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TITLE: Modular multilevel converter modulation using fundamental switching selective harmonic elimination method.

YEAR: 2016

Publisher citation: NAMPALLY, A. and SINHA, Y. 2016. Modular multilevel converter modulation using fundamental switching selective harmonic elimination method. In Proceedings of the 5th IEEE international conference on renewable energy research and applications (ICRERA 2016), 20 -23 November 2016, Birminham, UK. New York: IEEE [online], pages 736-741. Available from: https://doi.org/10.1109/ICRERA.2016.7884431.

OpenAIR citation: NAMPALLY, A. and SINHA, Y. 2016. Modular multilevel converter modulation using fundamental switching selective harmonic elimination method. In Proceedings of the 5th IEEE international conference on renewable energy research and applications (ICRERA 2016), 20 -23 November 2016, Birminham, UK. New York: IEEE, pages 736-741. Available from: https://doi.org/10.1109/ICRERA.2016.7884431. Held on OpenAIR [online]. Available from: https://openair.rgu.ac.uk.

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Modular Multilevel Converter Modulation Using Fundamental Switching Selective Harmonic Elimination Method

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***Abstract*—This paper address the issue of low order harmonics in a modular multilevel converter (MMC). Using fundamental switching selective harmonic elimination (SHE), the control angles are calculated from nonlinear equations by Newton-Raphson method. The selective harmonic elimination equations are solved in such a way that the first switching angle is used to control the magnitude of the fundamental voltage and the remaining angles are used to eliminate the lowest odd, non-triplen harmonics components as they dominate the total harmonic distortion of the converter. The concept is validated using a 9-level detailed model of MMC in PSCAD/EMTDC®. The simulation result shows a good agreement with theoretical analysis and in comparison with conventional sinusoidal pulse width modulation (SPWM), the proposed method, eliminates low order harmonics, leading to a low total harmonic distortion.**

Keywords—) Modular multilevel converter, pulse width modulation, selective harmonic elimination, Newton-Raphson method

I. INTRODUCTION

The modular multilevel converter (MMC) has become progressively relevant in recent years; notably in areas of high-power transmission/distribution systems and in industrial applications [1-6]. Its distinctive feature in contrast to two-level voltage source converter (VSC) that works with pulse width modulation (PWM), MMC use a couple of low voltage series connected capacitors to generate high AC voltage. This configuration results in a higher power-handling capability with reduced switching power losses and harmonic distortions [3]. The losses in two-level VSC stations are approximately 1.6% of the rated transmission capacity and approximately 70% of these are dispelled in the IGBT valves [7]. Although it is anticipated to have minimum valve losses with MMCs, the efficiency of MMC is however related to the modulation technique which regulates the switching frequency and capacitor voltage ripple in the converter station.

MMC can operate at fundamental and high switching frequency PWM. It is generally known that the lower switching frequency causes lower switching losses and higher efficiency. In order to produce output at multilevel AC voltage through various levels of DC inputs, operation of semiconductor devices must be done in such a manner that the expected fundamental voltage is achieved with lower harmonic distortion. To reduce this harmonic distortion for effective results, some modulation methods are employed which are operated with high switching frequency and the low switching frequency. To obtain high switching frequency case, the former sinusoidal pulse (SPWM) and space vector pulse width modulation (SVPWM) are often applied. While in the case of low switching frequency, the space vector modulation (SVM) and selective harmonic elimination (SHE) have been mostly adopted. The inability of the SPWM technique to completely eradicate low order harmonics, which results in the need for a high filter requirement is a major drawback in its application. In the case of SVPWM and SVW, the non-applicability for unbalanced DC voltages is a major drawback. This implies only the SHE stands out as a technique that can eliminate the low order harmonics and also accounts for unbalanced DC voltages.

Fundamental switching frequency, which is also known as the selective harmonic elimination method based on harmonic elimination theory [8-9]. Despite the advantages stated above, the difficulty in using this method is obtaining the finest solution of nonlinear and transcendental equations to compute the switch angles. There are various mathematical based methods such as Newton-Raphson method [10], resultant theory [11], genetic algorithm [12], and particle swarm optimization [13], etc. In the resultant theory method, it is required to solve a polynomial equation which is a time-consuming method. The proper selection of parameters requires in population-based methods such as cost function, population size, etc. Newton-Raphson method requires random, initial guess values, which it is easy to compute and also converges faster than other methods. Hence, the Newton -

Raphson method is chosen in this paper to solve non-linear transcended equations.

The cascade configuration of the submodules (SMs) in MMC limits the easy to combine many modules without increasing its power circle complexity. The advantage of fundamental switching frequency modulation used in this paper is that each switching device (IGBT) is turned on and turned off once every fundamental cycle, causing low switching losses. One switching angle 'α_1' from '*m*' angles will be dedicated for control fundamental voltage, and rest of the *'m-1'* angles are used to cancel *'m-1'* non-triplen harmonics from the baseband; thus, the minimum harmonic distortion in the output voltage could result should the number of MMC submodules (voltage levels) be sufficiently high. Thus, the proposed modulation scheme for MMC addresses the extensive linear modulation choice, low total harmonic distortion (THD), low switching losses, with easy development and less computation burden.

II. OPERATIONAL PRINCIPLE OF MMC

Fig.1 shows the electrical equivalent diagram of the MMC. The IGBT elements that perform switching acts like VSC valve in SMs distribute DC capacitors. The valve functions like a controllable voltage source, that is linked between corresponding phase unit of the AC and terminal of the DC.

The model consists of two arms (Upper and Lower) of the converter, each one formed by a series connection of SMs and an inductor whose function is to limit the arm fault current. For *n*-level converter we need 2(*n*-1) SMs where '*n*' is a number of levels, for example, we need 12 SMs for the 7-level converter. Fig. 1 also shows the structure of one SM of an MMC.

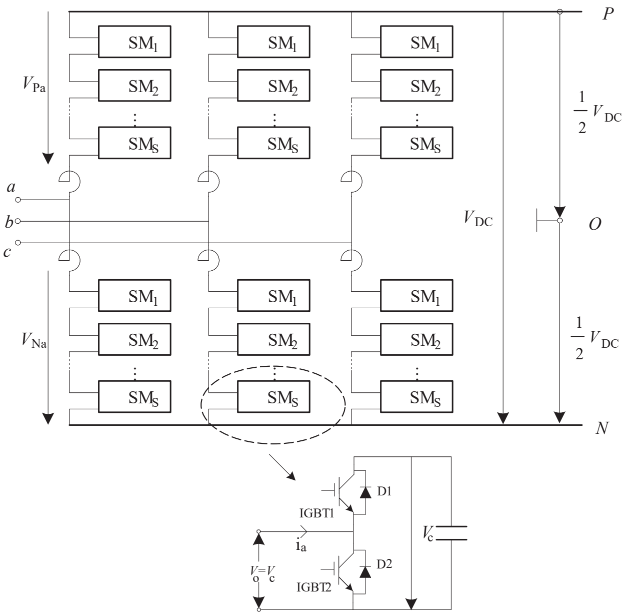

Fig. 1. Circuit configuration of MMC

Table I: MMC Current Paths and States of a Power Module

IGBT1	IGBT2	Current direction	Output Voltage(V_O)	Power path	Capacitor state
Off	On	$i_a > 0$	0	IGBT2	unaffected
Off	On	$i_a < 0$	0	D2	unaffected
On	Off	$i_a > 0$	V_C	D1	charging
On	Off	$i_a < 0$	V_C	IGBT1	discharging

When devices IGBT1 is on & IGBT2 is off, output voltage $V_0 = V_c$ and when its vice versa voltage $V_0 = 0$. Table I summarizes switch states of a submodule and their subsequent impact on related capacitor voltages. In Fig. 1, point *"P"* represents the positive DC bus and point *"N"* represents the negative DC bus. Point *"O"* is the imaginary DC side neutral point and the DC voltage is V_{DC}.

At any time N_T submodules are on.

$$N_P + N_N = N_T \tag{1}$$

Where, N_P and N_N are the number of inserted SMs from the upper and lower arms, N_T is a total number of on SMs. Suppose, capacitor voltage of each submodule is fixed to V_c, then the AC voltage V_{ao} represent the voltage of phase output terminal with respect to the imaginary DC side neutral point "*O*" is represented as

$$V_{ao} = -N_P V_C + \frac{1}{2} V_{DC} = N_N V_C - \frac{1}{2} V_{DC} \tag{2}$$

Voltages of upper and lower bridges

$$V_{Pa} = \frac{1}{2} V_{DC} - V_{ao} \tag{3}$$

$$V_{Na} = \frac{1}{2} V_{DC} + V_{ao} \tag{4}$$

In the three-phase conventional AC/DC converters, each of the phase is coupled to the grid side via one converter reactor. These reactors help to distribute the linking of power exchange among the converter and the grid. Six converter reactors are needed to couple six converter arms to grid in MMC, therefore; control schemes for the conventional AC & DC converters are not directly used in MMC control.

III. PROPOSED HARMONIC ELIMINATION SCHEME

In the proposed SHE method, the objective is to regulate the switching angles to attain preferred fundamental component and reduce harmonic content particularly lower order harmonics. By using Fourier transformation, control angles values of SHE are within the range of 0° and 90° and are computed and stored in a lookup table. The implementation of fundamental frequency SHE modulation scheme for a nine-level MMC is shown in Fig. 2.

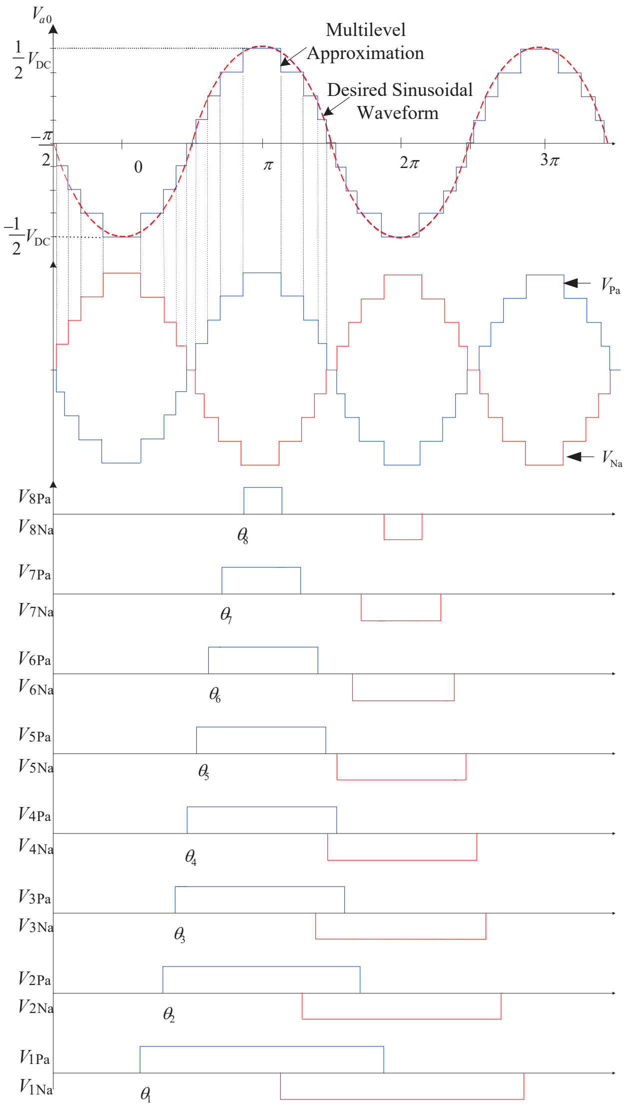

Fig. 2. Implementation of fundamental frequency switching SHE modulation for a 9-level MMC

Generally, the Fourier series development of the staircase output voltage waveform as demonstrated in Fig. 2 can be expressed by

$$V_{an}(\omega t)=\frac{4V_{DC}}{\pi}\sum_{k}^{\infty}\left[\begin{array}{l}\cos(k.\alpha_1)+\cos(k.\alpha_2)+\\ \ldots+\cos(k.\alpha_s)\end{array}\right]\frac{\sin(k\omega t)}{k} \quad (5)$$

In the above k=1, 3, 5, 7 odd harmonics, s is a number of SMs linked in each arm. It can be observed from (5) that only the odd harmonics leads to voltage and current harmonics.

For a specified preferred fundamental peak voltage V_{an1}, it is essential to regulate the switching angles such that $\alpha_1 \le \alpha_2 \le \ldots\ldots\alpha_{m-1} \le \alpha_m \le \frac{\pi}{2}$ and some major lower order harmonics of phase voltage are zero. Among m number of switching angles, usually one switching angle is chosen for fundamental voltage selection and the remaining (m-1) switching angles are choose to eliminate certain leading lower order harmonics. In a three-phase power system, triplen harmonics are cancelled out automatically in line-to-line voltage, therefore, only non-triplen odd harmonics are present in line to- line voltages [14-15].

From the expression (5), the fundamental voltage in terms of switching angles is represented by

$$V_{an1}=\frac{4V_{DC}}{\pi}[\cos(\alpha_1)+\cos(\alpha_2)+\ldots+\cos(\alpha_s)] \quad (6)$$

Furthermore, the fundamental voltage and the maximum obtainable voltage relation is defined by the modulation index, 'm_I' and is defined as fundamental output voltage V_{anI} to the maximum attainable amplitude of fundamental voltage V_{1max} ratios, thus; when all the switching angles are zero maximum fundamental voltage is obtained i.e.,

$$V_{1\max}=\frac{4sV_{DC}}{\pi} \quad (7)$$

Hence, the modulation index (m_I) expression is

$$m_1=\frac{V_{an1}}{\left(\frac{4sV_{DC}}{\pi}\right)}=\frac{\pi V_{an1}}{4sV_{DC}} \quad (8)$$

As the voltage harmonics are dependent on pre-selected control angles $(\alpha_1,\alpha_2,\alpha_3,\ldots\alpha_s)$, they are determined in a way to eliminate the predominant lower frequency level harmonics.

By using an MMC converter which is a 9-level as an example and its output voltages waveforms which are depicted in Fig. 2. The corresponding output voltage will have four switching angles that results in four degrees of freedom. The first switching is used in order to control the magnitude of the fundamental voltage and the three degrees of freedom are used to eradicate the lowest odd and non-triplen harmonics such as 5th, 7th and 11th harmonic components as they lead the total harmonic distortion. Note that, by connecting an appropriate number of SMs, a closely sinusoidal output voltage waveform can be produced, with a lower THD.

The conditions stated above can also be written in following way by the combination of (5) and (8) as

$$\begin{cases}\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)+\cos(\alpha_4)=4m_1\\ \cos(5.\alpha_1)+\cos(5.\alpha_2)+\cos(5.\alpha_3)+\cos(5.\alpha_4)=0\\ \cos(7.\alpha_1)+\cos(7.\alpha_2)+\cos(7.\alpha_3)+\cos(7.\alpha_4)=0\\ \cos(11.\alpha_1)+\cos(11.\alpha_2)+\cos(11.\alpha_3)+\cos(11.\alpha_4)=0\end{cases} \quad (9)$$

Equation (9) portrays four transcendental equations system, which is called as selective harmonic elimination (SHE) equation, in terms of four unknowns $\alpha_1,\alpha_2,\alpha_3$ and α_4. For the values given for m_I (from 0 to 1), it is important to get complete probable solutions of (9) when they exist with least computing time and complexity. The aforementioned Newton-Raphson method is used to solve the above-mentioned nonlinear transcendental equations and the solution set is plotted in Fig. 3. Thus, from Fig. 3 with a modulation index of 0.8, the solution for expression (9) is obtained as

$$\alpha_1 = 9.8°, \alpha_2 = 20.27°, \alpha_3 = 38.24°, \alpha_4 = 60.31° \tag{10}$$

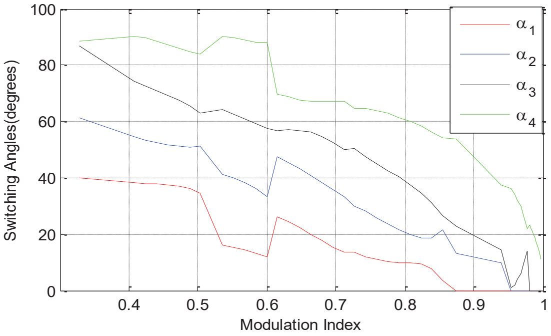

Fig. 3. Newton-Raphson method solution sets calculated with an arbitrary initial guess

Therefore, by substituting (10) in equation (9), the solution for the firing angles θ_1 to θ_8 is obtained as

$$\begin{aligned} &\theta_1 = 90° - \alpha_1, \theta_2 = 90° - \alpha_2, \theta_3 = 90° - \alpha_3, \theta_4 = 90° - \alpha_4, \\ &\theta_5 = 90° + \alpha_1, \theta_6 = 90° + \alpha_2, \theta_7 = 90° + \alpha_3, \theta_8 = 90° + \alpha_4 \end{aligned} \tag{11}$$

Fig. 4. shows the generation of switching pulses using proposed SHE modulation scheme.

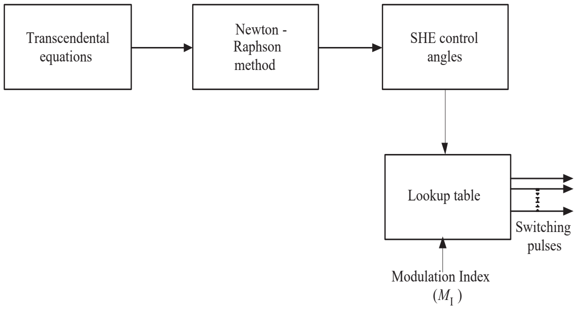

Fig. 4. Generation of switching pulses using SHE.

IV. A CASE STUDY

For further study, the Fig. 5. shows a model of a 1000 MVA ±200kV grid side MMC station has been built in PSCAD /EMTDC.

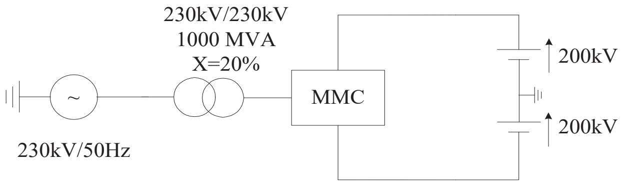

Fig. 5. MMC test system

The SHE and SPWM modulation approach for the MMC are considered and simulated with the simulation parameters shown in Table II.

Table II: Parameters of MMC

Power Rating	1000 MVA
AC Voltage Rating	230 kV
DC voltage	400 kV
System Frequency	50 Hz
Switching Frequency of SHE	50 Hz
Switching Frequency of SPWM	600 Hz
Number of SM per arm	8
Module Capacitance C	5000 µF
Arm Inductance L	1.26 mH
Total switching resistor per arm	0.08 ohm

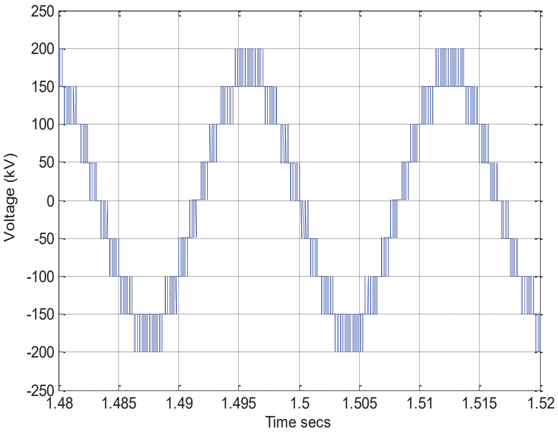

Fig. 6. Phase voltage of a 9-level MMC using SPWM modulation

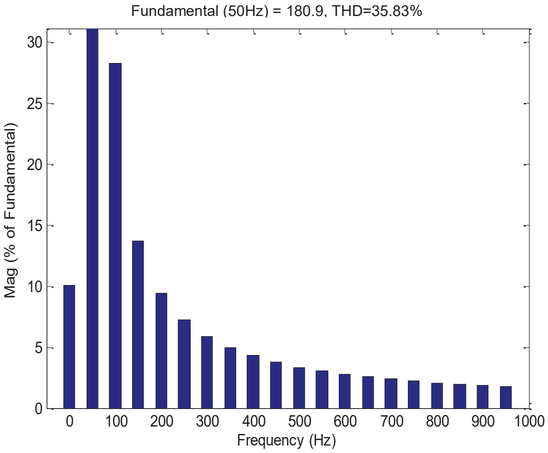

Fig. 7. Harmonic spectrum showing magnitudes of respective harmonics

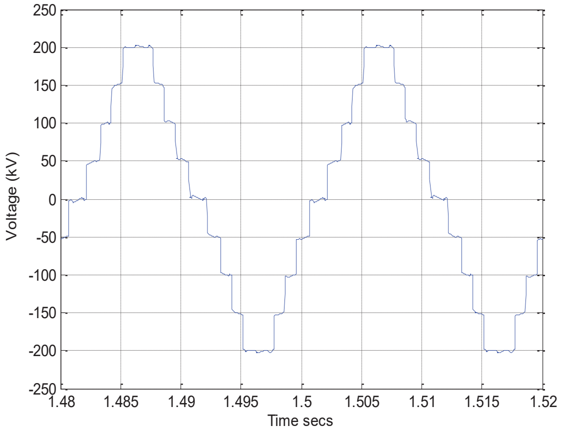

Fig. 8. Phase voltage of a 9-level MMC using SHE modulation

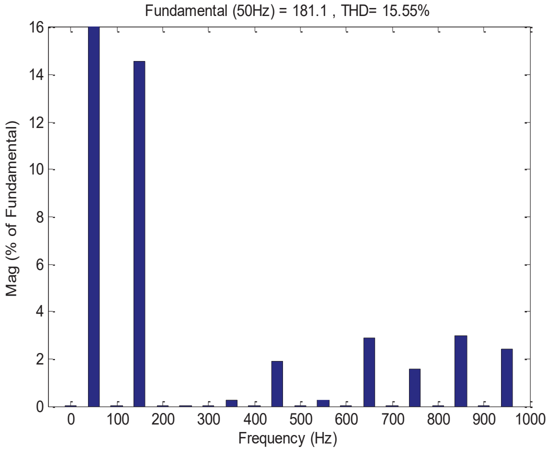

Fig. 9. Harmonic spectrum showing magnitudes of respective harmonics

Fig. 6 and Fig. 7, which signifies the output phase voltage of a phase-leg under SPWM and the corresponding harmonic spectrum indicates the presence of lower harmonics. Similarly, Fig. 8 and Fig. 9 show the phase voltage and harmonic spectrum using SHE.

An aggregate of four switching instances considered in the SHE modulation for the nine-level waveform which eliminates the first four low-order non-triplen harmonics while maintaining the fundamental to the required level. The existence of the low-order triplen harmonics in the harmonic spectrum of the phase-leg is a result of non-eradication through the modulation and the first non-triplen harmonics are the 5^{th}, 7^{th} and 11^{th} harmonics which are eliminated in Fig. 9. Table III captures the comparison of the THD with various modulation index; as expected the low order non-triplen harmonics are less significant in the SHE modulation against the SPWM with minimum total harmonic distortion.

Table III: THD of 9-level MMC for SHE and SPWM modulation

Modulation Index(m_1)	**Total Harmonic Distortion (%)**	
	SHE	**SPWM**
1	9.86	26.21
0.95	11.23	28.76
0.9	12.92	30.15
0.85	14.06	32.93
0.8	15.55	35.83

V. CONCLUSIONS

In this study, a comprehensive approach based on the fundamental frequency switching selective harmonic elimination scheme has been reported. All possible sets of solution have been presented using the Newton-Raphson method. Compared to various mathematical methods for solving transcendental equations, this method produces all possible solution sets for any levels of MMC without a much computational time and the speed of convergence is faster. This is clearly laid out that there were output waveforms with eliminated low order harmonics when MMC operated under SHE as compare to the SPWM technique. In both techniques, there was an analogy between the rigorous simulation results and the theoretical postulations couple with the ability to modulate the converter with SHE using pre-calculated switching patterns.

REFERENCES

[1] M. Hagiwara and H. Akagi, "Control and Experiment of Pulsewidth-Modulated Modular Multilevel Converters," in *IEEE Transactions on Power Electronics*, vol. 24, no. 7, pp. 1737-1746, July 2009.

[2] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," *Power Tech Conference Proceedings, 2003 IEEE Bologna*, 2003, pp. 6 pp. Vol.3-.

[3] M. Saeedifard and R. Iravani, "Dynamic Performance of a Modular Multilevel Back-to-Back HVDC System," in *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2903-2912, Oct. 2010.

[4] U. N. Gnanarathna, A. M. Gole and R. P. Jayasinghe, "Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs," in *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 316-324, Jan. 2011

[5] L. Harnefors, A. Antonopoulos, S. Norrga, L. Angquist and H. P. Nee, "Dynamic Analysis of Modular Multilevel Converters," in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2526-2537, July 2013.

[6] M. Glinka and R. Marquardt, "A new AC/AC multilevel converter family," in *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 662-669, June 2005.

[7] HVDC Light transmission losses, http:www.abb.com, 2010.

[8] H. S. Patel and R. G. Hoft, “Generalized Harmonic Elimination and Voltage Control in Thyristor Converters: Part I – harmonic elimination,” IEEE Transactions on Industry Applications, vol. 9, May/June 1973. pp. 310-317.

[9] H. S. Patel and R. G. Hoft, “Generalized Harmonic Elimination and Voltage Control in Thyristor Converters: Part II –Voltage Control

Technique," IEEE Transactions on Industry Applications, vol. 10, Sept./Oct. 1974, pp. 666-673.

[10] J. N. Chiasson, L. M. Tolbert, K. J. McKenzie, Z. Du, "A Complete Solution to the Harmonic Elimination Problem," IEEE Transactions on Power Electronics, March 2004, vol. 19, no. 2, pp. 491-499.

[11] J. N. Chiasson, L. M. Tolbert, K. J. McKenzie, and Z. Du, "Control of a multilevel converter using resultant theory", IEEE Trans. Cont.Sys. Tech., vol. 11, no. 3, pp. 345-354, May 2003.

[12] R. Salehi, N.Farokhnia, M. Abedi, and S. H. Fathi,"Elimination of low order harmonics in multilevel inverter using genetic algorithm",J. Power Electron., vol. 11, no. 2, pp. 132-139, Mar. 2011.

[13] R. N. Roy, D. Chatterjee and S. K. Goswami, "Harmonics elimination in a multilevel inverter using the particle swarm optimisation technique," IET Power Electron., vol. 2, no. 6, pp. 646-652, 2009.

[14] F. Z. Peng, J. W. McKeever, and D. J. Adams, "Cascade Multilevel Inverters for Utility Applications", IECON Proceedings (Industrial Electronics Conference), vol. 2, pp. 437-442, 1997.

[15] L. M. Tolbert, F. Z. Peng, and T.G. Habetler, "Multilevel converters for large electric drives", IEEE Transactions on Industry Applications, vol. 35, no. 1, pp. 36-44, Jan. /Feb. 1999.