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ANALYZING THE IMPACT OF HVDC TRANSMISSION ON A DISTRIBUTION SYSTEM LOADED WITH NONLINEAR LOADS

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Abstract
Owing to several economic and technical benefits over AC transmission, High Voltage Direct Current Transmission (HVDC) has drawn a lot of attention in recent times. HVDC gives rise to harmonic distortion due to the power flow through power electronic inverters. The scenario gets even more critical by considering the increased influx of nonlinear loads in distribution systems. This research work strives to evaluate the impact of HVDC inverters on such distribution systems. The harmonic model of the inverter, developed by experimentation, is modified to decrease the harmonic distortion; which is then used for simulating a generic UK residential distribution system deploying Electrical Transient Analyzer Program. The simulation results indicate increased harmonic distortion in voltage beyond standard limits at high tension as well as low tension sides of the distribution transformer. The results also show that harmonic distortion produced by the HVDC inverters may trigger resonance at a particular harmonic frequency.

Keywords: Distribution Systems, Harmonic Distortion, HVDC, Inverters, Nonlinear Loads

1. Introduction

The occurrence of undesired frequency components as a integer multiple of fundamental frequency is referred to as harmonic distortion [1] which is evaluated using the term Total Harmonic Distortion (THD), mathematically given as]:

$$(\%)\ THD = \frac{\sqrt{\sum_{k=2}^{\infty} X_k^2}}{X_1} \times 100 \qquad (1)$$

Where X_1 gives the value of the fundamental component and X_k gives the value of the k^{th} harmonic constituent of the respective waveform.

Table 1 gives the limits for the maximum allowable values, at the Point of Common Coupling (PCC), for the Total Harmonic Distortion in Voltage (THD_v) as well as Individual Harmonic Distortion in Voltage (IHD_v) and Table 2 gives the maximum values allowed for the Individual Harmonic Distortion in Current (IHD_i) for power system voltages up to 69 kV [2]. Performance of power systems gets seriously hampered with the increasing harmonic distortion. This is due to the increased line & transformer losses, ageing of the insulation, damaged conductors and mal operating equipments [3].

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High Voltage Direct Current (HVDC) transmission has attracted a lot of technical attraction in the recent years due to its high reliability, operational flexibility, reduced lines losses and lower transmission cost; for long transmission lines; owing to lesser conductor and right of ways requirements as compared to AC transmission [4]. It is more economically viable as compared to AC transmission for transmission distances more than 500 km [5]. In addition to being a cost effective solution for power transmission from the off-shore wind farms, it also forms the backbone to tie up two unsynchronised systems [6, 7]. However, for HVDC transmission the power is required to flow through the power electronic converters and major concerns have been raised in the past regarding the harmonic distortion produced due to nonlinear nature of power electronic converters [8, 9]. Power electronic converter provide the flexibility and better control of power flow at the cost of increasing harmonic pollution in the power system [10]. On the other hand, modern distribution systems are increasingly subject to nonlinear loads which draw harmonically distorted current [11]. Therefore, the THD level in a power system deploying HVDC is due to a combination of harmonic distortion caused by HVDC converters and the nonlinear loads being supplied [12]. Several efforts have been made to investigate the impact of nonlinear loads on the distribution systems [13-15]. However, this research work attempts to analyze the interaction between a typical UK residential distribution system, loaded with nonlinear loads, and an HVDC transmission system.

Table 1. THD_v and IHD_v Limits

Voltage Level (V)	V ≤ 1.0 kV	1.0 kV < V ≤ 69 kV
THD_v (%)	8.0	5.0
IHD_v (%)	5.0	3.0

Table 2. IHD_i Limits

Harmonic Number	k < 11	11 ≤ k < 17	17 ≤h < 23	23 ≤ k < 35	k ≥ 35
IHD_i (%)	15.0	7.0	6.0	2.5	1.4

2. Experimental Arrangement and Results

The experiments were performed in Smart Grids Lab at Glasgow Caledonian University, UK to analyze the harmonic content in the current waveforms drawn by various nonlinear residential loads. The experimental setup already presented in [16] is given in Figure 1.

2.1. Nonlinear Loads

The current waveform of a DC supply used to supply an alarm clock was analyzed to obtain the amplitude as well as the phase spectrum. The current waveform is given in Figure 2 and the amplitude spectrum is given in Figure 3. The True Power Factor (PF_{true}) was found to be equal to 0.55 with a THD_i equal to 31.81 %. This harmonic model is assumed to represent the family of various household electronic appliances including televisions, DVD players, gaming consoles and other power supply units. Similarly harmonic analysis was performed to acquire harmonic models for microwave ovens, laptops, Personal Computers (PC), washing machines, Compact Fluorescent Lamps (CFL) refrigerators, freezers and fridge-freezers. These harmonic models were presented in [16].

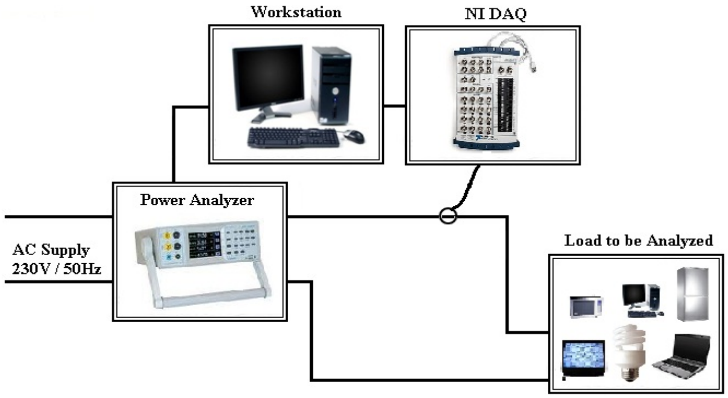

Figure 1. Experimental Setup

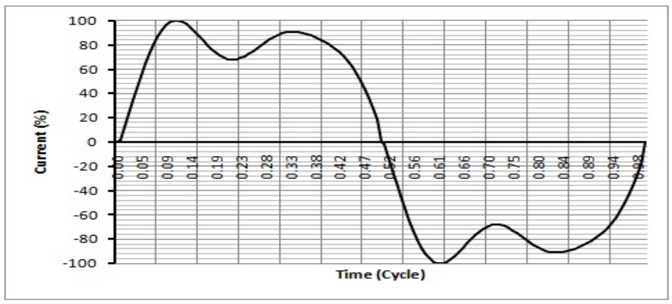

Figure 2. Current Waveform of Power Supply

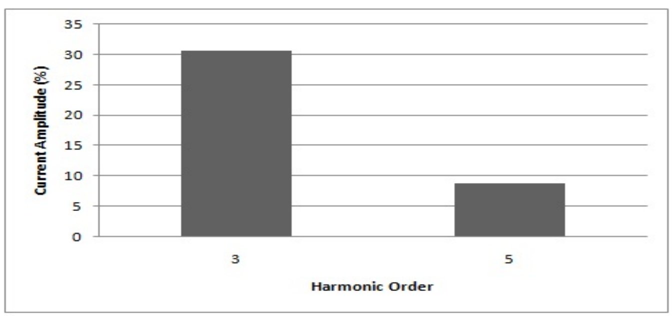

Figure 3. Amplitude Spectrum of Current Waveform of Power Supply

2.2. HVDC Inverter

Most of the current HVDC systems deploy multi-level Voltage Source Converters (VSC) utilizing Pulse Width Modulated (PWM) switching for the inversion purpose [17]. To avoid harmonics high frequency PWM switching is recommended but it increases the system losses which call for special PWM switching patterns [18]. Similarly, harmonic distortion may be reduced by increasing the number of pulses and using specific patterns of transformer connections [19]. Such an effort was made in [20] to eliminate lower order and triplen harmonics and [21] showed that a very low THD_v equal to 1.02 % is achievable. Research team analyzed a commercially available inverter to identify very high THD_v being equal to 27.55 % as presented in [22]. The significant contributions come from 3^{rd} and 9^{th} harmonic components having IHD_v equal to 19.27 % and 11.57 % respectively. However, the harmonic model was modified according to the proposed design given in [20, 21] where the THD_v is very low. The output voltage waveform and amplitude spectrum of the modified inverter are given in Figure 4 and Figure 5 respectively. It can be clearly seen that the current waveform of the improved inverter design is nearly sinusoidal with very small harmonic content.

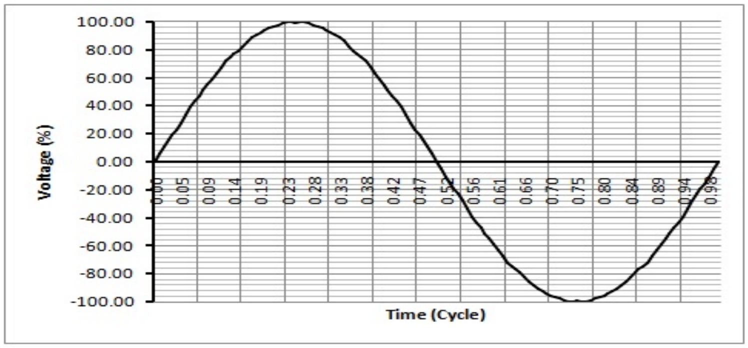

Figure 4. Output Voltage Waveform of Inverter

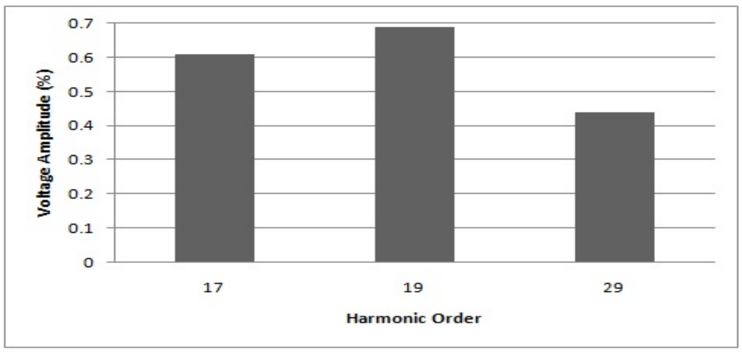

Figure 5. Amplitude Spectrum of Output Voltage Waveform of Inverter

3. Harmonic Analysis

The harmonic models of various nonlinear loads introduced in previous section were then inserted in the harmonic library of Electrical Transient Analyzer Program (ETAP) for simulating a typical UK residential distribution system as shown in Figure 6 [23].

The distribution system is being supplied by a UK standard 275 kV transmission line emanating from a transmission substation. The loading details of the 500 kVA distribution transformer (T1) are given in Table 3. The nonlinear loads, considered, account for 62 % of the total domestic load which approximately agrees with the UK National Statistics [24]. As the distribution transformers are designed to give maximum efficiency at 75 % loading, the total load on T1 is assumed to be as such [25].

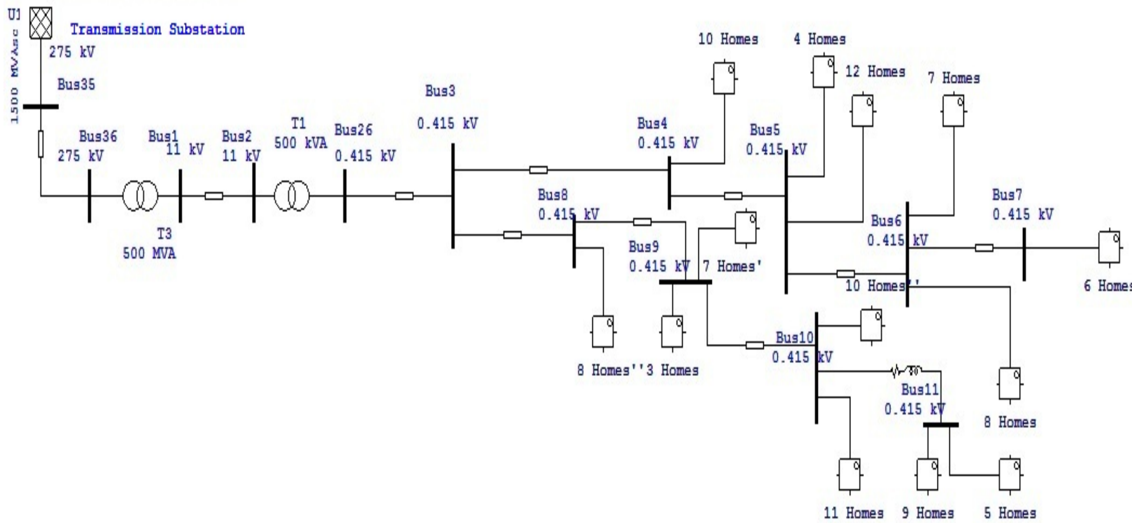

Figure 6. Distribution System Considered for the Simulation

Table 3. Loading Detail

Load Type	Load (kW)	Load Type	Load (kW)
Refrigerator	5.52	Power Supply Units	67.20
Fridge-Freezer	23.90	Microwave Oven	7.36
Freezer	7.36	Laptop	4.60
CFL	12.88	Washing Machine	14.70
PC	15.60	Linear Load	98.44

3.1. Without HVDC

For the first study, the transmission substation is modeled as a linear source; free of harmonics.

3.1.1. Voltage Waveform and Amplitude Spectrum at High Voltage (HV) side of the T1: Voltage waveform at HV side of T1 is given in Figure 7 along with its amplitude in Figure 8. The THD_v is equal to only 0.5 %. The results indicate that THD_v is well within the IEEE limits which should not be a major concern for the power utilities. The results also show that the harmonics caused by nonlinear loads are eliminated while travelling to HV side. This is due to the fact that triplen harmonics are trapped by the delta winding of the transformers.

3.1.2. Voltage Waveform and Amplitude Spectrum at Low Voltage (LV) side of T1: The voltage waveform and amplitude spectrum at LV side of the T1, which is also PCC for all the homes, are presented in Figure 9 and Figure 10 respectively. The value of THD_v is equal to 4.62 % which is within the standard limit. The results show that system is already under a lot of stress due to the influx of various nonlinear loads.

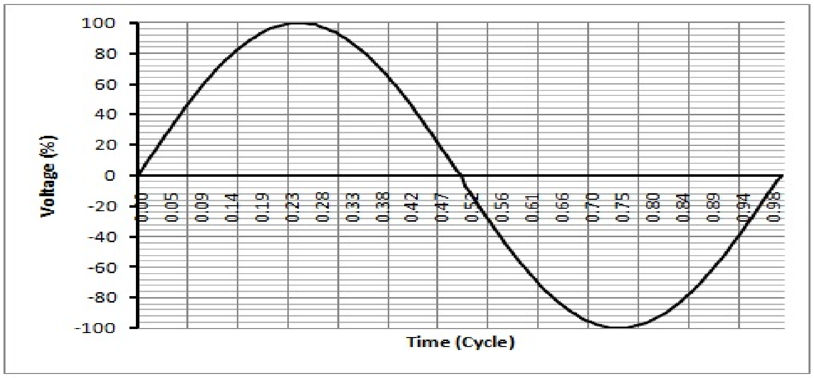

Figure 7. Voltage Waveform at HV Side of T1

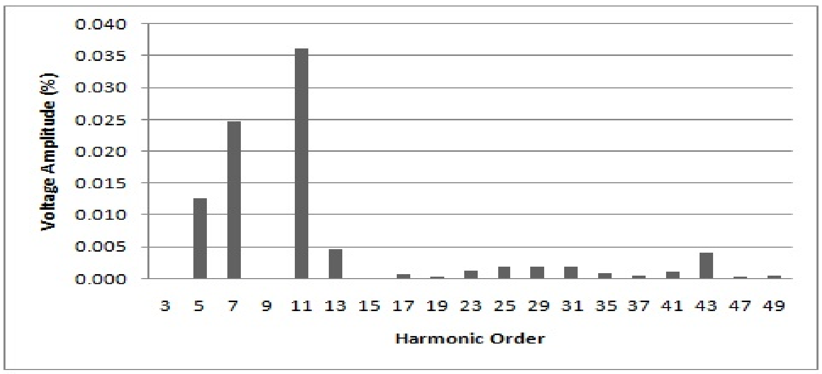

Figure 8. Amplitude Spectrum of Voltage Waveform at HV Side of T1

3.1.3. Voltage Waveform and Amplitude Spectrum at Far End: Voltage waveform at Bus 7 along with its amplitude spectrum is presented in Figure 11 and Figure 12 respectively. This bus bar represents the users farthest from the T1 in terms of conductor length. The situation for the users at the far end of the system is yet more serious as THD_v is equal to 5.5 %.

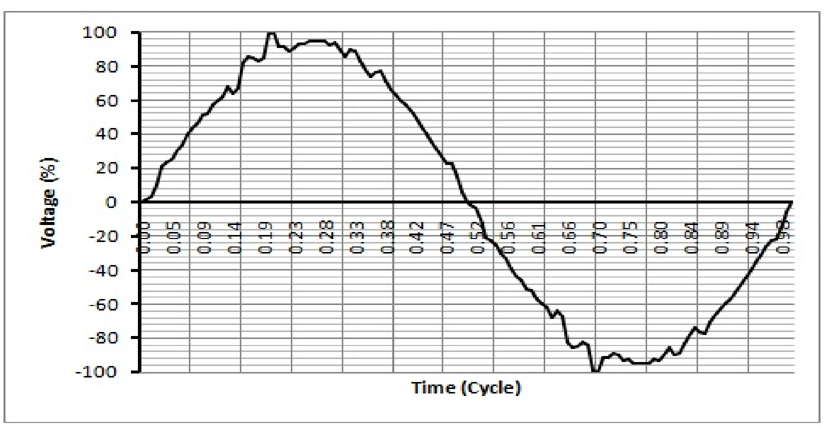

Figure 9. Voltage Waveform at LV Side of T1

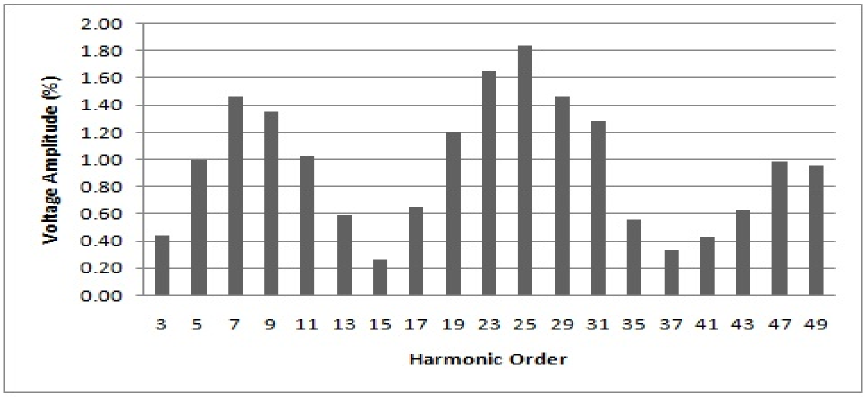

Figure 10. Amplitude Spectrum of Voltage Waveform at LV Side of T1

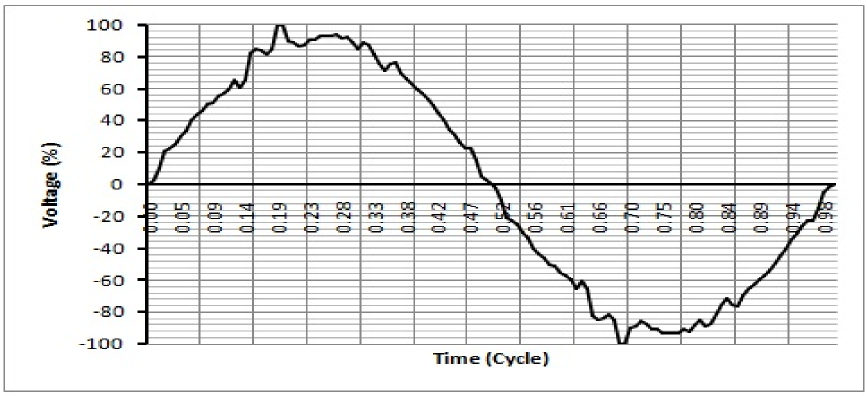

Figure 11. Voltage Waveform at Far End

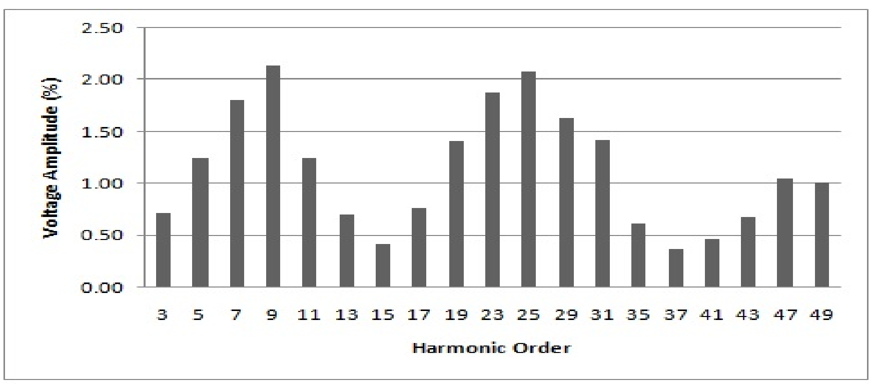

Figure 12. Amplitude Spectrum of Voltage Waveform at Far End

3.2. With HVDC

To analyze the impact of HVDC converter station, the transmission substation is modeled as a harmonic source as per harmonic model of the inverter given in Section 2.2.

3.2.1. Voltage Waveform and Amplitude Spectrum at HV side of the T1: The voltage waveform at the HV side is presented in Figure 13 and its amplitude spectrum is illustrated in Figure 14. With HVDC, THD_v sees a major increase in value from 0.5 %; without HVDC; to 10.78 % which is beyond the standard limit. This can be attributed to the increase in 17^{th}, 19^{th} and 29^{th} harmonic. IHD_v for 19^{th} harmonic, being equal to 10.4 %, is also not acceptable as per standard limits.

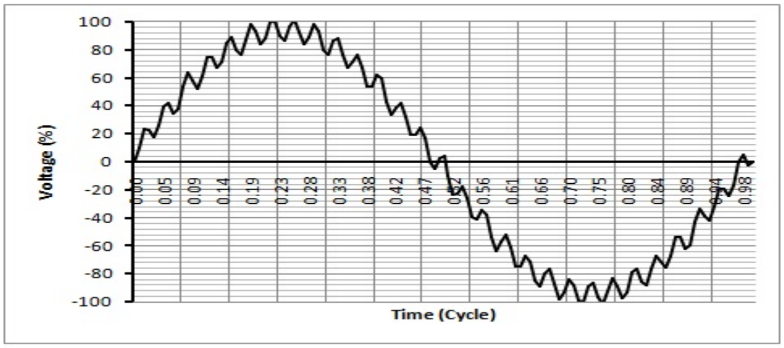

Figure 13. Voltage Waveform at HV Side of T1 with HVDC

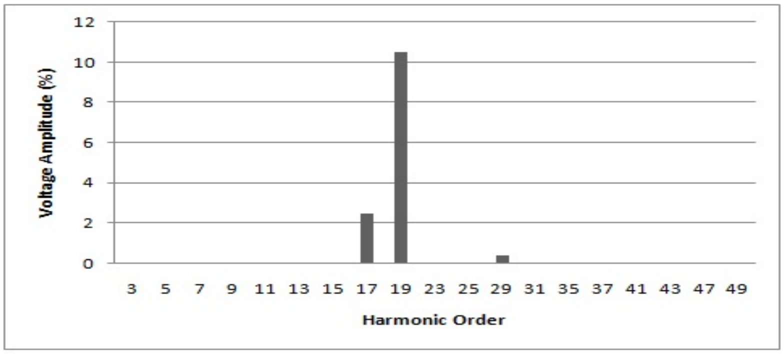

Figure 14. Amplitude Spectrum of Voltage Waveform at HV Side of T1 with HVDC

3.2.2. Voltage Waveform and Amplitude Spectrum at LV side of T1: Voltage waveform at the LV side of T1, in the presence of HVDC, is given in Figure 15 along with its amplitude spectrum in Figure 16. The system which was already frazzled by the presence of nonlinear loads goes beyond the IEEE standard limits as THD_v reaches a value of 9.91 % with IHD_v for 19^{th} harmonic being equal to 8.46 %.

3.2.3. Voltage Waveform and Amplitude Spectrum at Far End: The situation is further aggravated at the far end of the distribution system where THD_v attains a value equal to 10.13 % with 19^{th} harmonic being equal to 8.19 %. Both of these values are beyond the standard values. The voltage waveform is given in Figure 17 with its amplitude spectrum in Figure 18.

3.3. Discussion

The results show that the THD_v is increased in the power system due to the deployment of HVDC transmission. While the system experiences increased THD_v due to HVDC, the highest increase is observed in 19th harmonic which can be regarded to occur due to the resonance [26]. The harmonic resonance occurs due to the interaction of system impedances at a particular frequency [27].

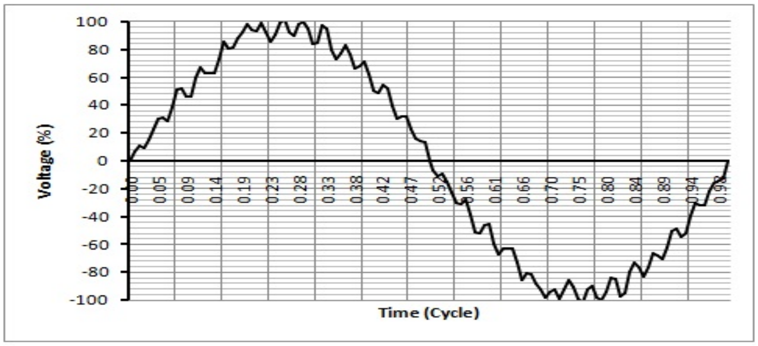

Figure 15. Voltage Waveform at LV Side of T1 with HVDC

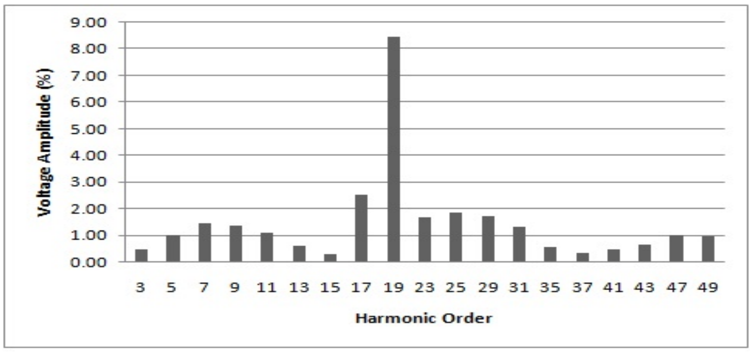

Figure 16. Amplitude Spectrum of Voltage Waveform at LV Side of T1 with HVDC

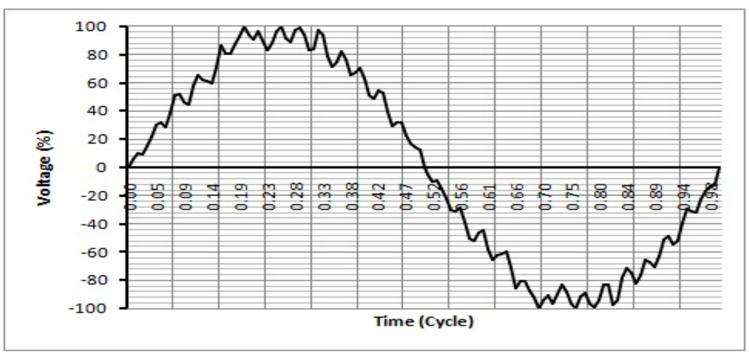

Figure 17. Voltage Waveform at Far End with HVDC

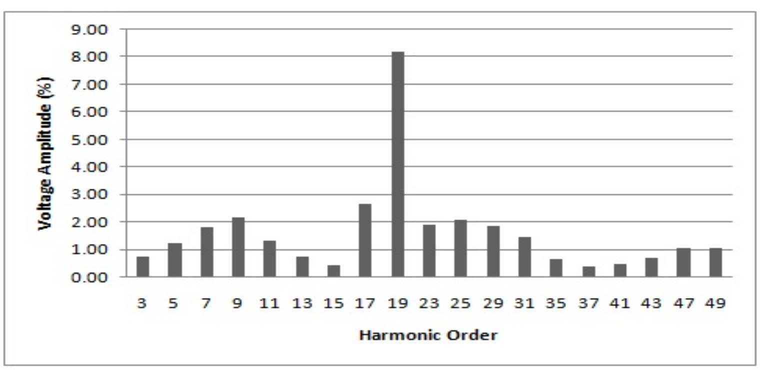

Figure 18. Amplitude Spectrum of Voltage Waveform at Far End with HVDC

4. Conclusions

The impact of harmonic distortion, caused by HVDC transmission, upon a distribution system loaded with various nonlinear loads is analyzed in this research paper. The harmonic model of an improved inverter design is deployed along with harmonic models of several residential nonlinear loads to complete the study. The results show that distribution systems are already marginally within acceptable standard limits and situation gets aggravated under the influence of harmonic distortion produced by the inverters in the HVDC converter station. The value of THD_v goes beyond the acceptable limits not only on the HV side but also on the LV side of the distribution transformer. The situation is even more critical for the users at the far end of the distribution system. The IHD_v for the 19^{th} harmonic increased substantially owing to resonance phenomenon. Considering this, PWM switching patterns should be carefully designed to avoid the resonance at any particular harmonic frequency. Sophisticated harmonic mitigation techniques must also be adapted before the mass scale influx of HVDC technology.

References

[1] Claudio De Capua and Emilia Romeo, A Smart THD Meter Performing an Original Uncertainty Evaluation Procedure, IEEE Trans. on Instrumentation and Measurement, 56 (2007) 1257 – 1264.

[2] Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, IEEE Std. 519-2014, (March 2014) 1 – 213.

[3] Rana A. Jabbar Khan and Muhammad Akmal, Mathematical Modelling of Current Harmonics Caused by Personal Computers, International Journal of Electrical and Information Engineering, 2 (2008) 336 – 340.

[4] R.B. Roy and M.R. Amin, Analysis of Proposed Controlling Topology of the HVDC Link Between Bangladesh and India, Proc. of 9th International Forum on Strategic Technology, Chittagong, Bangladesh, (2014) 390 – 395.

[5] Lee Wei Sheng, Ahmad Razani and Neelakantan Prabhakaran, Control of High Voltage Direct Current (HVDC) Bridges for Power Transmission Systems, Proc. Of IEEE Student Conf. on Research and Development, Putrajaya, Malaysia, (2010) 430 – 435.

[6] L. He, Chen-Ching Liu, A. Pitto and D. Cirio, Distance Protection of AC Grid with HVDC-Connected Offshore Wind Generators, IEEE Trans. on Power Delivery, 29 (2014) 493 – 501.

[7] H. Wang and M.A. Redfern, The Advantages and Disadvantages of Using HVDC to Interconnect AC Networks, Proc. of 45th International Universities Power Engineering Conf., Cardiff, UK, (2010) 1 – 5.

[8] L. Lou, Y. Li, K. Nakamura, G. Krost, J. Li, J. Xu and F. Liu, Harmonic Characteristics of New HVDC Transmission Systems Based on New Converter Transformer, Proc. of 3rd International Conf. on Electric Utility Deregulation and Restructuring and Power Technologies, Nanjing, China, (2008) 1868 – 1872.

[9] K.W. Louie, P. Wilson, R.W. Wachal, A. Wang and P. Buchanan, HVDC Power System Harmonic Analysis in the Time and Frequency Domains, Proc. of International Conf. on Power System Technology, Chongqing, China, (2006) 1 – 8.

[10] Rakan Kh. Antar, Basil M. Saied, Rafid A. Khalil and Ghanim A. Putrus, HVDC Link Power Quality Improvement using A Modified Active Power Filter, Proc. of 47th International Universities Power Engineering Conf., London, UK, (2012) 1 – 5.

[11] M.I. Abu Bakar, Assessments for the Impact of Harmonic Current Distortion of Nonlinear Load in Lower System Harmonics, Proc. of IEEE/PES Transmission and Distribution Conf. and Exposition: Latin America, Bogota, Colombia, (2008) 1 – 6.

[12] Mohamed H. Okba, Mohamed H. Saied, M. Z. Mostafa and T. M. Abdel- Moneim, Harmonics in HVDC Links, Part II - Effects and Reduction Techniques, Proc. of 38th Annual Conf. on IEEE Industrial Electronics Society, Montreal, QC, Canada, (2012) 1328 – 1336.

[13] V.K. Sharma, Moinuddin, M. N. Doja, I. Ibraheem and M.A. Khan, Power Quality Assessment and Harmonic Comparison of Typical Nonlinear Electronic Loads, Proc. of IEEE Int. Conf. on Industrial Technology, Goa, India, (2000) 729 – 734.

[14] Haroon Farooq, Chengke Zhou, Malcolm Allan, Mohamed Farrag, R. A. Khan and M. Junaid, Investigating the Power Quality of an Electrical Distribution System Stressed by Non-Linear Domestic Appliances, Renewable Energy and Power Quality Journal, 9 (2011).

[15] E. Miyata, S. Hishikawa, K. Matsumoto, M. Nakaoka, D. Bessyo, K. Yasoi, I. Hirota and H. Omori, Quasi-Resonant ZVS-PWM Inverter-Fed DC-DC Converter for Microwave Oven and its Input Harmonic Current Evaluations, The 25th Annual Conf. of IEEE Industrial Electronics Society, California, USA, (1999) 773 – 778.

[16] H. Farooq, C. Zhou and M.E. Farrag, Analyzing the Harmonic Distortion in a Distribution System Caused by the Non-Linear Residential Loads, International Journal of Smart Grid and Clean Energy, 2 (2013) 46 – 51.

[17] C. Guo and C. Zhao, Supply of an Entirely Passive AC Network Through a Double-Infeed HVDC System, IEEE Trans. on Power Electronics, 25 (2010), 2835 – 2841.

[18] F. Schettler, H. Huang and N. Christl, HVDC Transmission Systems Using Voltage Sourced Converters Design and Applications, Proc. of IEEE Power Engineering Society Summer Meeting, 2 (2000) 715 – 720.

[19] Mohamed H. Okba, Mohamed H. Saied, M. Z. Mostafa and T. M. Abdel- Moneim, Harmonics in HVDC Links, Part I – Sources, Proc. of 38th Annual Conf. on IEEE Industrial Electronics Society, Montreal, QC, Canada, (2012) 1320 – 1327.

[20] G. Ding, M. Ding and G. Tang, An Innovative Hybrid PWM Technology For VSC in Application of VSC-HVDC Transmission System, Proc. of IEEE Electric Power and Energy Conf., Canada, (2008) 1 – 8.

[21] R.K. Antar, B.M. Saied and R.A. Khalil, Using Seven-Level Cascade H-Bridge Inverter with HVDC System to Improve Power Quality, Proc. of 1st Int. Conf. for Engineering Sciences, (2012) 1 – 7.

[22] H. Farooq, C. Zhou, M.E. Farrag and M. Ejaz, Investigating the Impacts of Distributed Generation on an Electrical Distribution System Already Stressed by Non-Linear Domestic Loads, Proc. of Asia-Pacific Power and Energy Engineering Conf., Shanghai, China, (2012) 1 – 4.

[23] H. Farooq, K. Qian, M.E. Farrag, M. Allan and C. Zhou, Power Quality Analysis of Distribution Systems Incorporating High Penetration Level of EV Battery Chargers,

Proc. of 21st International Conf. and Exhibition on Electrical Distribution, Frankfurt, Germany, (2011).

[24] Department of Energy and Climate Change, Domestic Data Tables, National Statistics, UK, (Sep. 2014).

[25] D.P. Kothari and I.J. Nagrath, Electric Machines, 3rd edition. Tata McGraw-Hill, Delhi, (2006) 93.

[26] M. Cespedes and Sun Jian, Mitigation of Inverter-Grid Harmonic Resonance by Narrow-Band Damping, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2 (2014) 1024 – 1031.

[27] Esmaeil Ebrahimzadeh, Frede Blaabjerg, Xiongfei Wang and Claus Leth Bak, Efficient Approach for Harmonic Resonance Identification of Large Wind Power Plants, Proc. of IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems, Vancouver, BC, Canada, (2016), 1 – 7.