Performance and Cost Comparison of NPC, FC and SCHB Multilevel Converter Topologies for High-Voltage Applications

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Abstract — The rapid increase in global energy consumption and the impact of greenhouse gas emissions have accelerated the renewable energy technology into a more competitive area. Due to the variable nature of renewable energy resources and power demand by the consumers, grid based renewable generation has gained significant popularity in the world. High-voltage converter can interconnect the renewable systems to the grid directly without introducing a lossy, costly and bulky transformer. Three popular multilevel converter topologies: Neutral Point Clamped (NPC), Flying Capacitor (FC) and Series Connected H-Bridge (SCHB) have successfully made their way into the industry and therefore can be considered a mature and proven technology for low and medium voltage applications. But most of them are not suitable for high-voltage applications. This paper presents the comparison of a Five-Level (5L)-NPC, a 5L-FC, a 5L-SCHB, an Eleven-Level (11L)-NPC, an 11L-FC and an 11L-SCHB topologies for an 11 kV Voltage Source Converter (VSC). The comparison is made in terms of number of semiconductors, semiconductor cost, Total Harmonic Distortion (THD), filter size and control complexity.

Keywords— Multilevel converter topologies, high-voltage applications, grid based renewable systems.

I. Introduction

The global energy consumption has been continually increasing day by day. According to the latest report of International Energy Agency (IEA) the global energy demand growth will add 36% in the period between 2008 and 2035, an average of 1.2% per year. The yearly global growth of primary energy (mainly oil, coal and natural gas) consumption is shown in Fig. 1 [1]. This continual growth of fossil fuels consumption is accelerating the growth of CO_2 emissions and reduction of natural resources in the world. Global CO_2 emissions represented a growth rate of 1.5% per year. The yearly global growth of CO_2 emissions is shown in Fig. 2 [2]. Increased CO_2 emission is one of the primary factors to raise the earth's temperature (global warming).

In order to solve the global energy crisis and global warming, renewable energy has attracted people's attention and has been widely studied. The solar and wind are main renewable energy sources for the future energy needs. The global renewable energy achievement rate from these two sources is also high. Solar Photovoltic (PV) generates electricity in well over 100 countries and continues to be the fastest growing renewable source in the world. Between 2004 and 2009, grid connected PV capacity increased at an annual average rate of 60% and over this five year period, annual growth rates for cumulative wind power capacity averaged 27%. The capacity installed in 2009 is equivalent to nearly a quarter of total global installations, and cumulative capacity has doubled in less than three years. The global wind and solar PV power installed capacity is shown in Table I [3], [4].

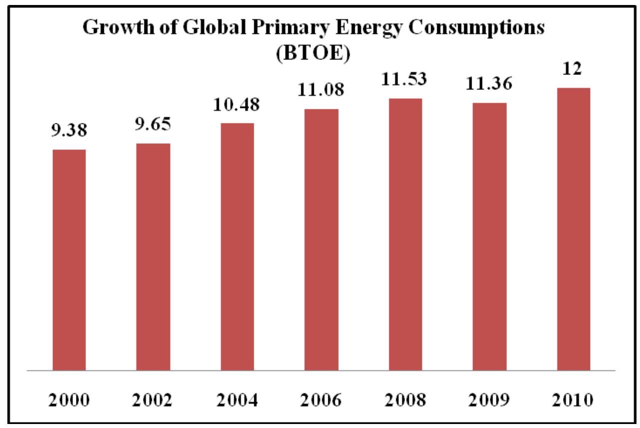

Fig. 1. Global yearly growth of primary energy consumptions in Billion Tonnes of Oil Equivalent (BTOE).

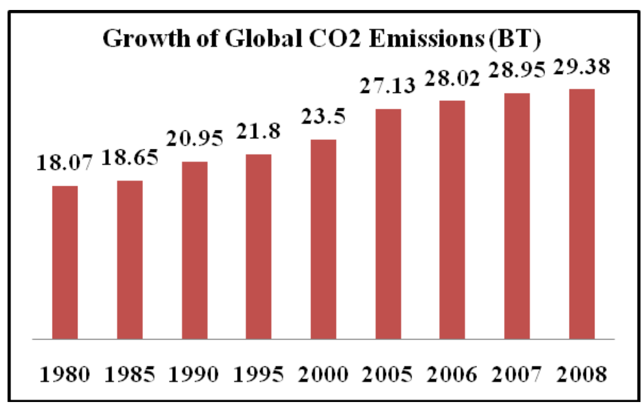

Fig. 2. Global yearly growth of CO_2 emissions in Billion Tonnes (BT).

But the availability of renewable energy sources has strong daily and seasonal patterns and the power demand by the consumers could have a very different characteristic. So, it is difficult to operate a power system installed with only one type of renewable energy resource. The grid based renewable generation may be the only solution to overcome this problem but for connecting these systems to power grids it is required to adjust the output voltage and the frequency to the grid level. Different power electronic converters have been developed using conventional topologies to fulfill the requirements of renewable generations [5]. All of them contain magnetic components e.g. transformer to step up the system voltage at grid level, which not only increases the size, weight and loss but also increase the cost and complexity of the system operation. To reduce the size and weight of the power transformer different topologies in literature have been presented [6], [7]. All of the topologies are based on high frequency link. The high frequency link based power electronic transformer also contains a high frequency transformer, whose insulation and the high voltage and high frequency operation of power switches are challenging issues. Moreover the system loss also increases.

TABLE I
GLOBAL WIND AND SOLAR INSTALLED CAPACITY

Year	Wind (MW)		PV (MW)	
	Annual	Cumulative	Annual	Cumulative
2000	3760	17400	278	1428
2001	6500	23900	334	1762
2002	7270	31100	477	2236
2003	8133	39431	583	2818
2004	8207	47620	1122	3939
2005	11531	59091	1422	5361
2006	15245	74052	1596	6956
2007	19866	93820	2594	9550
2008	26560	120291	6090	15675
2009	38793	158908	7203	22878

In terms of semiconductor technology development, a continuous race to develop higher-voltage and higher-current power semiconductors for utilization in high power systems still goes on. Many recent generations of devices are suitable for medium voltage applications while high voltage semiconductors are still under development [8]. The price of power semiconductor devices increases rapidly with their voltage ratings as shown in Table II [9], [10]. The series-parallel connection of lower rated semiconductors is a cost effective solution for high voltage applications. Maybe only multilevel converter topology have the simple way to connect the semiconductor devices in series. There are three popular topologies in multilevel converter: Neutral Point Clamped (NPC), Flying Capacitor (FC) and Series Connected H-Bridge (SCHB) [11], [12]. In recent years they have acquired much attraction in low and medium-voltage applications with the mature semiconductor technology due to a number of special features like low harmonic distortion of the AC currents, low switching losses, less blocking voltage of the switching device. But the selection of multilevel converter topology is very critical for high-voltage applications because the component numbers of NPC and FC converters scale quadratically with the number of levels. Also the voltage balancing becomes a significant problem for high level numbers [13]. On the other hand the component numbers of the SCHB converters scale linearly with the numbers of levels. Many publications have addressed the limitation of the SCHB converter since the requirements of multiple-isolated DC sources, and therefore its application is not straightforward [14].

In order to stabilize the operation of the system, harmonic control is also important. To implement harmonic control it is essential to use a filter coil, which also increases the system complexity and cost. The output voltage of the converter could be improved by increasing the level numbers of the converter as shown in Table III. This may reduce the size of the input and output filter requirements.

Therefore, mature semiconductor based high level multilevel converter allows the possibility of direct converter connection to the medium or high voltage line. This not only minimizes the size of the output filter but also eliminates bulky, lossy and costly power transformers from the system.

TABLE II
PRICE OF IGBTS

Voltage (kV)	Current (kA)	Brand	Price (AU$)
0.6	0.4	Powerex	157.91
	0.3	Powerex	118.28
1.2	3.6	Eupec	2072.31
	2.4	Eupec	1582.39
	1.4	Infineon	1100.02
	0.6	Powerex	414.51
	0.4	Powerex	200.44
	0.3	Powerex	207.28
	0.2	Eupec	151.64
1.7	3.6	Eupec	2624.48
	2.4	Eupec	2017.17
	1.2	Eupec	1106.11
	0.6	Infineon	425.00
	0.45	Eupec	339.60
	0.3	Eupec	238.36
	0.225	Eupec	195.21
	0.15	Semikron	168.00
3.3	1.5	Eupec	3007.82
	1.2	Eupec	2431.88
	0.4	Eupec	1369.31
6.5	0.6	Eupec	3997.60
	0.4	Eupec	3078.18
	0.2	Eupec	1918.98

TABLE III
HARMONICS COMPARISON OF THE CONVERTERS

Level	2L	3L	5L	11L
THD (%)	107	42	17.26	7.07

The main aim of this work is to find out a suitable converter topology, which can interconnect the renewable energy systems to the local grid directly by using mature semiconductor technology. This paper compares different types of multilevel converters topologies for an 11kV, 4.76 MVA Voltage Source Converter (VSC). Both theoretical and simulation results are used to determine the ratings of power components and their availability is also considered. The performance and complexity are analyzed and compared among all multilevel converter topologies. The cost of power semiconductors and passive components is calculated and compared.

II. DESIGN AND SPECIFICATION

Fig. 3 shows the basic block diagrams for multilevel converter topologies. The operating conditions and basic converter data are shown in Table IV. The minimum DC-link voltage necessary to achieve an output line to line voltage of 11 kV can be calculated from

$$V_{dc(\min)} = \sqrt{2} \times V_{ll(rms)} \tag{1}$$

To determine the nominal DC link voltage of the converter, a voltage reserve of 4 % is assumed [15], i.e.

$$V_{dc(nom)} = 1.04 \times V_{dc,\min}$$
$$= 1.04 \times 15556.4 \text{ V} = 16.179 \text{ kV} \quad (2)$$

The apparent converter output power can be calculated using:

$$S_c = \sqrt{3} \times V_{ll(rms)} \times I_{p(rms)}$$
$$= \sqrt{3} \times 11 \text{ kV} \times 250 \text{ A} = 4.76 \text{ MVA} \quad (3)$$

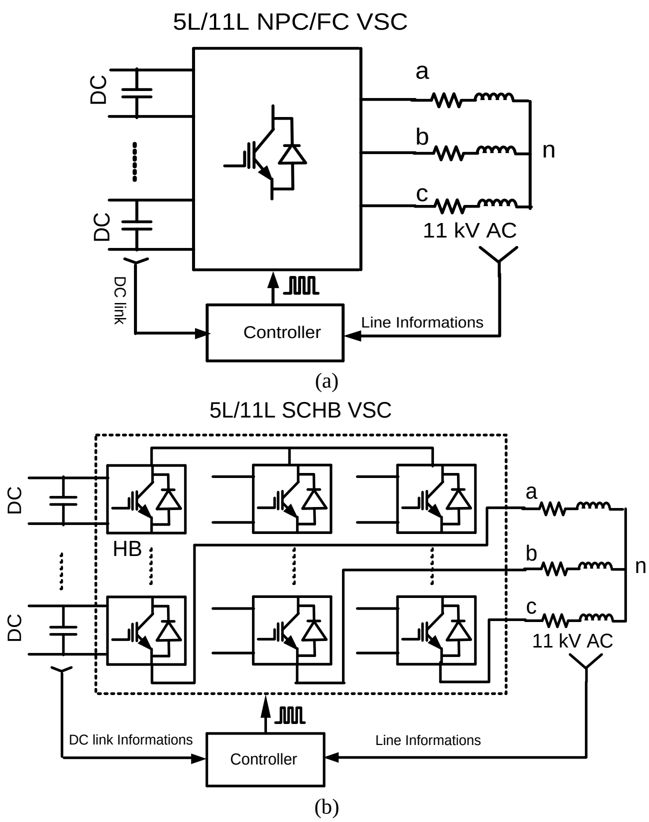

Fig. 3. Basic block diagram (power section only) of: (a) 5L/11L NPC/FC VSC (b) 5L/11L SCHB VSC.

The DC link voltage needs to be considered when selecting IGBTs and diodes voltage ratings; and cosmic ray effects assessment may also be necessary. In addition to the output capacity and voltage ratings of the converter, the availability of IGBT and diode modules in the market needs to be considered in design process. Two 4.5 kV series-connected IGBTs are assumed as a single switch for all the Five Level (5L) converter topologies. Table V summarizes the design of the power semiconductors for the converter specification in Table IV, with a carrier frequency of 1-2 kHz. To enable a converter output phase current of 250 A, a 400 A rated semiconductor is chosen for 5L and 360 A rated semiconductor is chosen for Eleven Level (11L) converters.

Different modulation schemes have been adapted or developed depending on the application and the converter topology, and each has its unique advantages and disadvantages. The most common modulation method in industry is carrier-based sine-triangle modulation. The Level Shifted-Sine Pulse Width Modulation (LS-SPWM) method is especially useful for NPC converters, since each carrier can be easily associated to two power switches of the converter and the Phase Shifted-Sine Pulse Width Modulation (PS-SPWM) method is especially useful for FC and SCHB converters [16]. Fig. 4 shows LS-SPWM scheme and PS-SPWM scheme for 5L converter and the modulation scheme for 11L converter is shown in Fig. 5. In this paper an LS-SPWM scheme is used for NPC topologies and a PS-SPWM scheme is used for FC and SCHB topologies to compare the converter performances.

TABLE IV
BASIC CONVERTER DATA

Technical Data	Abbreviations	Value
Converter line-to-line voltage	$V_{ll(rms)}$	11 kV
Minimum DC-link voltage	$V_{dc(\min)}$	15556 V
Nominal DC-link voltage	$V_{dc(nom)}$	16179 V
Phase current	$I_{p(rms)}$	250 A
Apparent converter output power	S_c	4.76 MVA
Converter carrier frequency	f_c	1-2 kHz
Output frequency	f_o	50 Hz

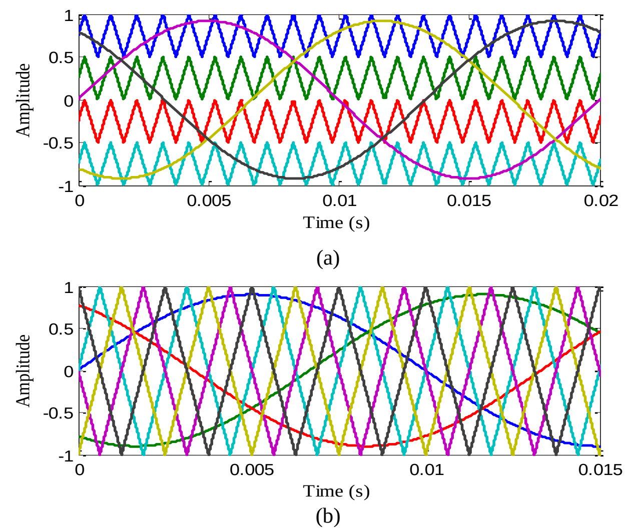

Fig. 4. Modulation scheme for 5L multilevel VSC: (a) LS-SPWM (b) PS-SPWM

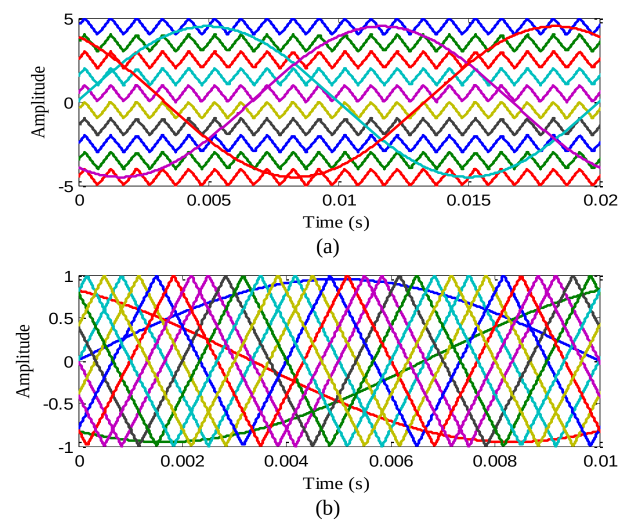

Fig. 5. Modulation scheme for 11L multilevel VSC: (a) LS-SPWM (b) PS-SPWM

TABLE V
POWER SEMICONDUCTOR RATING

	5L-NPC	5L-FC	5L-SCHB	11L-NPC	11L-FC	11L-SCHB
$V_{dc(nom)}$	16179 V	16179 V	16179 V	16179 V	16179 V	16179 V
Rated device voltage (IGBT)	2×4.5 kV	2×4.5 kV	2×4.5 kV	3.3 kV	3.3 kV	3.3 kV
Commutation voltage of respective commutation cells , V_{com}	2022 V	2022 V	2022 V	1618 V	1618 V	1618 V
The device commutation voltage for a device reliability of 100FIT due to cosmic radiation, $V_{com@100FIT}$	2×2250 V	2×2250 V	2×2250 V	1800 V	1800 V	1800 V
Device voltage utilization factor, $V_{com}/V_{com@100FIT}$	0.90	0.90	0.90	0.90	0.90	0.90

III. SIMULATION RESULTS

The performance is analyzed and compared in Matlab/Simulink environment. To generate switching pulses an LS-SPWM scheme is used for NPC topologies and a PS-SPWM scheme is used for FC and SCHB topologies with a carrier frequency of 1 to 2 kHz and modulation index of 0.8 to 0.9. 5L converter output line voltages are shown in Fig. 6 to Fig. 8 and 11L converter output line voltages are shown in Fig. 9 to Fig. 11 where V_o is the converter output voltage and R_e is the reference sine function. In order to measure the harmonic content of the output current and the harmonic losses in the load the harmonic spectrum of the line voltage is evaluated. The harmonic spectrums of 5L converters are shown in Fig. 12 to Fig. 14 and those for 11L converters are shown in Fig. 15 to Fig. 17.

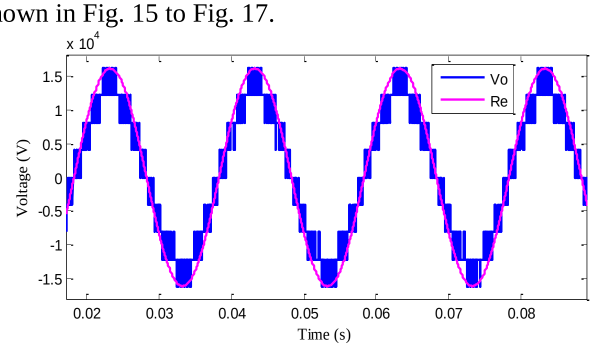

Fig. 6. Line voltage of 5L-NPC VSC.

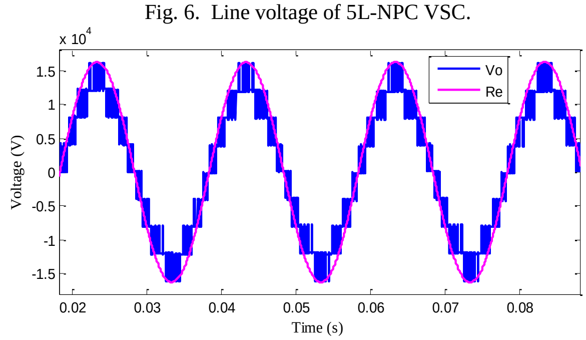

Fig. 7. Line voltage of 5L-FC VSC.

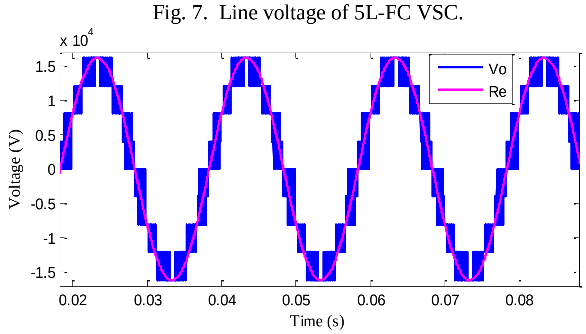

Fig. 8. Line voltage of 5L-SCHB VSC.

The output voltage wave shape of 5L-NPC converter much more coincides with the reference sine wave as compared with other 5L converters output. All 11L converters output voltage wave shapes are very close to reference sine wave while NPC converter performance is better than others. Moreover from the output Figures it is clear that increasing the level numbers means improving the converter performance.

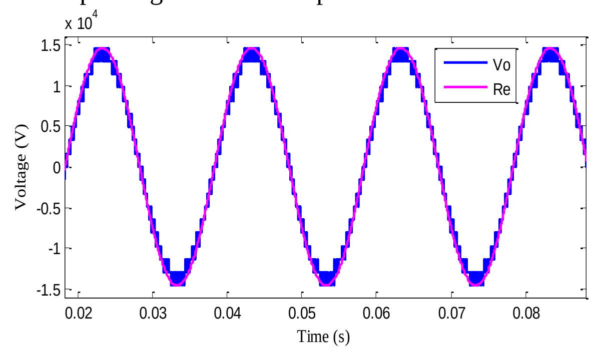

Fig. 9. Line voltage of 11L-NPC VSC.

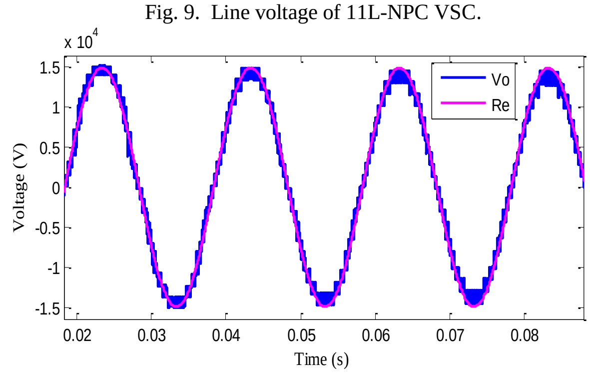

Fig. 10. Line voltage of 11L-FC VSC.

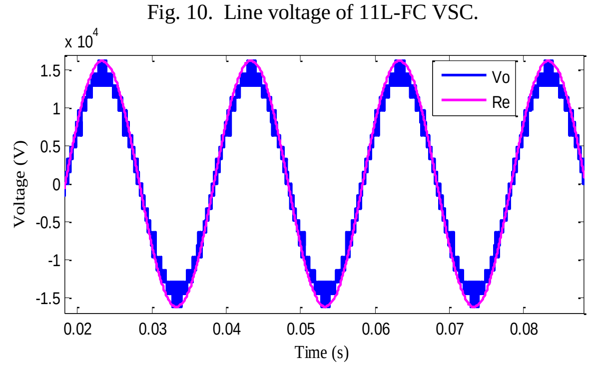

Fig. 11. Line voltage of 11L-SCHB VSC.

IV. COMPARISON

If it is assumed that each blocking diode voltage rating is the same as the active device voltage rating, the number of diodes required for each phase will be (m-1)×(m-2). When m is sufficiently high, the number of diodes required will make the system impractical to implement. A total of 90 diodes are required for each phase of the 11L converter. This large number of diodes affects the reverse recovery of the clamping diodes which is a major design challenge in high-voltage high-power systems. A list of the number of power components required for each converter topology is shown in Table VI. As already stated, the availability of IGBT and diode modules is also considered when designing the converter. For the 5L NPC, FC and SCHB converter topology, each IGBT switch is formed from the series connection of two 4.5 kV IGBTs so the number of IGBTs is 24+24. To enable a converter output phase current of 250 A, the simulation result is used to determine the current rating of the power semiconductors.

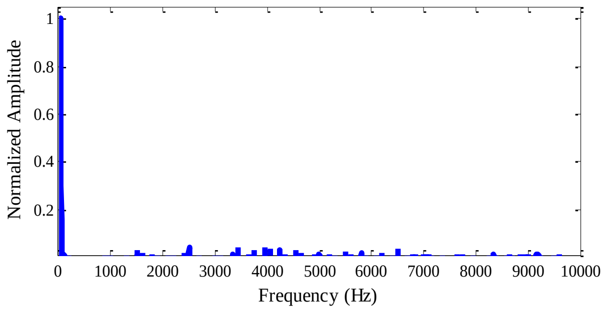

Fig. 12. Line voltage harmonic spectrum of 5L-NPC VSC.

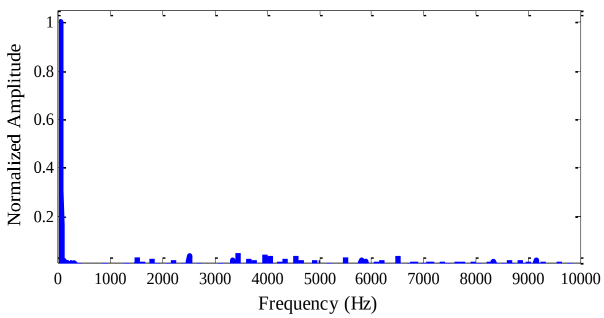

Fig. 13. Line voltage harmonic spectrum of 5L-FC VSC.

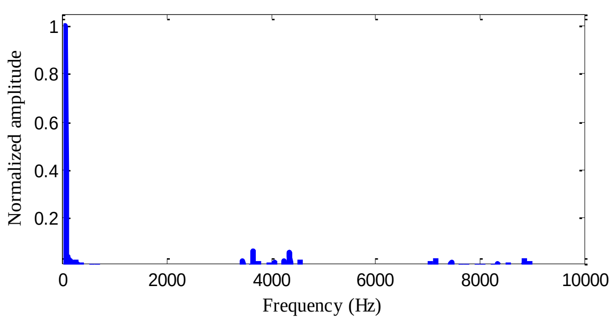

Fig. 14. Line voltage harmonic spectrum of 5L-SCHB VSC.

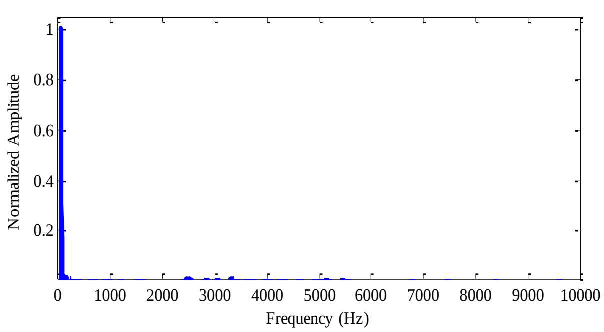

Fig. 15. Line voltage harmonic spectrum of 11L-NPC VSC.

A total of 45 clamping capacitors are required for each phase of the 11L converter. These large numbers of bulky and heavy capacitors increase the converter size and cost and reduce the overall lifetime of the converter. The capacitor voltage balancing problem also becomes a challenging issue with this high level of component numbers. There are no blocking diodes or clamping capacitors in the SCHB topology. The component numbers of this topology scale linearly with the number of levels. Hence, the overall number of components is much lower than that with other topologies.

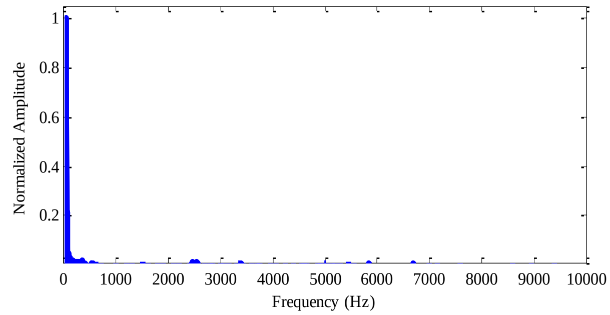

Fig. 16. Line voltage harmonic spectrum of 11L-FC VSC.

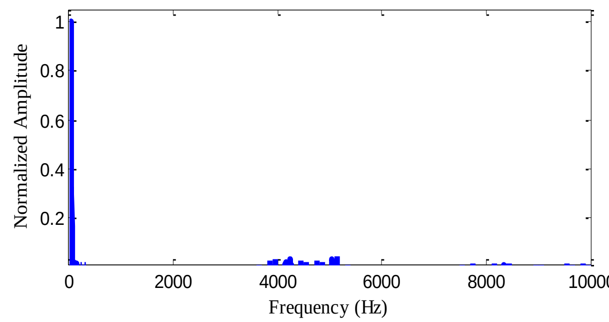

Fig. 17. Line voltage harmonic spectrum of 11L-SCHB VSC.

The individual modules are similar and totally modular in construction, which makes it easy to implement for any number of levels. The higher number of attainable levels provides more scope for reducing harmonics. The high number of levels means that it is possible to connect the converter to the AC network directly. To evaluate the harmonic spectrum of the line-to-line voltage, the total harmonic distortion (THD) has to be considered.

Table VI also shows the THD for different multilevel converter topologies. Among these three converter topologies, the NPC converter topology has the best harmonic performance. The harmonic performance of the SCHB topology is not as good as that of the NPC converter topology. The harmonic content decreases rapidly with increasing number of levels. The size of the LC filter also reduces. This means that by increasing the levels of the converter, it is possible to keep the output voltage total harmonic distortion to less than, or equal to 5 % (according to IEEE standard 519-1999). The SCHB converter is more economical than the others. The 11L SCHB converter is the low cost high performance converter and it is suitable for the connection of an 11 kV system directly. The price data quoted for the semiconductor devices and capacitors were collected from the Galco Industrial Electronics and Farnell catalogues [9], [10] where devices were chosen from the same family so that it was possible to fit with requirements. The IGBTs chosen are with integrated freewheel diodes and hence these diodes do not appear in costings. The current rating of most of devices is selected on the basis of simulation results. Table VI also shows the estimated cost of different converter topologies. The number of semiconductor increases with the number of levels but the change of cost is small because the price of the lower rated device is comparatively much lower. Because of the lower voltage and current requirements, the total semiconductor cost of the 11L-SCHB converter is lower than all other topologies.

TABLE VI
COMPARISON OF DIFFERENT TOPOLOGIES

Level	5L			11L		
Topology	NPC	FC	SCHB	NPC	FC	SCHB
IGBTs	48	48	48	60	60	60
Diodes	36	---	---	270	---	---
Capacitors	---	18	---	---	135	---
Total comp.	84	66	48	330	195	60
Total cost (AU$)	90,962	113,131	82,027	115,663	125,359	82,159
THD (%)	17.26	17.80	18.13	7.07	7.28	8.00

V. CONCLUSION

Although the harmonic performance of NPC and FC converter topologies is better than that of SCHB but NPC and FC topologies have the disadvantages that the number of components scale quadratically with respect to the number of output levels. This means that NPC and FC topologies are not feasible for high voltage converters. The component numbers of the SCHB converter scale linearly with the number of levels. Due to the identical modular nature of the construction it is easy to attain high level numbers. The high number of levels means that output filter size can be minimized, and allowing the possibility of direct connection to the medium or high voltage network. This direct connection means elimination of heavy, bulky, lossy and costly transformers from the system. Multiple independent generator stator windings and multistring photovoltaic configurations are possible solutions to overcome the requirement of isolated sources. According to converter cost, complexity and performance, it is concluded that the SCHB topology is the most feasible for high-voltage applications.

REFERENCES

[1] BP. (June 2011). "BP Statistical Review of World Energy June 2011, Primary Energy". [Online]. Available at: http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/primary_energy_section_2011.pdf

[2] International Energy Agency. (June 2011). "CO_2 Emission from Fuel Combustion". [Online]. Available at: http://www.iea.org/co2highlights/co2highlights.pdf

[3] Global Wind Energy Council. (June 2011). "Global Wind Report, Annual Market Update 2010". [Online]. Available at: http://www.gwec.net/fileadmin/images/Publications/GWEC_annual_market_update_2010_-_2nd_edition_April_2011.pdf

[4] European Photovoltaic Industry Association (June 2011), "Global Market Outlook for Photovoltaics Until 2014". [Online] Available: http://www.epia.org/fileadmin/EPIA_docs/public/Global_Market_Outlook_ for_Photovoltaics_until_2014.pdf

[5] S. Kouro, M. Malinowski, K. Gopakumar and *et al*., "Recent Advances and Industrial Applications of Multilevel Converters", *IEEE Transactions on Industrial Electronics*, vol. 57, no. 8, pp. 2553-2580, 2010.

[6] M. Sabahi, A. Y. Goharrzi, S. H. Hosseini, M. B. B. Sharifian and G. B. Gharehpetian, "Flexible Power Electronic Transformer", *IEEE Transactions on Power Electronics*, vol. 25, no. 8, pp. 2159-2169, 2010.

[7] Dan Wang and *et al.*, "The Research on Characteristics of Electronic Power Transformer for Distribution System', Proceedings of *IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific*, pp. 1-5, 18-18 August, Dalian, China, 2005.

[8] J. Rodriguez, L. G. Franquelo, J. I. Leon and *et al*, "Multilevel Converters: an Enabling Technology for High-Power Applications", *Proceedings of IEEE*, vol. 97, no. 11, pp. 1786-1817, 2009.

[9] Galco Industrial Electronics. (January 2011). "Semiconductors". [Online]. Available at: http://www.galco.com/scripts/cgiip.exe/wa/wcat/catalog. htm

[10] Farnell/Element14. (December 2010). "Semiconductor Modules and Passive Components". [Online]. Available at: http://au.element14.com

[11] J. S. Lai and F. Z. Peng, "Multilevel Converters - a New Breed of Power Converters", *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 509-517, 1996.

[12] A. Nabae, *et al*., "A New Neutral-Point-Clamped PWM Inverter", *IEEE Transactions on Industry Applications*, vol. 17, pp. 518-523, 1981.

[13] F. Z. Peng, *et al*., "A Multilevel Voltage Source Inverter with Separate DC Sources for Static VAR Generation", *IEEE Annual Meeting*, pp. 2541-2548, vol. 3, 1995.

[14] P. W. Hammond, "A New Approach to Enhance Power Quality for Medium Voltage AC Drives", *IEEE Transactions on Industry Applications*, vol. 33, pp. 202-208, 1997.

[15] D. Krug, S. Bernet, S. S. Fazel, and *et al*., "Comparison of 2.3 kV Medium Voltage Multilevel Converters for Industrial Medium Voltage Drives", *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 2979-2992, 2007.

[16] J. Rodriguez, J. S. Lai and F. Z. Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications", *IEEE Transactions on Industrial Electronics*, vol. 49, no. 4, pp. 724- 738, 2002.