptable limit of 5%. It can also be observed that THD_v goes low if the injection current frequency is kept as near as possible to the fundamental frequency.

B. Load Current THD vs GSC Filter Quality Factor

This section plots the curve between load current THD (THD_i) and GSC quality factor (Q_{fg}). In this case also, Q_{fg} is varied from 10 to 50 and THD_i is measured at each Q_{fg} for the two same scenarios as discussed in the previous subsection i.e. (a) First the injection current amplitude is kept variable and the injection current frequency is kept constant; (b) Later the injection current frequency is kept variable and injection current amplitude is kept constant. The simulation model of the test system undertaken is run for 1s every time by injecting a periodic current signal of variable amplitude (1% to 5% of the rated DG capacity) and constant frequency of 30Hz from q-axis current controller of GSC. The THD_i is measured every time by FFT analyses of the current waveform for a set value of quality factor of the GSC filter for 30cycles of the signal. The obtained values of THD_i with respect to GSC filter quality factor are tabulated in Table IV. Later, the injection current amplitude is kept constant to 5% and injection current frequency is varied from 10Hz to 50Hz. The THD_i is again measured by FFT analyses of the current waveform for a set value of Q_{fg}. The obtained values of THD_i with respect to GSC filter quality factor for the two scenarios taken are tabulated in Table IV and Table V respectively. The corresponding THD_i vs Q_{fg} curves are plotted for both the scenarios as in Fig.7 and Fig.8 respectively. This is done to observe the injection current amplitude and frequency effect on the THD_i when varied individually. It can be seen from Fig.7 and Fig.8, that GSC filter has very important role in controlling the THD_i, the THD_i is very high at lower value of Q_{fg}. It can be seen from Figs. 5-8 that for the same condition THD_i is more severe than THD_v. A Q_{fg} below 30 is not acceptable as there is a chance of THD_i crossing its permissible limit of 5%. Injection current effects the THD_i to a great extent. It can be seen from Table IV and Fig.7 that more is the amplitude of injection current, the higher is THD_i. The injection current amplitude of 5% deteriorates the current waveform and has a high THD_i of around 4-5%, even at a high filter quality factor of 50. THD_i increases with the increase in the amplitude of injection current, thus injection current amplitude should be kept as low as possible. It can also be concluded here that if

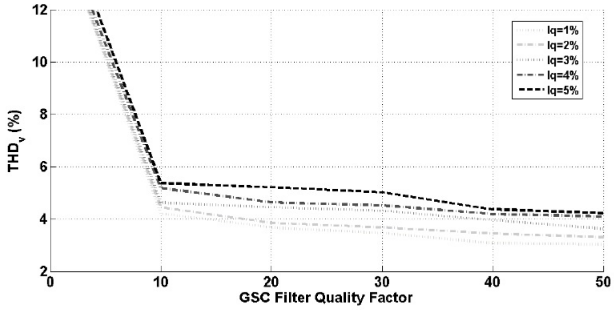

Fig. 5. THD_v Vs GSC filter quality factor for variable injection current amplitude and constant frequency f_q=30Hz

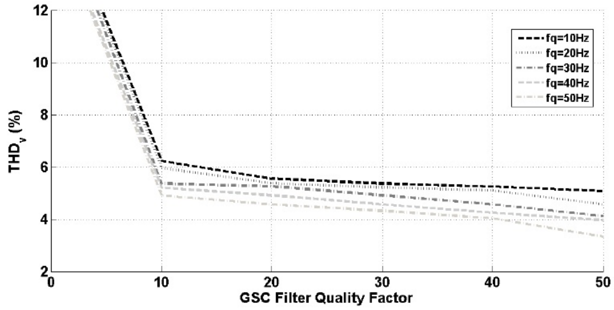

Fig. 6. THD_v Vs GSC filter quality factor for variable injection current frequency and constant amplitude I_q=5%

the GSC filter quality factor is kept above 30 and the injection current frequency is kept above 30 Hz, than injection current amplitude of up to 5% can be accepted. But it is preferable to keep the injection current amplitude as low as possible and injection current frequency as near as possible to fundamental frequency.

C. THD vs Injection Current Amplitude Curves (at Constant GSC Q_{fg} and Variable Injection Current Frequencies)

THD_v and THD_i values for varying injection current amplitude and frequencies at constant GSC filter quality factor are obtained through simulations and the corresponding THD curves are plotted in Figs. 9-12 respectively. These curves will be of great help to protection engineers for selecting the right value of injection current amplitude and frequency needed to be injected from q-axis current controllers of GSC for islanding detection as well as maintaining the harmonics level. For an active IDT, once the Q_{fg} and sensitivity of IDT is known, the right amount of injection current can be determined from the THD curves plotted in Figs. 9-12. It can be observed from all the curves in Figs. 9-12, that THD rises for higher value of I_q and decreases for ω_q chosen near to the ω_0. In all the cases, the THD_i is greater than THD_v for same value of GSC filter quality factor and injection current. Hence, it is recommended to select the injection current amplitude and frequency on the basis of THD_i rather than THD_v. It can also be seen that current injection based IDT are suitable for only those converters which has high filter quality factor. The converters which have low value of filter quality factor,

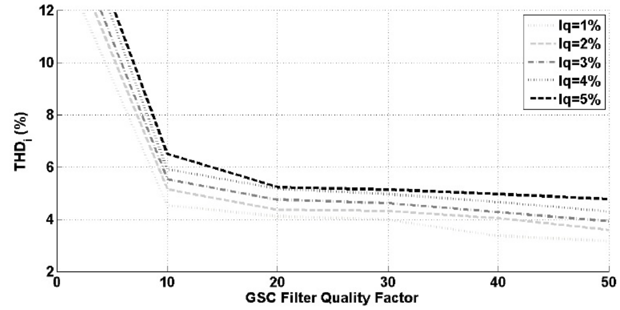

Fig. 7. THD_i Vs GSC filter quality factor for variable injection current amplitude and constant frequency f_q=30Hz

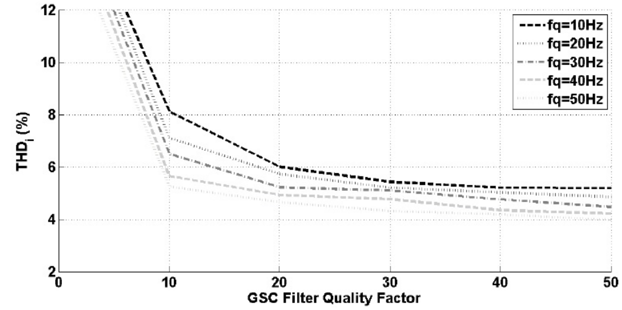

Fig. 8. THD_i Vs GSC filter quality factor for variable injection current amplitude and constant frequency I_q=5%

are more prone adverse effect of injection current IDT and therefore have poor quality factor with a higher value of THD.

V. Conclusions

It has been shown that the current injection through q-axis controllers of grid side converter for islanding detection causes deterioration of voltage quality by increasing the THD. The maximum and minimum permissible current for an IDT can be fixed on the basis of sensitivity of islanding detection technique, THD values and GSC's filter quality factor. All the measurement is done on per unit basis thus the generalized and specific observation can be listed as following:

- THD_v and THD_i may increase out of permissible limit of 5% for higher values of injection current amplitude.
- An injection current frequency near to fundamental frequency has less impact on THD as compared to far frequencies.
- Current injection based IDT are not a suitable method for converters having a low filter quality factor as the THD values are very high even with small amount of current injection.
- THD_i are more sensitive to injection current compared to THD_v and thus IDT should be designed keeping in view the increase in THD_i rather than THD_v.

THD_v and THD_i curves for varying q-axis injection current amplitude and frequencies at various GSC's filter quality factors have been obtained in this work. These curves

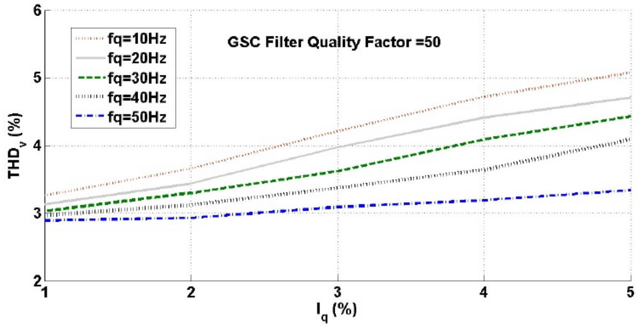

Fig. 9. THD_v Curves for Q_{fg}=50

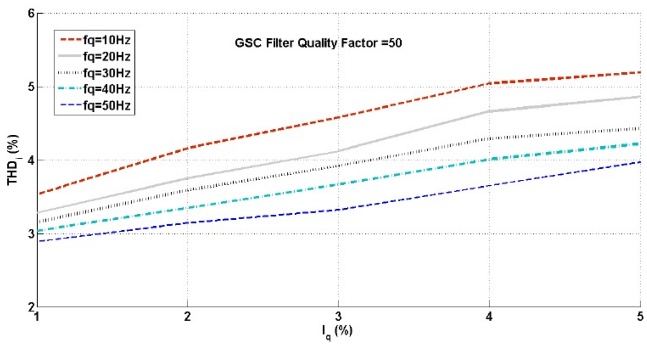

Fig. 10. THD_i Curves for Q_{fg}=50

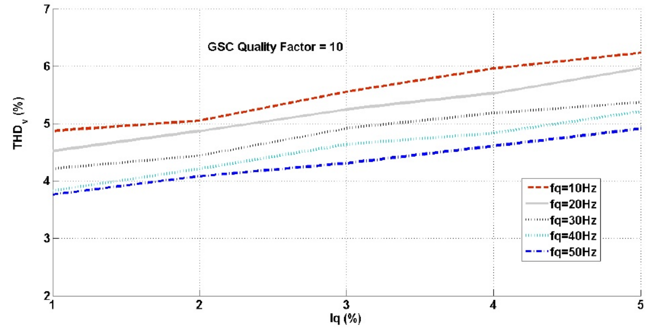

Fig. 11. THD_v Curves for Q_{fg}=10

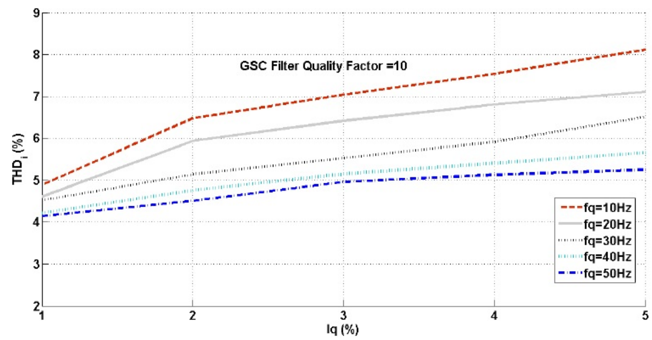

Fig. 12. THD_i Curves for Q_{fg}=10

can be referred while designing and implementing the q-axis current injection based IDT.

REFERENCES

[1] Z. Chen, and E. Spooner, "Grid power quality with variable speed wind turbines", IEEE Transactions on Energy Conversion, vol. 16, no. 2, pp.148-154, 2001.

[2] S. Papathanassiou, and M. P. Papadopoulos, "Harmonic analysis in a power system with wind generation", IEEE Transactions on Power Delivery, vol. 21, no.4, pp. 2006-2016, 2006.

[3] T. S. Tentzerakis, and S. Papathanassiou, "An investigation of the harmonic emissions of wind turbines", IEEE Transactions on Energy Conversion, 22, no. 1, pp. 150-158, 2007.

[4] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "High performance current controller for selective harmonic compensation in active power filters", IEEE Transactions on Power Electronics, vol. 22, no. 5, pp.1826-1835, 2007.

[5] Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines", IEEE Transactions on Power Electronics, vol. 24, no. 8, pp. 1859-1875, 2009.

[6] T. Soong, and P. W. Lehn, "Evaluation of emerging modular multilevel converters for BESS applications", IEEE Transactions on Power Delivery, vol. 29, no. 5, pp. 2086-2094, 2014.

[7] A. M. Trzynadlowski, "Introduction to modern power electronics", John Wiley Sons, 2015.

[8] R. R. Chilipi, N. Al Sayari, A. R. Beig, and K. Al Hosani, "A multitasking control algorithm for grid-connected inverters in distributed generation applications using adaptive noise cancellation filters", IEEE Transactions on Energy Conversion, vol. 31, no. 2, pp.714-727, 2016.

[9] K. Yang, M. H. Bollen, and E. A. Larsson, "Aggregation and amplification of wind-turbine harmonic emission in a wind park", IEEE Transactions on Power Delivery, vol. 30, no. 2, pp. 791-799, 2015.

[10] G. Hernandez – Gonzalez and R. Iravani, "Current injection for active islanding detection of electronically - interfaced distributed resources", IEEE Transactions on Power Delivery, vol. 21, no.3, pp. 1698-1705, July. 2006.

[11] P. Gupta, R. S. Bhatia, and D. K. Jain, "Average absolute frequency deviation value based active islanding detection technique", IEEE Transactions on Smart Grid, vol. 6, no.1, pp. 26-35, Jan. 2015.

[12] H. Y. Lee, B. M. Han and H. J. Cha, "Novel islanding detection method for distributed generation", IEEE Energy Conversion Congress and Exposition, 20-24 Sept. 2009.

[13] H. Karimi, A. Yazdani and R. Iravani, "Negative – sequence current njection for fast islanding detection of a distributed resource unit", IEEE Transactions on Power Electronics, vol. 23, no.1, pp. 298 – 307, Jan. 2008.

[14] F. J. Lin, Y. S. Huang, K. H. Tan, J. H Chiu, and Y. R. Chang, "Active islanding detection method using d-axis disturbance signal injection with intelligent control", IET Generation, Transmission Distribution, vol. 7, no. 5, pp. 537-550, 2013.

[15] P. Gupta, R. S. Bhatia, and D. K. Jain, "Active ROCOF relay for islanding detection", IEEE Transactions on Power Delivery, vol. 32, no.1, pp. 420-429, Feb. 2017.

[16] A. Samui, and S. R. Samantaray, "New active islanding detection scheme for constant power and constant current controlled inverter-based distributed generation", IET Generation, Transmission Distribution, vol. 7, no. 7, pp. 779-789, 2013.

[17] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators", Proceedings of Inst. Electr. Eng., vol.15, no.3, pp.299-306, Jul.1993.

[18] I. E. C Standard 61000-4-7, "General guide on harmonics and interharmonics measurements for power supply systems and equipment connected thereto", 2002.

[19] I. E. C Standard 61400-21, "Measurement and assessment of power quality of grid connected wind turbines", 2002.

[20] D. Shmilovitz, "On the definition of total harmonic distortion and its effect on measurement interpretation", IEEE Transactions on Power Delivery, vol. 20, no. 1, pp. 526-528, 2005.

[21] Standard for interconnecting distributed resources with electric power systems, IEEE Std. 1547, 2003.