Harmonic Distortion of LCC-HVDC and VSC-HVDC Link in Eskom's Cahora Bassa HVDC Scheme

Oluwafemi E. Oni
Electrical Engineering Discipline
University of KwaZulu-Natal
Durban, 4001, South Africa
maxiphem@yahoo.com

Innocent E. Davidson
Department of Electric Power Engineering
Durban University of Technology
Durban 4001, South Africa
InnocentD@dut.ac.za

***Abstract*—Cahora Bassa, a thyristors based HVDC link transmits 1,920 MW of power from hydropower plant located in Zambezi river, north of Mozambique to Johannesburg, South Africa. This HVDC converter suffer few deficiency in its high level of harmonics distortion that transferred into its AC side of the transmission network couple with persistence rate of commutation failure. AC and DC filters with rugged controller are often used to minimize this effect but are limited in some aspect. Modern converter technology used for different HVDC links reduces harmonics content level, increases power transfer capabilities, enhances network stability and finally reduced the rate of commutation failure. This paper therefore investigate the level of harmonic distortion in line commutated converter used in Cahora Bassa link and thus proffer a suitable solution with the use of VSC-HVDC link. Current waveform characteristics and latest developments was also addressed. Simulation analysis was carried out using DigSILENT PowerFactory.**

Keywords*— *HVDC, line commutated converter, voltage sourse converter, Harmnic distortion

I. INTRODUCTION

Nowadays, quality of power supply is a major concern for any power utilities due to increase in industrial and residential activities. Inability to accurately classify different types of consumer loads threatens the quality of supplies of these power producer further. Most common disturbance can be voltage sag, short or long interruption, voltage spike, voltage swell, harmonic distortion, noise or voltage unbalance. All these have a negative impact on the quality of electric power supply to different consumers.

Non-linear loads are basically the cause of harmonics distortion. This loads, being voltage dependent generates a non-sinusoidal waveform because its impedances changes with applied voltage. Therefore, it draws a none-linear current. Semiconductor devices used for different converter circuits also contribute to high non-linear loads in a power system. Harmonic content in form of voltage distortion is mostly observed at the Point of Common Coupling (PCC) of the converter circuits. Ideally, High Voltage Direct Current (HVDC) system with pulse 'p' converter circuits will generates ±np+1 characteristic harmonic current order on the AC side and ±np on the DC side. Though, uncharacteristic harmonics current order are also present due to converter imperfection and unbalanced AC system voltage. Lower frequencies harmonics order must be totally minimized in power systems because they tends to interfere with the system fundamental frequency. They are the major reason for high transmission losses, increased thermal stress to converter valve, radio interference due to noise, and oftentimes lead to system failure. AC and DC filters are always used to minimize the effect of different harmonics distortion [1, 2].

The strategic placement of thyristors based HVDC system on Eskom network for stability enhancement was discussed in [3]. HVDC systems harmonics are well reviewed in the literature. The causes, interaction with weak AC system, means of mitigation and filters analysis are well discussed in [4-11].

II. HVDC HAMONICS ANALYSIS

Harmonic current in Line Commutated Converter (LCC) HVDC based scheme can best be analyzed using impedance model. AC characteristics is given by (1, 2) while (3–5) analyzes the DC harmonics characteristic [12].

$$I_{h0} = \frac{I_{10}}{h} \tag{1}$$

$$I_{10} = \frac{2\sqrt{6}}{\pi} I_d \tag{2}$$

$$V_h = \frac{V_{d0}\left[C^2 + D^2 - 2CD\cos(2\alpha + \mu)\right]^{1/2}}{\sqrt{2}} \tag{3}$$

$$C = \frac{\cos[h+1]\mu/2}{h+1} \tag{4}$$

$$C = \frac{\cos[h-1]\mu/2}{h-1} \tag{5}$$

For VSC-HVDC, after performing Fourier transform on two-level converter switching waveform commutating at fundamental frequency, the total harmonic voltage transferred

978-1-5090-3388-1/16/$31.00 ©2016 IEEE

from DC side to AC side when a DC voltage harmonics is introduced at $\omega = 2\pi f$ was given by (6). This condition holds only if ($\omega > \omega_1$). Also for $\omega - \omega_1$ <0, it implicates a negative phase sequence component while $\omega + \omega_1$ >0 gives a positive phase sequence component [13].

$$U_v(t) = \frac{2U_{dc0}}{\pi} e^{j(w_1 t-\delta)} + \frac{U_{dch}}{\pi} e^{j((w_1+w)t-\delta)} + \frac{U_{dch}}{\pi} e^{j((w_1-w)t-\delta)} \tag{6}$$

III. CAHORA BASSA HVDC SCHEME

Cahora Bassa HVDC link is a thyristor based converter technology. It transmits 1,920 MW of power from hydropower plant located in Zambezi River, north of Mozambique to Johannesburg, South Africa. The rectifier station, located at Songo station of Mozambique is connected to the inverter station located at Apollo station using a 1414km, ±533kV bipolar lines. 64.2% of the transmission length is located in Mozambican territory while the remaining 35.8% resides in South Africa. An approximate of 7,000 towers span averagely over 426 meters of the transmission network. Reinforced towers with earth return are provided using buried graphite electrodes located at considerable distance from the converter station. Smoothing reactors and surge arrester and capacitors bank are provided at each of the converter station so as to have a stable system. The inverter side of this scheme was refurbished in 2008, equipping it with 5'' electrically triggered thyristor valve capable of withstanding 3.3KA, 8.5 kV switching capacity [14]. Fig. 1 show the detailed diagram of Cahora Bassa HVDC link as modeled on DigSILENT. This diagram shows the hydro-power plant, low-frequency/high-frequency filter and capacitor bank in Songo rectifier station. Inverter station located at Apollo has the equivalent load (external grid) and different compensating devices attached to its substation.

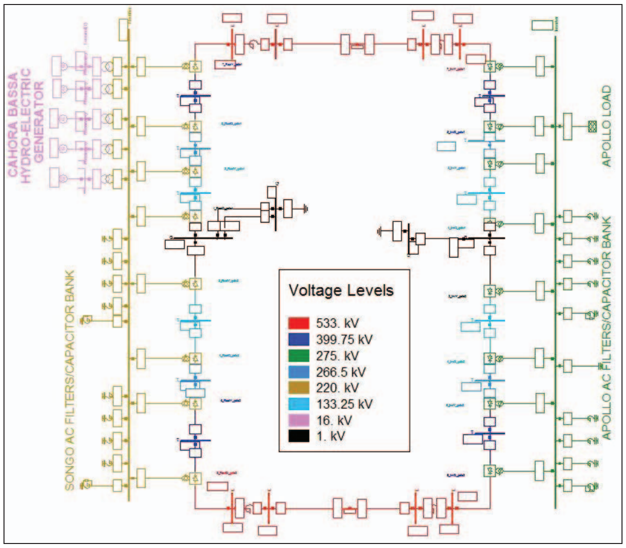

Fig. 1. Detailed network diagram of Cahora Bassa HVDC scheme

IV. PERFORMANCE ANALYSIS

The performance analysis used for Cahora Bassa is to analyze the harmonics and voltage distortion during a three phase short circuit fault. Inverter side fault will be consider in this analysis because it has more impact on the HVDC link than rectifier station fault. This inverter fault increase the rate commutation failure occurrence at inverter station. Thus, a three-phase short circuits with zero fault reactance was applied at the inverter AC busbar for t=200ms, using electromagnetic EMT simulation tool which was ran for 1.00 seconds simulation time. The busbar voltage and converter current were represented in a graph.

Fig. 2 present AC busbar voltage of both converter station during AC system fault. The rectifier (Songo) station witness reduction in voltage during the fault, while the inverter (Apollo) station experienced long interruption due to a fault. Converter AC current rise in Fig. 2 while inverter station suffers commutation failure. Effective controller aid HVDC scheme during system fault. This graph was then zoomed (0.03s – 0.28s) to investigate different harmonics/distortion on the waveform of the converter current and busbar voltage. It could be observed that, though the system regains its normal operating condition after successful clearing of the fault but the AC voltage waveform which was expected to be perfect sinusoidal form has few distortion as seen in Fig. 4. Furthermore, the current waveform of an LCC HVDC is more or less like a trapezoid form rather than a perfect sinusoidal shape couple with commutation failure at the inverter side. This can be seen in Fig. 5.

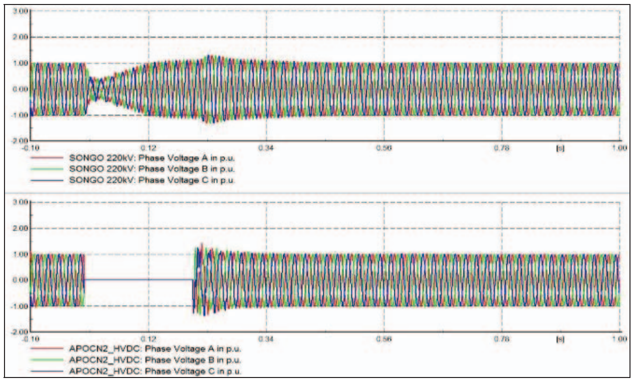

Fig. 2. AC busbar voltage of LCC-HVDC

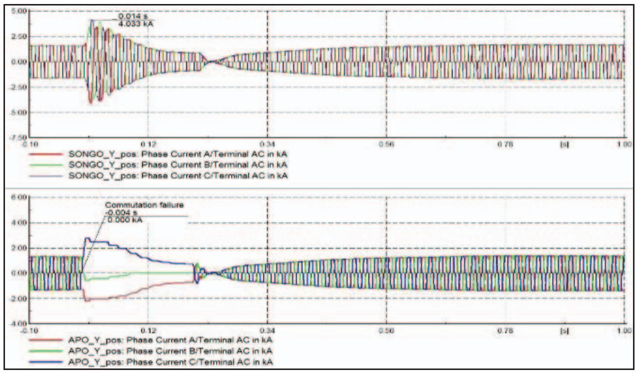

Fig. 3. LCC-HVDC converter current

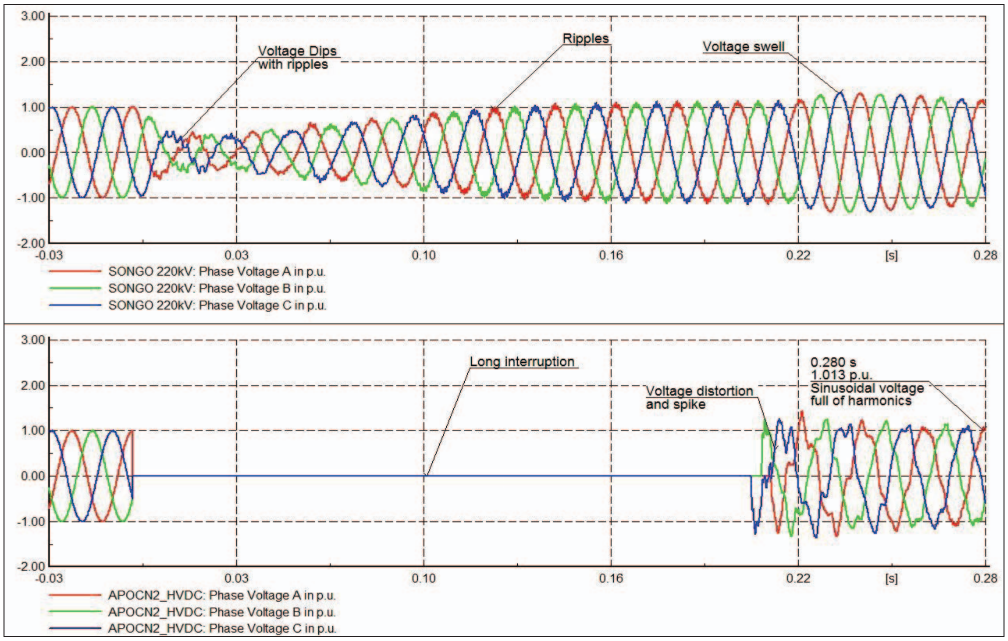

Fig. 4. Zoomed LCC voltage waveform between -0.03 to 0.28 simulation time

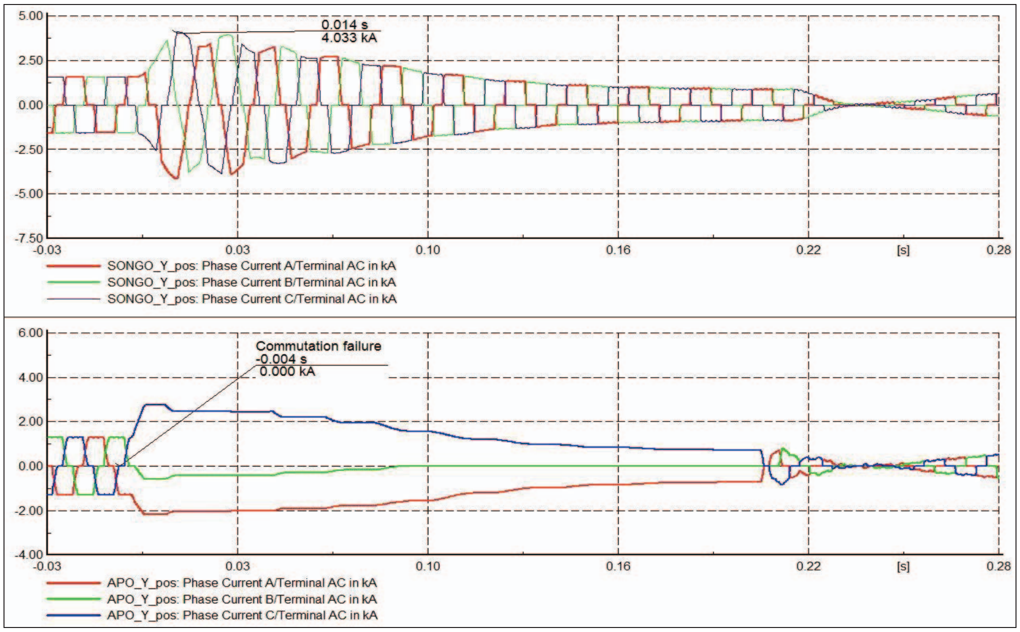

Fig. 5. Zoomed LCC converter current between -0.03 to 0.28 simulation time

V. RE-ENGINEERING USING VSC-HVDC

Voltage Source Converter (VSC), shown in Fig. 6, uses Insulated Gate Bipolar Transistor (IGBT) technology. It creates its own AC voltages in case of black start thus helping the current be switched on and off at any time independent of the AC voltage. Its converters operate at a high frequency with pulse width modulation PWM which allows simultaneous adjustment of the amplitude and phase angle of converter while keeping the voltage constant. It has a high degree of flexibility with an inbuilt capability to control both its active and reactive power, which makes it more useful in urban power network area [15]. Most new VSC-HVDC technology converter stations uses multi-level converter circuits [16, 17] as shown in Fig. 7. It was proposed in 2003, at the University of Bundeswehr in Munich, Germany, by Prof. Rainer Marquardt [18]. Recent VSC HVDC installation can been seen on Table 1.

Independent control of power at each converter is possible, with one converter controlling the DC voltage at the link to match the nominal level and the other converter sets the amount of active power through the link. With the help of the phase reactor from the series inductance between the converter and the AC grid, active and reactive power control was achieved as depict in (7) and (8) [19].

$$P = \frac{U_{ac} U_{conv} \sin\delta}{X} \tag{7}$$

$$Q = \frac{U_{conv}(U_{conv} - U_{ac} \sin\delta)}{X} \tag{8}$$

X-represent the series reactance of the phase reactor and the transformer in the converter station.

APPLICATION OF VSC-HVDC

Project Name	Location	Characteristics			
		(KV)	*Year*	*(MW)*	*(Km)*
Borwin 1	Germany	±150	2009	400	200
Caprivi link	Namibia	±350	2010	300	951
Transbay	USA	±200	2010	400	85
EWIC	UK	±200	2012	500	261
Inelfe	France	±320	2013	1000	65
Skagerrak 4	Norway	±500	2014	700	244

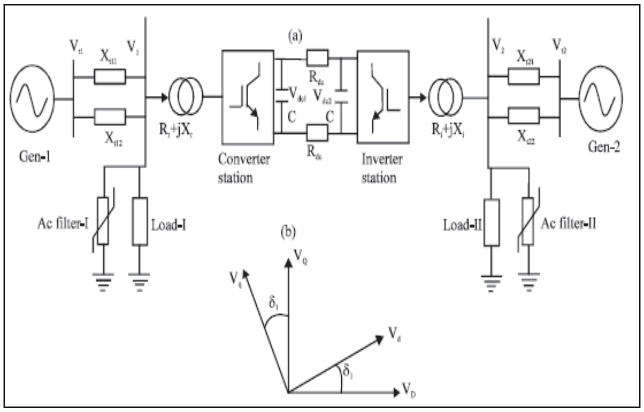

Fig. 6. VSC-HVDC scheme design

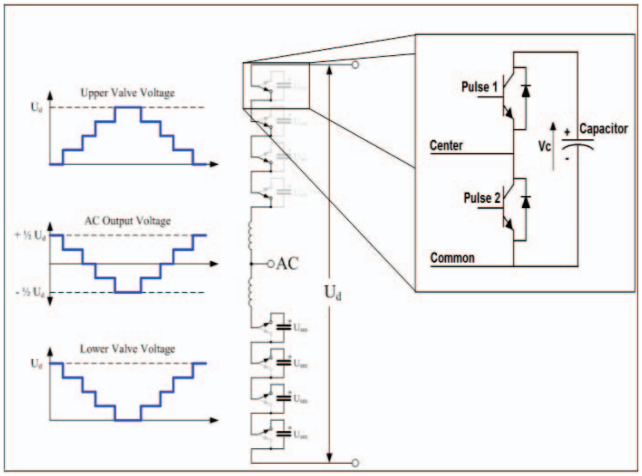

Fig. 7. Modular multilevel converter topology

Cahora Bassa LCC-HVDC scheme is mostly responsible for instabilities in Eskom EHV network due to in-part aging and infrastructure. Therefore, the need for proper effectiveness and good power controllability with enhanced systems stability requires a re-engineering of Cahora Bassa HVDC scheme with the use of ±500kV, 1500MW VSC-HVDC on DigSILENT PowerFactory according to Fig. 8. Three-phase short circuits fault was also applied at AC busbar of the inverter station and cleared at t=200ms. This is to compare the effect of fault analyzed during LCC-HVDC to VSC-HVDC system by looking into the harmonics/distortion generated after fault and also to look into how perfect the waveforms during and after fault condition.

Fig. 9 show Songo and Apollo busbars voltages which were zoomed in Fig. 11 between -0.03- 0.28 seconds simulation time. Unlike the LCC-HVDC, the Apollo voltage waveform suffer no reduction in bus voltage during a fault, as it can be seen that it maintained an amplitude ±1.00p.u peak to peak voltage. The long interruption occurred at Apollo station during fault condition but the retained back its perfect ±1.00p.u peak to peak sinusoid voltage waveform after a fault. The conclusion can thus be reached that VSC provides more stability enhancement to AC system than conventional LCC counterpart. One of the major reason for this stability enhancement is due to the fast frequency at which VSC HVDC switches during converter operation which LCC can not achieve. However, high rate of this switching of frequency resorted in more power loss and heat generation although, modern VSC circuit overrides this challenges. Therefore, with the increase in technological advancement of different VSC converter circuits, more ground breaking solutions will be proffer for high power transmission with reduced transmission losses.

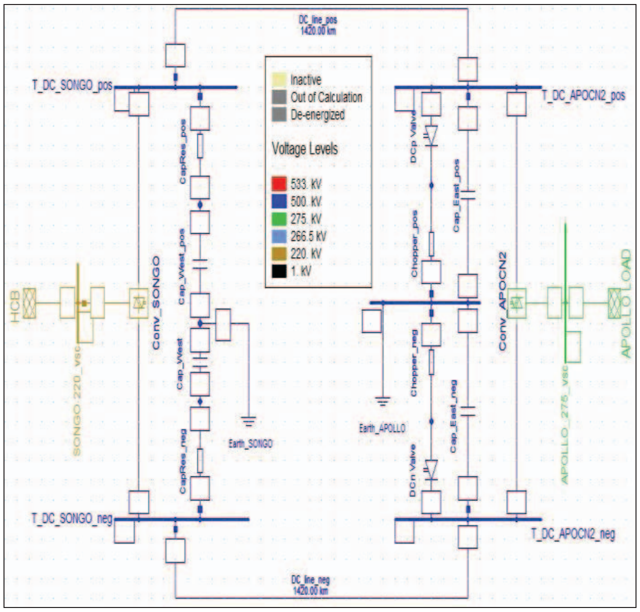

Fig. 8. VSC-HVDC model for new Cahora Bassa network

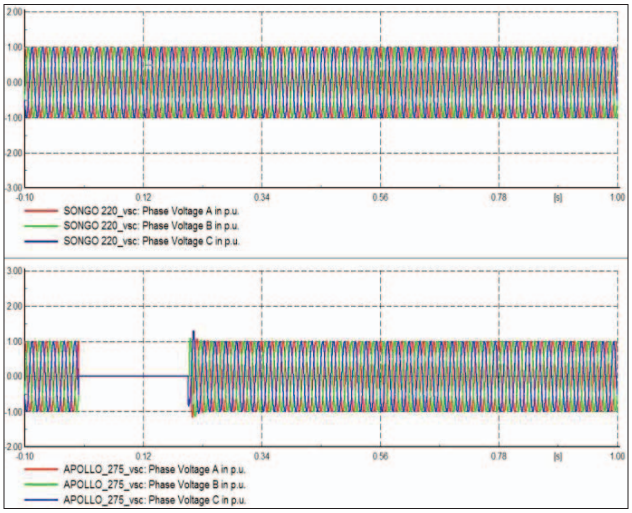

Fig. 9. AC busbar voltage of VSC-HVDC

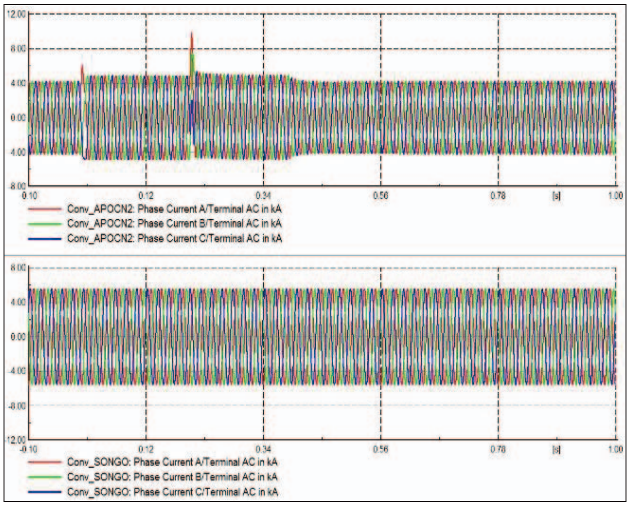

Fig. 10. VSC-HVDC converter current

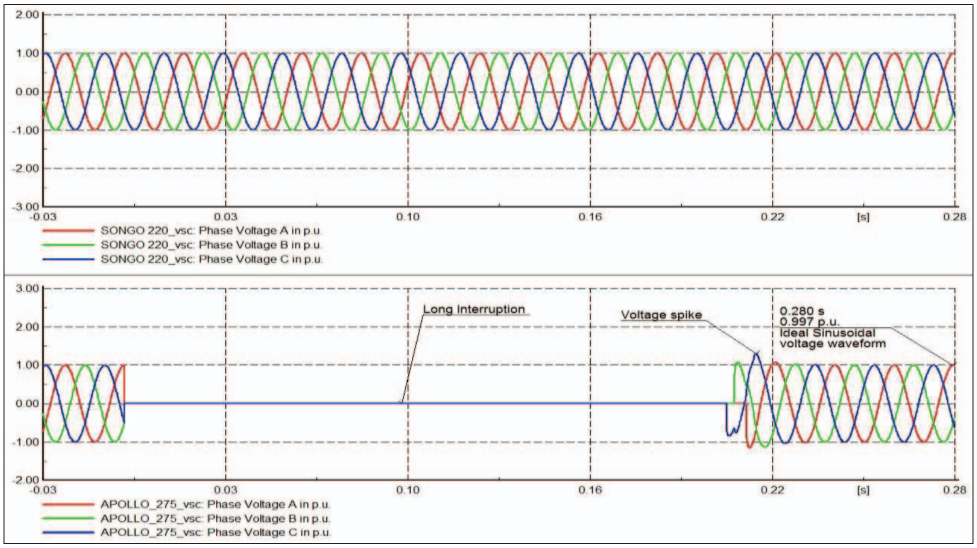

Fig. 11. Zoomed VSC busbar voltage between -0.03 to 0.28 simulation time

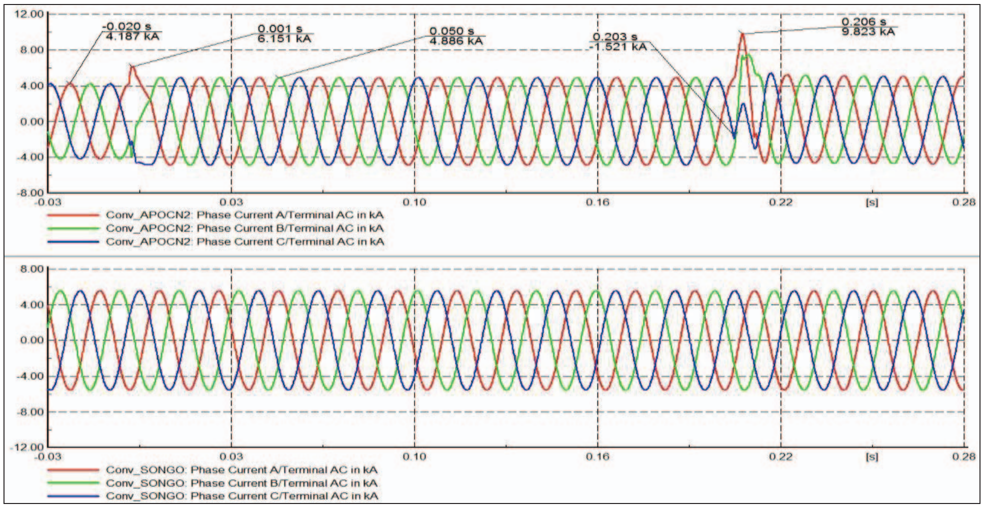

Fig. 12. Zoomed VSC converter current between -0.03 to 0.28 simulation time

VI. CONCLUSION

This study carried out harmonic and distortion analysis on ±533kV Cahora Bassa HVDC scheme, this was to investigate few limitations of LCC-HVDC with regards to harmonic distortion, imperfect current waveform, and frequent occurrence of commutation failure at the inverter side of the converter station. A better means of power transfer with enhanced system stability couple with a perfect sinusoidal waveform was suggested with the use of VSC-HVDC technology.

REFERENCES

[1] S. Luo, X. Dong, S. Shi, and B. Wang, "A Directional Protection Scheme for HVDC Transmission Lines Based on Reactive Energy," IEEE Transactions on Power Delivery, vol. 31, pp. 559-567, 2016.

[2] V. Anuradha, S. Anitha, D.C. Apoorva, N. Priyanka, and B. Somashekar, "Harmonic Analysis in HVDC System," International Journal of Emerging Technology and Advanced Engineering, vol. 4, 2014.

[3] K. N. I. Mbangula, I. E. Davidson, and R. Tiako, "Improving Power System Stability of South Africa's HVAC Network Using Strategic Placement of HVDC Links," CIGRE Science & Engineering Journal (CSE), vol. 5, pp. 71-78, 2016.

[4] W. Kang, H. MinXiao, and W. Jun, "Research on Harmonic Characteristics of UHVDC," in Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific, 2011, pp. 1-4.

[5] J. Das, Power system harmonics and passive filter designs: John Wiley & Sons, 2015.

[6] M. Sreedhar, A. Dasgupta, and S. Mishra, "New harmonic mitigation scheme for modular multilevel converter–an experimental approach," IET Power Electronics, vol. 7, pp. 3090-3100, 2014.

[7] N. Shore, G. Andersson, A. Canelhas, and G. Asplund, "A three-pulse model of DC side harmonic flow in HVDC systems," IEEE Transactions on Power Delivery, vol. 4, pp. 1945-1954, 1989.

[8] M. Rastogi, N. Mohan, and A.-A. Edris, "Hybrid-active filtering of harmonic currents in power systems," IEEE Transactions on Power Delivery, vol. 10, pp. 1994-2000, 1995.

[9] B. Liu, Z. Du, and C. Li, "Harmonic power flow of VSC-HVDC based AC/DC power systems," Electric Power Systems Research, vol. 133, pp. 355-364, 2016.

[10] L. Hu and R. Yacamini, "Harmonic transfer through converters and HVDC links," IEEE Transactions on power electronics, vol. 7, pp. 514-525, 1992.

[11] W. Chen, L. Huang, C. Hong, Y. Zhang, L. Lin, and Q. Zhong, "Analysis of Reactive Power Exchanging between Converter Station from YunGuang ±800Kv UHVDC Projection," in Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, 2010, pp. 1-4.

[12] D. Edison Selvaraj, K.S. Gouthama Priyan, Firoz Alam, Vinay Kumar Singh, A. Syed Mohamed Meeran, C. Pugazhendhi Sugumaran, et al., "A Short note on Harmonics and Filters in HVDC systems," Journal Club for Electrical Engineering, vol. 1, 2014.

[13] E. Krige, "Harmonic Interaction between weak AC systems and VSC-based HVDC schemes," Master of Science, Electrical Engineering, University of Stellenbosch, 2012.

[14] P. Goosen, C. Reddy, B. Jonsson, T. Holmgren, O. Saksvik, and H. Bjorklund, "Upgrade of the Apollo HVDC Converter Station," presented at the 6th Southern Africa Regional Conference, Cape town, South Africa, 2009.

[15] K. N. I. Mbangula, O. E. Oni, and I. E. Davidson, "The Impact of HVDC Schemes on Network Transient Rotor Angle Stability,," presented at the 24th Southern African Universities Power Engineering Conference, South Africa, 2016.

[16] G. P. Adam, S. Finney, B. Williams, I.E. Davidson, and A. Y. M. Abbas, "Full-bridge Modular Multilevel Converter (FB-MMC) with Extended Control Range," in 12th IEEE Region 8 (Africon) International Conference, Addis Ababa, Ethiopia, 2015, pp. 833-837.

[17] G. P. Adam and I. E. Davidson, "Robust and Generic Control of Full-Bridge Modular Multilevel Converter High-Voltage DC Transmission Systems," IEEE Transactions on Power Delivery, vol. 30, pp. 2468-2476, 2015.

[18] M. Glinka and R. Marquardt, "A new AC/AC multilevel converter family," IEEE Transactions on Industrial Electronics, vol. 52, pp. 662-669, 2005.

[19] O. E. Oni, K. N. Mbangula, and I. E. Davidson, "A Review of LCC-HVDC and VSC-HVDC Technologies and Applications," presented at the 16th IEEE international Conference on Environment and Electrical Engineering, Florence, Italy, 2016.