Design and Comparison of 11 kV Multilevel VSCs for Local Grid Based Renewable Energy Systems

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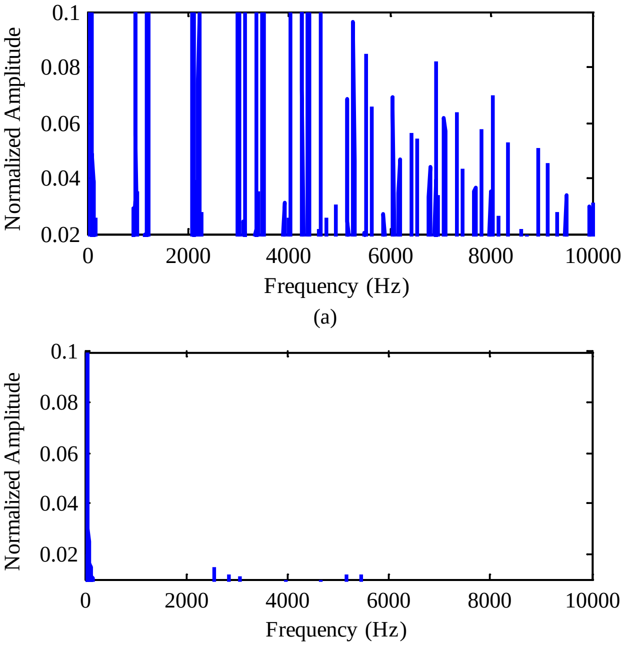
***Abstract*- Because the availability of renewable energy is highly variable and the power demand by the consumers could have a very different characteristic, it is very desirable to operate a renewable generation system with grid interfacing. In this respect, the 11 kV multilevel Voltage Source Converter (VSC) is the transformer less, cost effective solution to interface the renewable generation system to the local grid directly. This paper presents the design and comparison of a Five-Level Neutral Point Clamped (5L-NPC), a Five-Level Flying Capacitor (5L-FC), a Five-Level Series Connected H-Bridge (5L-SCHB), an Eleven-Level Neutral Point Clamped (11L-NPC), an Eleven-Level Flying Capacitor (11L-FC), and an Eleven-Level Series Connected H-Bridge (5L-SCHB) VSC for an 11 kV local grid based converter. The cost of power semiconductors and capacitors, modulation schemes and harmonic spectra of the converters are the bases for comparison.**

***Keywords*— Renewable energy, 11 kV multilevel converter, transformer less direct connection, MATLAB simulation.**

I. INTRODUCTION

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. Therefore, it is difficult to operate a power system installed with only one type of renewable energy resource. The local grid based renewable generation is the only solution to overcome this problem but due to the variable nature of renewable energy sources, output voltage and frequency adjustments are the challenging issues to connect these systems to power grids. Different power electronic converters have been developed using conventional topologies to fulfill the requirements of renewable generations. In order to step up the converter output voltage to grid level, an additional power transformer is required to interconnect the renewable generation with the grid [1]. The additional bulky and weighty transformer again increases the system size, weight, cost and power loss. An isolation transformer may represent 30%-50% of the total system size and 50%-70% of the system weight [2]. An 1-MVA transformer generates a large amount of heat energy (up to 6800 Btu/h) and requires a significant amount of air conditioning. Thus, the transformer less solution would result in large amount of energy saving.

In order to stabilize the system operation, the harmonic control is also important. To mitigate this harmonic effect it is essential to use a filter coil, which also increases the system complexity and cost. Output voltage waveforms of the converter could be improved by increasing the level of the converter, which may reduce the size of the input and output filter requirements. Output voltage Frequency Spectrum (FS) of two level and eleven level converter is shown in Fig. 1.



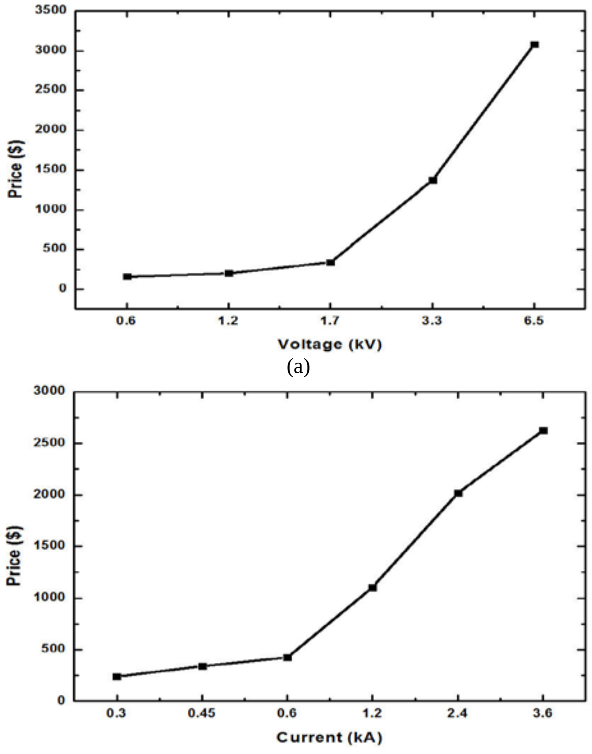
(a)

(b)

Fig. 1. Frequency spectrum of (a) two level (b) eleven level VSCs

On the other hand, a continuous race to develop higher voltage and higher current power semiconductors to drive high power systems still goes on. In this way, last generation devices are suitable to support medium voltages but high voltage semiconductor is still under development [3]. The price of power semiconductor devices increases rapidly with their power ratings as shown in Fig. 2 [4]. The series-parallel connection of lower rated semiconductors could be the cost effective solution for high voltage applications.

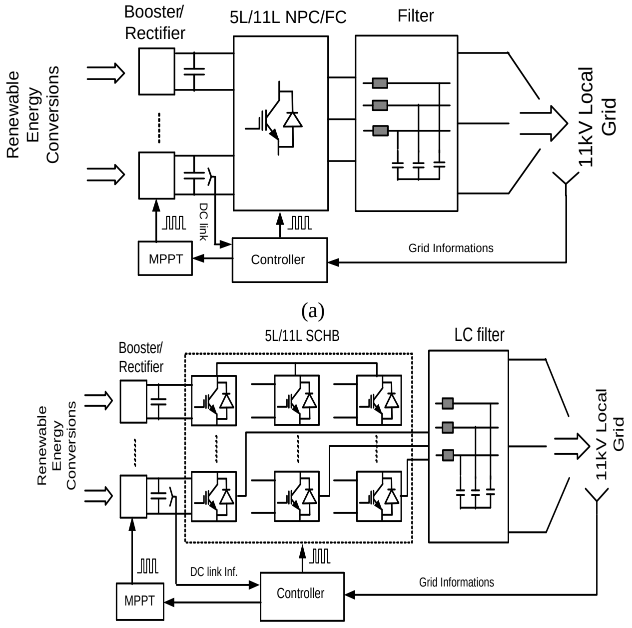
So, it is required and not difficult to develop an 11 kV multilevel voltage source converter, which can be able to connect the renewable generation system to the local grid without introducing a power transformer. Fig. 3 shows the basic block diagram of the proposed converters. This paper compares a 5L-NPC converter, a 5L-FC converter a 5L-SCHB converter, an 11L-NPC converter, an 11L-FC converter and an 11L-SCHB converter for an 11 kV local grid based renewable generation systems. The cost of power semiconductors and passive components is calculated and compared for all available multilevel converter topologies. Level Shifted (LS) Sine-Pulse Width Modulation (SPWM) and Phase Shifted (PS) SPWM are used to compare the performances.



(a)

(b)

Fig. 2. Price of IGBT (AU$) when (a) rated current is 0.4 A (b) rated voltage is 1.7 KV



(a)

(b)

Fig. 3. Basic block diagram of local grid based directly connected (a) 5L/11L-NPC/FC VSC (b) 5L/11L-SCHB VSC

II. CONVERTER DESIGN

Design conditions identification is the vital part of design process. The conditions and basic converter data are shown in Table I. The minimum DC-link voltage to achieve an output line-to-line voltage of 11 kV can be calculated by

$$\begin{aligned} V_{dc(\min)} &= \sqrt{2} \times V_{ll(rms)} \\ &= \sqrt{2} \times 11kV = 15{,}556.4V \end{aligned} \tag{1}$$

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

$$\begin{aligned} V_{dc(nom)} &= 1.04 \times V_{dc,\min} \\ &= 1.04 \times 15556.4V = 16{,}178.7V \end{aligned} \tag{2}$$

The apparent converter output power can be calculated by

$$\begin{aligned} S_c &= \sqrt{3} \times V_{ll(rms)} \times I_{p(rms)} \\ &= \sqrt{3} \times 11kV \times 250A = 4.76MVA \end{aligned} \tag{3}$$

TABLE I
BASIC CONVERTER DATA

Technical Data	Abbreviations	Value
Converter line-to-line voltage	$V_{ll(rms)}$	11 kV
Minimum DC-link voltage	$V_{dc(\min)}$	15,556.4 V
Nominal DC-link voltage	$V_{dc(nom)}$	16,178.7 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
Maximum junction temperature (IGBT, diode)	$T_{j(\max)}$	$125\,^{o}C$
Heat sink temperature	T_h	$80\,^{o}C$
Converter efficiency	η	98%

The semiconductor utilization is a very important part to evaluate high-voltage topologies due to the high share of semiconductor costs. Considering the nominal DC-link voltage and cosmic ray effect the IGBTs and diodes voltage rating is chosen. According to the output capacity and voltage ratings of the converters the availability of IGBT and diode modules in the market is also considered in design process. Two 4.5 kV series connected IGBTs are considered in place of single switch for all 5L converter topologies. Table II summarizes the design of the power semiconductors for the converter specification of Table I, with a carrier frequency of 1 kHz. To enable a converter output phase current of 250 A, the 400 A current rating is chosen for the power semiconductors. To compute the capacity of flying capacitor, a maximum capacitor voltage ripple (ΔV_c) is assumed to be 5% of the DC-link voltage and the DC output current (I_{dc}) is approximated to the maximum amplitude of the phase current ($I_{p(rms)}$) [5], i.e.

$$C = \hat{I}_{p(rms)} \Big/ (n \cdot \Delta V_c \cdot f_c) \quad (4)$$

where n is the number of series-connected flying capacitor cells.

A large number of 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 the carrier-based sine-triangle modulation. The LS-SPWM method is especially useful for Neutral Point Clamped (NPC) converters, since each carrier can be easily associated to two power switches of the converter and the PS-SPWM method is especially useful for Flying Capacitor (FC) and Series Cascaded H Bridge (SCHB) converters. 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 II
POWER SEMICONDUCTOR RATING

	5L-NPC	5L-FC	5L-HB	11L-NPC	11L-FC	11L-HB
$V_{dc(nom)}$	16,178.7V	16,178.7V	16,178.7V	16,178.7V	16,178.7V	16,178.7V
Rated device voltage (IGBT)	2x4.5kV	2x4.5kV	2x4.5kV	3.3kV	3.3kV	3.3kV
Commutation voltage of respective commutation cells , V_{com}	2,022.35V	2,022.35V	2,022.35V	1617.87V	1617.87V	1617.87V
The device commutation voltage for a device reliability of 100FIT due to cosmic radiation, $V_{com@100FIT}$	2x2250V	2x2250V	2x2250V	1800V	1800V	1800V
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 11L NPC and SCHB converters output voltage and output current (without and with the filter) are shown in Figs. 4-11 respectively. 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.

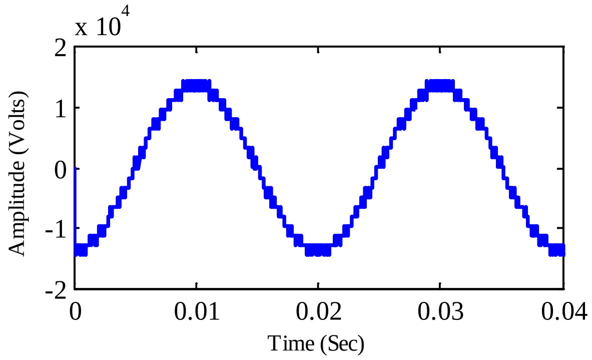


Fig. 4. Simulated line voltage (without filter) of 11L-NPC VSC

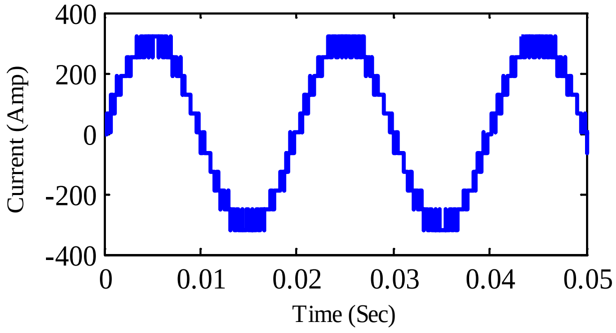


Fig. 5. Simulated line current (without filter) of 11L-NPC VSC

The harmonic content of the output voltage (without filter) of 5L and 11L NPC, FC and SCHB converters are shown in Figs. 12-17 respectively. Due to page limitation only a few of results are presented in this paper.

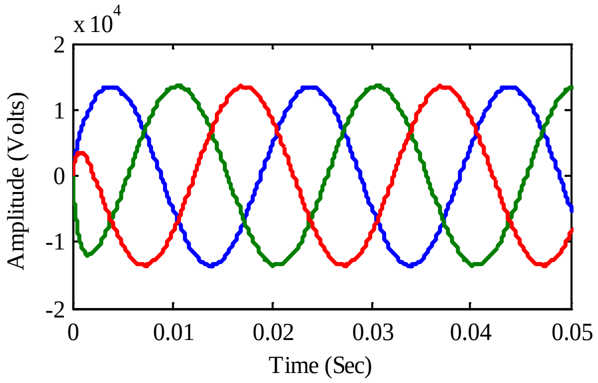


Fig. 6. Simulated line voltage (with filter) of 11L-NPC VSC

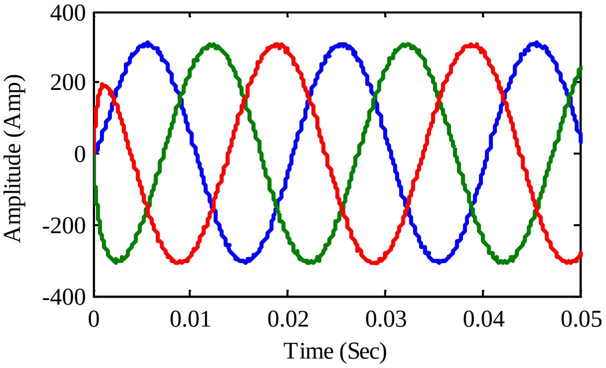


Fig. 7. Simulated line current (with filter) of 11L-NPC VSC

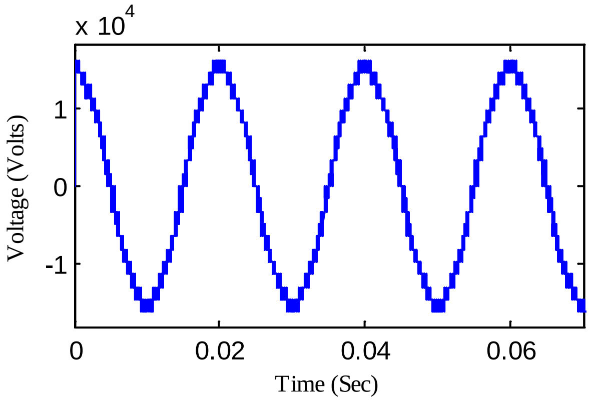


Fig. 8 Simulated line voltage (without filter) of 11L-SCHB VSC

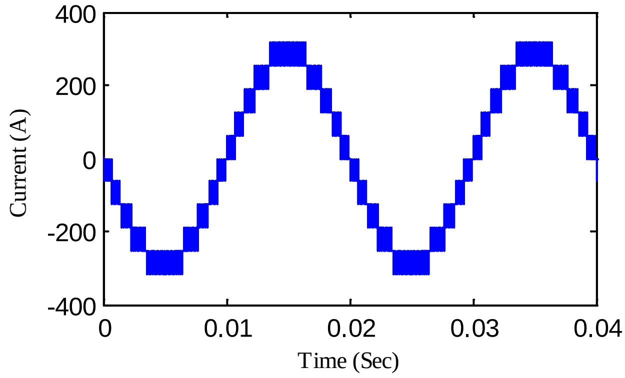


Fig. 9 Simulated line current (without filter) of 11L-SCHB VSC

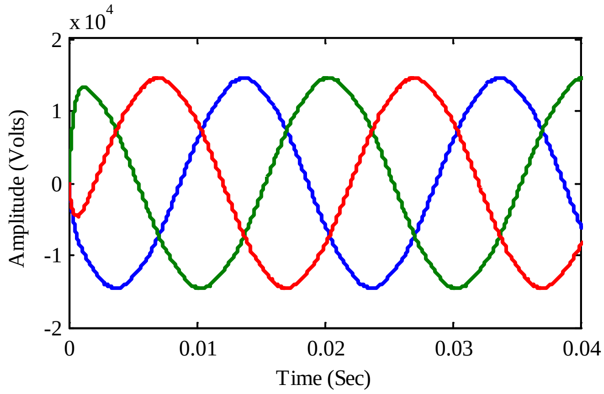


Fig. 10 Simulated line voltage (with filter) of 11L-SCHB VSC

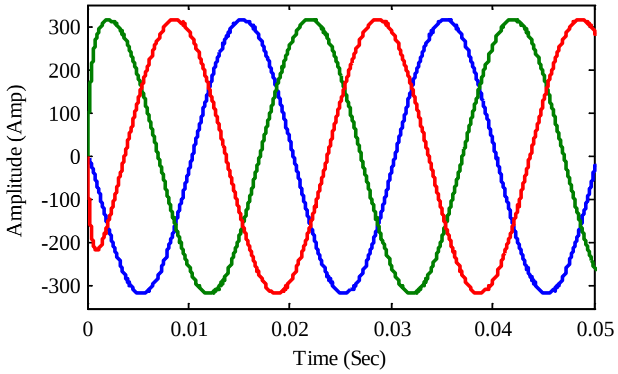


Fig. 11 Simulated line current (with filter) of 11L-SCHB VSC

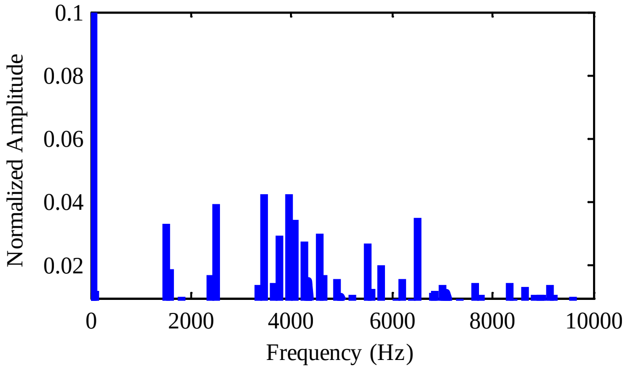


Fig. 12 Harmonic spectrum of line voltage of 5L-NPC VSC

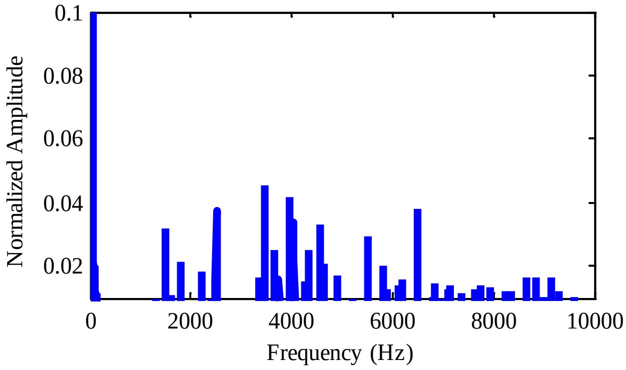


Fig. 13 Harmonic spectrum of line voltage of 5L-FC VSC

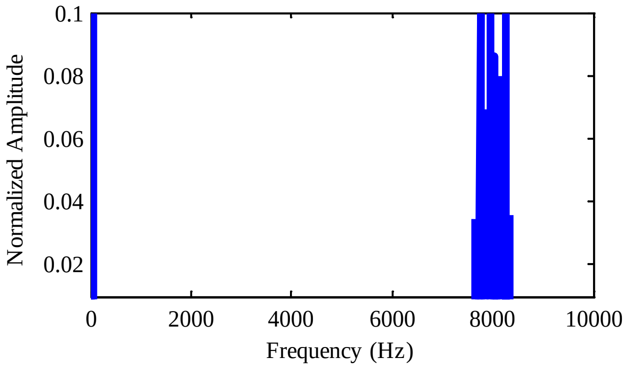


Fig. 14 Harmonic spectrum of line voltage of 5L-SCHB VSC

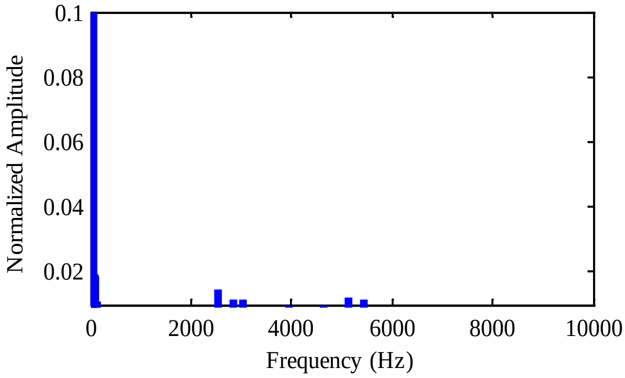


Fig. 15 Harmonic spectrum of line voltage of 11L-NPC VSC

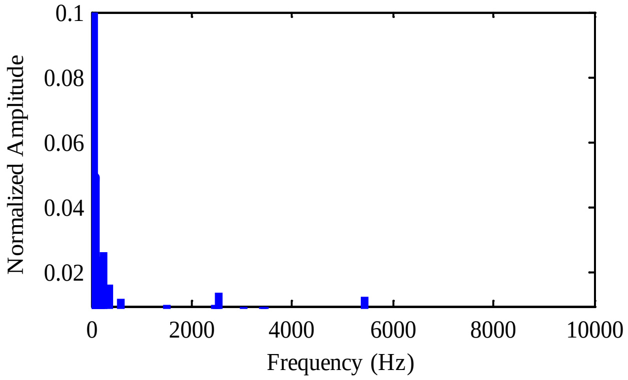


Fig. 16 Harmonic spectrum of line voltage of 11L-FC VSC

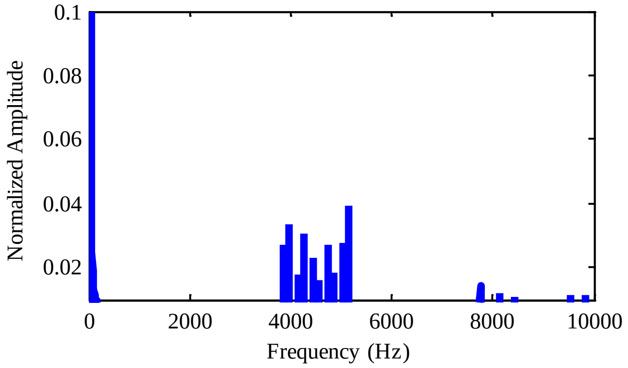


Fig. 17 Harmonic spectrum of line voltage of 11L-SCHB VSC

IV. CONVERTER COMPARISON

In NPC converter topology each active switching device is only required to block a voltage level of $V_{dc(nom)}/(m-1)$ but the clamping diodes must have different voltage ratings for reverse voltage blocking. 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 numbers of diodes is required for each phase of 11L converter. This large number of diodes affects the reverse recovery of the clamping diodes which is the major design challenge in high-voltage high-power systems. A list of number of power components for each converter topologies is shown in Table III. According to the output capacity and voltage ratings of the converters the availability of IGBT and diode modules in the market is also considered in design process. For 5L NPC/FC inverter topologies each IGBT switch is implemented by series connection of 6.5kV and 1.7 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 current rating of the power semiconductors. In booster section each IGBT is implemented by parallel connection of two series connected 6.5kV and 1.7 kV IGBTs. Similar to NPC topology, the FC topology requires a large number of bulk capacitors to clamp the voltage. Provided that the voltage rating of each capacitor used is the same as that of the main power switch, an m-level converter will require a total of (m-1)×(m-2)/2 clamping capacitors per phase. A total of 45 numbers of clamping capacitor is required for each phase of 11L converter. These large numbers of bulky and heavy capacitors increase the converter size and cost and reduce the overall lifetime of the converter. Moreover the capacitor voltage balancing problem becomes challenging issue with high level numbers. There are no blocking diodes or clamping capacitors in SCHB topology. The component number of this topology scales linearly with the number of levels. So, overall number of total components is much lower than that with other topologies. The individual modules are similar and totally modular in construction, which makes it easy to implement for any levels. The higher number of levels attainability 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) is considered. The THD can be computed by

$$THD_{(\%)} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{ll,n}^2}}{V_{ll,1}} \times 100 \tag{5}$$

Table IV shows the THD of different multilevel converter topologies. Among these three converter topologies the NPC converter topology has the best harmonic performance. The harmonic performance of SCHB topology is not as good as that of NPC converter topology. The harmonic content decreases rapidly with increasing number of levels and as well as reduces the size of the LC filter. This means that by increasing the levels of the converter it is possible to keep the output voltage total harmonic distortion of less than or equal to 5% (according to the standard IEEE 519-1999). The SCHB converter is more economical than the others. The 11L SCHB converter is the low cost high performance converter for 11 kV local grid based directly connected renewable generation systems. The price data of semiconductor devices and capacitors were collected from the Galco Industrial Electronics and Farnell catalogue [4, 6], where devices were chosen from the same family where possible to fit with requirements. But the filter inductor and booster inductor need to be customized. Therefore, their costs depend on the corresponding design. Due to large current and high frequency, the amorphous metal is chosen for the magnetic core and the copper tube is used for the windings of the inductors. The material costs of the inductor can thus be estimated. The IGBTs where chosen with integral freewheel diodes and hence these diodes did not appear in considerations. The current rating of most of devices is selected on the basis of simulation results. Table V 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 price of lower rated device is comparatively lower. Due to lower voltage and current requirements the total semiconductor cost of 11L-SCHB converter is lower than all other topologies.

TABLE III
NUMBER OF POWER COMPONENTS

		5L-NPC	5L-FC	5L-HB	11L-NPC	11L-FC	11L-HB
Inverter section	Number of IGBTs	24+24	24+24	24+24	60	60	60
	Number of diodes (NPC)	36	-----	-----	270	-----	-----
	Number of flying capacitors	-----	18	-----	-----	135	-----
	Sub total	84	66	48	330	195	60
Booster section	Number of inductors	4	4	6	10	10	15
	Number of IGBTs	2(1+1)×4	2(1+1)×4	2×6	10	10	15
	Number of diodes	4	4	6	10	10	15
	Number of DC link capacitors	4	4	6	10	10	15
	Sub total	28	28	30	40	40	60
Rectifier section	Number of diodes	24	24	36	60	60	90
	Number of filter capacitors	4	4	6	10	10	15
	Sub total	28	28	42	70	70	105
All sections	Total component count	140	122	120	440	305	225

Many publications have addressed the limitation of SCHB as the requirements of multiple isolated DC sources, and therefore, its application is not straightforward. Multiple independent generator stator windings and multistring photovoltaic configuration could be the possible solution to overcome the above limitation.

TABLE IV
THD OF THE LINE TO LINE VOLTAGE

Converter Topology	% of THD
5L-NPC	17.26
5L-FC	17.80
5L-HB	18.13
11L-NPC	7.07
11L-FC	7.28
11L-HB	8.00

V. CONCLUSIONS

Although the harmonic performance of NPC converter is better than the others, the NPC and FC converters have the disadvantages that the number of components scales quadratically with respect to the number of output levels. Moreover in FC converters the capacitor voltage balancing problems become challenging issue with high level numbers. This means that NPC and FC topologies are not feasible for high level converters. According to converter cost, complexity and performance the SCHB topology is feasible for high level converters. The high number of levels means that it is possible to connect the converter to the local AC network directly. This direct connection means elimination of heavy, bulky, lossy and costly transformer from the system. Transformer less operation will improve the performance of existing renewable generation system. The improved performance should lead to significant cost savings in the long run.

TABLE V
ESTIMATED COST FOR POWER COMPONENTS

		5L-NPC	5L-FC	5L-HB	11L-NPC	11L-FC	11L-HB
Cost of semiconductors	Costs of IGBTs (inverter)	82,027	82,027	82,027	82,159	82,159	82,159
	Costs of diodes (NPC)	8,934	-----	-----	33,504	-----	-----
	Costs of IGBTs (rectifier)	35,381	35,381	41,014	27,386	27,386	12,750
	Costs of Diodes (rectifier)	2,991	2,991	4,486	1869	1869	2,803
	Total cost of semiconductors	129,334	120,399	127,527	144,918	111,414	97,712
Costs of passive components	Material costs of LC filter	15,500	17,000	20,500	10,400	11,000	12,300
	Costs of flying capacitors	-----	37,400	-----	-----	50,500	-----
	Costs of DC capacitors	6,172	6,172	9,288	4,800	4,800	12,480
	Costs of boost inductors	30,300	30,300	25,200	20,400	20,400	18,900
	Total costs of passive components	51,972	90,872	54,988	35,600	76,700	43,680
Total	Total costs ($)	181,306	211,271	182,515	180,581	198,114	141,392

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