Electrical Power and Energy Systems 44 (2013) 1–6

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Analytical efficiency evaluation of two and three level VSC-HVDC transmission links

Giddani Kalcon [a,*], Grain P. Adam [b], Olimpo Anaya-Lara [b], Graeme Burt [b], K.L. Lo [b]

[a] Electrical Engineering Department, College of Engineering, Sudan University of Science and Technology Khartoum, Eastern Diem 11111, Sudan
[b] Electronic and Electrical Engineering Department, University of Strathclyde, Glasgow, UK

ARTICLE INFO

Article history:
Received 9 January 2011
Received in revised form 18 June 2012
Accepted 5 July 2012
Available online 9 August 2012

Keywords:
Conversion losses
IGBTs
Two-level VSC converter
Three-level VSC converter
VSC-HVDC

ABSTRACT

An analytical method to calculate the efficiency of VSC-HVDC links based on two-level and three-level VSCs is presented. The method uses the average and root mean square of the VSC converter current to estimate the conversion losses in the converters (conduction and switching losses). The remaining power losses (DC cable transmission losses due to I^2R, the losses in the coupling transformer, and AC harmonic filter losses) are evaluated using conventional well-known methods. Results obtained analytically are confirmed by digital simulations.

1. Introduction

High-voltage DC transmission based on voltage source converters (VSC-HVDC) presents a solution for many problems face nowadays by power networks, such as, network congestions, grid re-enforcements, wind farms connection, multi-terminal operation and asynchronous connections [1–3].

Currently, there are two established approaches for the construction of a VSC-HVDC system. The first approach uses a standard two-level converter or a neutral-point clamped converter with forced commutated devices such IGBTs. This approach imposes a high insulation requirement on the interfacing transformer due to the high dv/dt that results from switching high voltage with relatively low switching frequencies. This arrangement also requires fairly large filters at the output to attenuate the switching frequency components from the output voltage at the point of common coupling.

The second approach uses a two-switch modular multilevel converter with medium voltage devices such as 4.5 kV IGBTs. This approach produces lower dv/dt (allowing the use of a transformer with standard insulation requirements) and significantly lower voltage harmonic distortion (which may eliminate the need for the AC filters). This approach requires however, a large number of switching devices and capacitors and a relatively complex modulation strategy compared to the first approach.

Both approaches result in fast dynamic performance, independent control of active and reactive power, no commutation failures during ac faults, better fault ride-through capability, and the ability to provide damping and frequency support through active or reactive power modulation [4–7]. However, both approaches produce higher conversion losses compared to the conventional HVDC system. Estimation of the power losses during the design stage of the VSC-HVDC is essential, because it allows the designers to optimize the overall system performance through a compromise of several design indices. It also helps in the selection of heat sinking equipment and cooling system for the converters.

2. VSC losses calculation methods

There are many methods to calculate and evaluate the losses in a VSC converter [8].

2.1. Particle measure

In this method the input power and the output power at each component of the VSC-HVDC is measured and the difference is the losses inside the component. This method is reasonably reliable at low voltage and low power transmission.

2.2. Software model method

Computer simulation is one of the powerful methods to represent the VSC-HVDC transmission. VSC-HVDC transmission system model is built using software simulation program, therefore the voltages, currents and losses in each individual components can be calculated. In this case the accuracy of losses calculation of the VSC-HVDC system depends on how accurate the built model is [9].

* Corresponding author. Tel.: +249 121 077 716.
E-mail address: tjbo8132@eee.strath.ac.uk (G. Kalcon).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.07.018

2.3. Analytical method

Numerical equation for power losses is derived for each component. In this paper a relationship based on the average and root mean square of the VSC converter current is used to estimate the conversion losses in the VSC converters, while the conventional equations is used for computing losses in coupling transformer, smoothing reactor and the ac filter. The only disadvantage of this method comes from the parameters which may be different from the actual operation parameters used in a real application.

In [10], the authors introduced analytical method for conduction losses evaluation in inverters based on the probability of the inverter switching devices receiving ON signal and derived simple numerical equations to calculate the losses in: resonant-DC-link, hysteresis-current-controlled, and sinusoidal PWM inverters.

In this paper the evaluation of the efficiency of a VSC-HVDC system is carried on using two level and three level natural point clamp converters, the conversion losses of VSC converter formula is derived based on sinusoidal pulse, the datasheet of 3.3 kV is used to find the converter devices characteristics.

3. VCS-HVDC system structure

Fig. 1 shows a single-line diagram of the VSC-HVDC system, the main components of the system are [11–13]:

1. *Coupling transformer:* transforms the voltage of the ac system to a level suitable for the converter.
2. *Smoothing reactor:* used for controlling the active and the reactive power flow.
3. *AC harmonic filter:* eliminate the harmonics in voltage and current waveforms.
4. *VSC converter:* composes of series of switches to withstand the high voltage rating of the system, the basic component of single switch is IGBT device with anti-parallel freewheeling diode.
5. *DC cable:* transmit the power between the two converter stations.
6. *DC capacitor:* keep the power balance during transients and reduce the ripple on DC voltage.

3.1. VSC converter losses

The conversion losses on VSCs can be divided into two types as follow [8,14].

3.1.1. Conduction losses

The conduction losses occur due to device on-state voltage drop and computed by averaging the conduction losses in each switching cycle [14] as shown following equation:

$$P_C = \frac{1}{T}\int_0^T V_f(\omega t)\cdot i(\omega t)d\omega t \quad (1)$$

where P_C is the device conduction losses, T is the switching period, V_f (ωt) is the device forward voltage, i (ωt) is the current flow through the device in the conduction period. The value of V_f (ωt) is calculated as follow [14,15]:

$$V_f = V_{f0} + r_f i(t) \quad (2)$$

where V_{f0} is the device forward voltage at no load and r_f is the device forward resistance. The values of V_{f0} and r_f are calculated using the datasheet of device characteristics provided by manufacturing companies as shown in Fig. 2. The r_f is the ratio between the collector–emitter voltage difference and the collector current difference $(r_f = \Delta V_{CE}/\Delta I_C)$, while V_{f0} is the value in the curve corresponding to the actual collector current flow in the device.

Substituting the expression for the forward voltage in Eq. (2) into Eq. (1) gives:

$$P_C = V_f I_{av} + r_f I_{rms}^2 \quad (3)$$

where I_{av} and I_{rms} are the average and the rms current through the device in the conduction period, respectively. These are calculated as follows:

$$i_{av} = \frac{1}{T_s}\int_0^{T_s} i_a(t)d\omega \quad (4a)$$

$$i_{rms}^2 = \frac{1}{T_s}\int_0^{T_s} i_a^2(t)d\omega \quad (4b)$$

3.1.2. Switching losses

The switching losses are total sum of on-state switching losses and turn-off switching losses and it depends on the device characteristics, switching frequency, and device current [16]. The switching energy can be expressed as a function of the device current as [17,18]:

$$E_{sw} = k_1^i \quad (5)$$

where k_1 is obtained from the switching energy graph in the device datasheet shown in Fig. 2. The switching loss for the device is calculated as

$$P_{sw} = \frac{f_s}{2\pi}\int_0^{T_s} k_1 i d\omega t \quad (6)$$

4. Evaluation of conversion losses in two-level converters

Fig. 3 and Table 1 show the current direction in one leg of two-level converter during the switching period [19]. If the load current

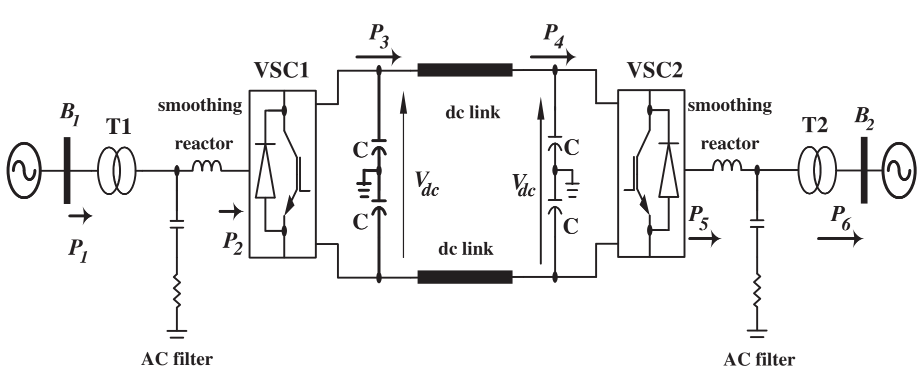

Fig. 1. VSC-HVDC transmission structure.

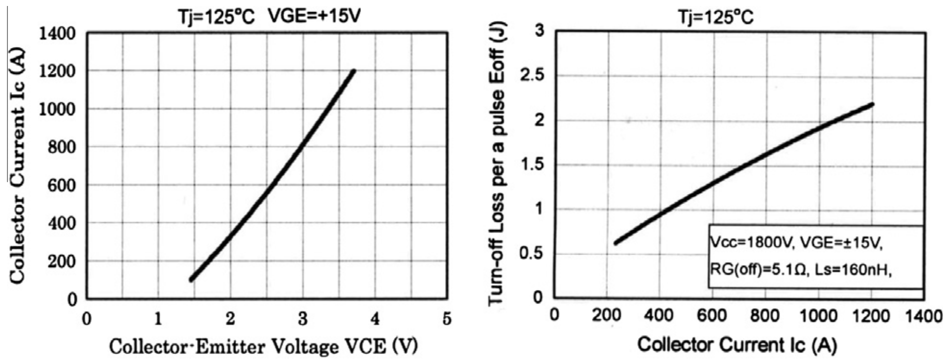

Fig. 2. Device characteristics datasheet.

is assumed as $i_a(t) = I_m \sin(\omega t - \theta)$, then the leg phase voltage is defined as $V_a(t) = V_m \sin \omega t$ and the duty cycle for the device switches is:

$$d_{T1} = d_{D2} = \frac{1}{2}[1 + M \sin \omega t] \tag{7a}$$

$$d_{T2} = d_{D1} = 1 - d_{T1} = \frac{1}{2}[1 - M \sin \omega t] \tag{7b}$$

The average and rms currents for IGBTs T_1 and T_2 are calculated using Eq. (4) and the duty cycle defined by (7) as:

$$I_{T1,av} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T1} i_a d\omega = I_m\left[\frac{1}{2\pi} + \frac{M\cos\theta}{8}\right] \tag{8}$$

$$I_{T2,av} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T2} i_a d\omega = I_m\left[\frac{1}{2\pi} - \frac{M\cos\theta}{8}\right] \tag{9}$$

$$I^2_{T1,rms} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T1} I_a^2 d\omega t = I_m^2\left[\frac{1}{8} + \frac{M\cos\theta}{3\pi}\right] \tag{10}$$

$$I^2_{T2,rms} = \frac{1}{2\pi}\int_\theta^{\pi+\theta} d_{T2} I_a^2 d\omega t = I_m^2\left[\frac{1}{8} - \frac{M\cos\theta}{3\pi}\right] \tag{11}$$

The average and rms currents for the lower free-wheeling diode are similar to that of the upper IGBT device but in opposite direction, therefore:

$$I_{D1,av} = -I_{T2,av} = -I_m\left[\frac{1}{2\pi} - \frac{M\cos\theta}{8}\right] \tag{12}$$

$$I_{D2,av} = -I_{T1,av} = -I_m\left[\frac{1}{2\pi} + \frac{M\cos\theta}{8}\right] \tag{13}$$

$$I^2_{D1,rms} = I^2_{T2,rms} = I_m^2\left[\frac{1}{8} - \frac{M\cos\theta}{3\pi}\right] \tag{14}$$

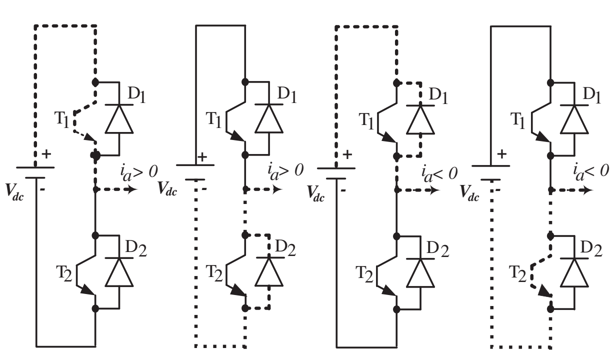

Fig. 3. Current direction in one leg of tow-level converter.

Table 1
The switching state of two level converter.

Devices	Devices state	
	$i_{a>0}$	$i_{a<0}$
T1	ON	OFF
T2	OFF	ON
D1	OFF	ON
D2	ON	OFF

$$I^2_{D2,rms} = I^2_{T1,rms} = I_m^2\left[\frac{1}{8} + \frac{M\cos\theta}{3\pi}\right] \tag{15}$$

The free-wheeling diode is switched on/off very fast compared to the IGBT so its switching losses are relatively small compared to that in an IGBT, therefore are not considered in the calculation. The switching losses for the IGBT are calculated using Eq. (6) as:

$$P_{sw} = \frac{k_1 f_s}{2\pi}\int_\theta^{\pi+\theta} I_m \sin(\omega t - \theta) d\omega t = \frac{k_1 f_s I_m}{\pi} \tag{16}$$

5. Evaluation of conversion losses in the three-level NPC converter

Fig. 4 and Table 2 summarize all the possible power paths and switching states in the three-level NPC converter [15]. The load current is $i_a(t) = I_m \sin(\omega t - \theta)$ and the phase leg voltage as $V_a(t) = V_m \sin \omega t$, and the duty cycle across the switching devices as:

$$d_{T1} = \begin{cases} M\sin\omega t & 0 \leqslant \omega t \leqslant \pi \\ 0 & \pi \leqslant \omega t \leqslant 2\pi \end{cases} \quad d_{T2} = \begin{cases} 1 & 0 \leqslant \omega t \leqslant \pi \\ 1 + M\sin\omega t & \pi \leqslant \omega t \leqslant 2\pi \end{cases}$$
$$d_{T3} = 1 - d_{T1} \qquad d_{T4} = 1 - d_{T2} \tag{17}$$

Then, the average and rms currents in the IGBTs are calculated as follows:

$$I_{T1,av} = I_{T4,av} = \frac{1}{2\pi}\int_\theta^{\pi} d_{T1} i_a d\omega = \frac{M I_m}{4\pi}[(\pi - \theta)\cos\theta + \sin\theta] \tag{18}$$

$$I_{T2,av} = I_{T3,av} = \frac{1}{2\pi}\left[\int_\theta^{\pi} i_a d\omega t + \int_\pi^{\pi+\theta} d_{T2} i_a d\omega t\right] = \frac{I_m}{4\pi}[4 + \theta M\cos\theta - M\sin\theta] \tag{19}$$

$$I^2_{T1,av} = I^2_{T4,av} = \frac{1}{2\pi}\int_\theta^{\pi} d_{T1} i_a^2 d\omega = \frac{M I_m^2}{12\pi}[3 + 4\cos\theta + \cos 2\theta] \tag{20}$$

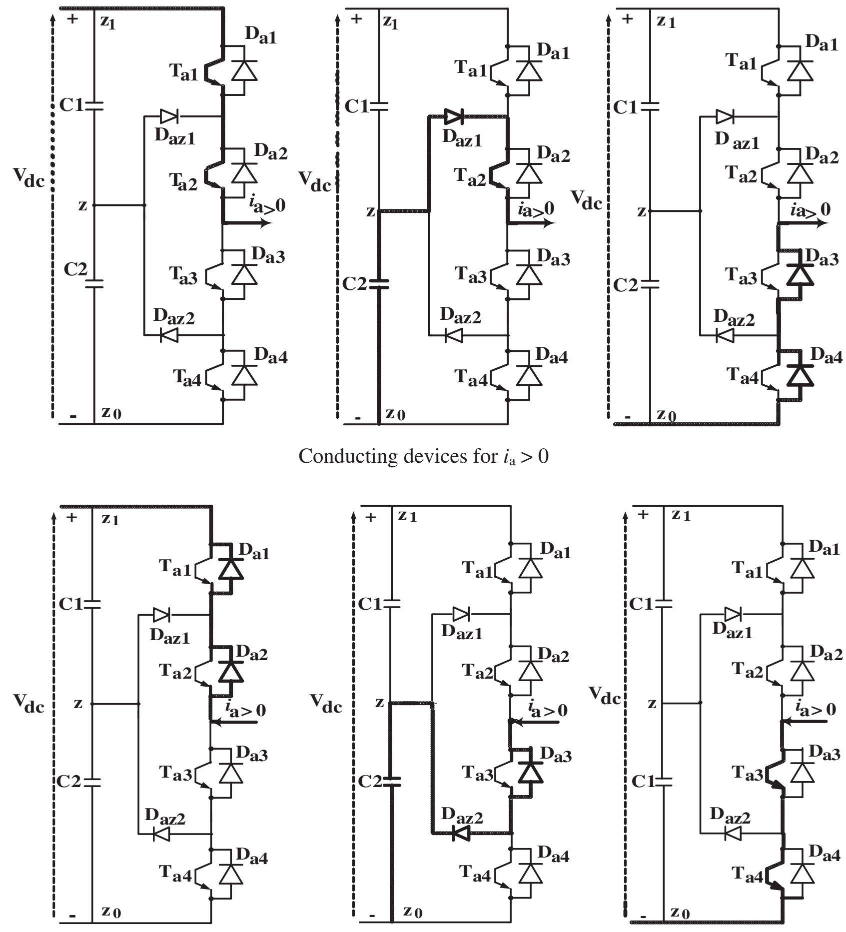

Fig. 4. Current direction in one leg of three-level converter.

Table 2
The switching state of three level converter.

Switching symbol	Switching devices			
	T1	T2	T3	T4
P	ON	ON	OFF	OFF
0	OFF	ON	ON	OFF
N	OFF	OF	ON	ON

$$I^2_{T2,rms} = I^2_{T3,rms} = \frac{1}{2\pi}\left[\int_\theta^\pi i_a^2 d\omega t + \int_\pi^{\pi+\theta} d_{T2} i_a^2 d\omega t\right] = \frac{I_m^2}{12\pi}[3(\pi - M) + 4M\cos\theta - M\cos 2\theta] \tag{21}$$

And the average and rms currents in the free-wheeling diodes are:

$$I_{Da1,av} = I_{Da4,av} = I_{Da3,av} = I_{Da4,av} = \frac{1}{2\pi}\int_0^\theta d_{da1} i_a d\omega = \frac{MI_m}{4\pi}[\theta\cos\theta - \sin\theta] \tag{22}$$

$$I^2_{Da1av} = I^2_{Da2,rms} = I^2_{Da3,rms} = I^2_{Da4,rms} = \frac{1}{2\pi}\int_0^\theta d_{T1} i_a^2 d\omega = \frac{MI_m^2}{4\pi}[3 - 4\cos\theta + \cos 2\theta] \tag{23}$$

The average and root mean square currents in the clamping diodes are:

$$I_{Ta5,av} = I_{Ta6,av} = \frac{1}{2\pi}\left[\int_\theta^\pi d_{da3} i_a d\omega t + \int_\pi^{\pi+\theta} d_{da2} i_a d\omega t\right] = \frac{I_m}{\pi} - \frac{MI_m}{4\pi}[(\pi - 2\theta)\cos\theta + 2\sin\theta] \tag{24}$$

$$I^2_{sa5,rms} = I^2_{sa6,rms} = \frac{1}{2\pi}\left[\int_\theta^\pi d_{sa3} i_a^2 d\omega t + \int_\pi^{\pi+\theta} d_{sa2} i_a^2 d\omega t\right] = \frac{I_m^2}{12\pi}[3\pi - 6M - 2M\cos 2\theta] \tag{25}$$

According to Eq. (6) and for a three-level NPC converter, the switching losses in the IGBTs T_1-to-T_4 are:

$$P_{T1,sw} = P_{T4,sw} = \frac{f_s}{2\pi}\int_\theta^\pi k_1 I_m \sin(\omega t - \theta) d\omega t = \frac{k_1 f_s I_m}{2\pi}[1 + \cos\theta] \tag{26}$$

$$P_{T2,sw} = P_{T3,sw} = \frac{f_s}{2\pi}\int_\pi^{\pi+\theta} k_1 I_m \sin(\omega t - \theta) d\omega t = \frac{k_1 f_s I_m}{2\pi}[1 - \cos\theta] \tag{27}$$

6. Transmission Losses

The transmission losses in a VSC-HVDC system include the losses in the dc cable, the coupling transformer, smoothing reactor and ac filters.

6.1. Coupling transformer losses

The transformer operating losses are the sum of the core and copper losses [20]. The copper losses in the primary and secondary winding can be calculated using the formula $(3 \cdot I_1^2 \cdot R_1 + 3 \cdot I_2^2 \cdot R_2)$, where I_1, I_2, R_1, and R_2 are the primary current, secondary current, primary effective resistance, and secondary effective resistance, respectively. The core losses are determined energizing the VSC-HVDC converter station with the valves blocked. The core losses always are determined as percentage of copper losses at full load.

6.2. AC filter losses

In VSC-HVDC, the switching of the IGBTs using high frequency PWM technique producing only high order harmonic components around and beyond the switching frequency components. Only passive high pass filter can be used to eliminate these high order harmonics which produce relatively small losses compared to filters with lower tuned frequencies used in conventional HVDC [4]. The fundamental and harmonics components of current flowing in the AC filter are used to determine the losses in each filter component as follow.

6.2.1. Filter resistance losses

The losses in the filter resistors are calculated using the rms current flowing in filter resistor based on Ohm law [20].

6.2.2. Filter reactance losses

The fundamental and harmonic currents in the filter reactors are calculated and reactor losses are calculated as follow [20]:

$$P_R = \sum_{n=1}^{n=49} \frac{(I_{\mathrm{Ln}})^2 X_{\mathrm{Ln}}}{Q_n} \tag{28}$$

where n is harmonic order, I_{Ln} is calculated current through reactor at nth harmonic, X_{Ln} is reactor reactance at nth harmonic, Q_n = quality factor of the filter at the nth harmonic and P_R is filter reactor loss.

In this paper, since high pass AC filter produced relatively small losses compared to total transmission losses, the filter losses are assumed approximately zero (actually it is not zero but this assumption for calculation simplicity) and neglected during efficiency evaluation of VSC-HVDC system.

6.3. DC cable losses

The losses in dc cable can be calculated as [21]:

$$P_{dc} = R_{dc} \cdot (P_4/V_{dc})^2 \tag{29}$$

where R_{dc} is cable resistance, V_{dc} is dc voltage at receiving side of the cable and P_4 is dc power at receiving side of the cable (see Fig. 1).

7. Efficiency evaluation of two level VSC-HVDC system

The typical system parameters of the VSC-HVDC test system shown in Fig. 1 are given below in Table 3. The system losses are evaluated using both the analytical method and software measuring method.

7.1. Analytical method

The transformer copper losses in T_1 and T_2 are calculated after obtaining the rms current which passes through the transformers. The iron losses are estimated as 20% of the copper losses. Then, the total losses are:

Table 3
System parameters.

Component	Actual value
Bus1 rated voltage	400 kV
Transformer rating	400/132 kV, 200 MVA
Transformer resistance	0.2178 Ω
Transformer reactance	55.49 mH
Coupling reactor	41.6 mH
VSC converter rating	200 MVA
DC cable resistance	0.0125 Ω/km (150 km long)
DC link voltage	300 kV

$$I_{T1} = \frac{P_1}{\sqrt{3} \cdot V_{P1}} = \frac{200 * 10^3}{\sqrt{3} \cdot 132} = 875\ \mathrm{A},$$
$$I_{T2} = \frac{P_2}{\sqrt{3} \cdot V_{P2}} = \frac{195 * 10^3}{\sqrt{3} \cdot 132} = 853\ \mathrm{A}$$

$$P_{T1} = 3 * 1.20 * \cdot I_{T1}^2 \cdot R_{T2} = 0.6\ \mathrm{MW}$$
$$P_{T2} = 3 * 1.20 * \cdot I_{T2}^2 \cdot R_{T2} = 0.57\ \mathrm{MW}$$

The switches of the two-level converter valve are composed of 105 series-connected 3.3 kV IGBTs switches with 15% redundancy to withstand 300 kV (the dc link voltage).

Using the parameters provided in the datasheets of Fig. 2.

- Number of series IGBTs = 105.
- IGBT forward resistance = 3.5 mΩ.
- IGBT threshold voltage V_T = 3.5 V.
- Freewheeling diode forward resistance = 3.0 mΩ.
- Freewheeling diode forward voltage = 2.5 V.

The switching energy due to turn-on/0ff losses is expressed as: $E = ki$ where k = 225 J/A.

The operational parameters of the converter are: $I_M = \sqrt{2} * I_{T1} = 1237$ A, Converter power factor = 0.85 lead, Modulation index = 0.856.

Then the conduction and switching losses are:

$$P_{con} = 6 * [I_{T1,av} \cdot V_{f0T1} + r_{T1} \cdot I_{T1,rms}^2 + I_{D1,av} \cdot V_{f0D1} + r_{D1} \cdot I_{D1,rms}^2] = 2.438\ \mathrm{MW}$$

$$P_{sw} = \frac{f_s}{2\pi} \int_0^{T_s} k_1 i d\omega t = 0.00852\ \mathrm{MW}$$

The dc link losses (for 192 MW and 300 kV at the receiving end of the cable) is:

$$I_{dc} = \frac{P_4}{V_{dc2}} = \frac{192 \times 10^3}{300} = 640\ \mathrm{A} \quad P_{dclosses} = 2 \cdot I_{dc}^2 \cdot R_{dc} = 1.875\ \mathrm{MW}$$

7.2. Software measuring method

After modeling the VSC-HVDC transmission system in Matlab/Simulink, the input and output powers at each component are

Table 4
Losses in the two-level VSC-HVDC system.

Component	Measured losses	% From the total losses	Analytical losses	% From the total losses
AC side1	0.55	06.88	0.6	07.58
VSC_1	2.55	31.87	2.438	30.79
DC cable	1.8	22.50	1.875	23.68
VSC_2	2.55	31.87	2.438	30.79
AC side2	0.55	0.688	0.57	07.20
Total	8.0	100	7.921	100

Table 5
Losses in the three-level VSC-HVDC system.

Component	Measured losses (MW)	%	Analytical losses (MW)	%
AC side1	0.55	08.45	0.6	08.76
VSC_1	1.8	27.70	1.9	27.74
DC cable	1.8	27.70	1.875	27.37
VSC_2	1.8	27.70	1.9	27.74
AC side2	0.55	08.45	0.57	08.32
Total	6.5	100	6.85	100

measured using discrete 3-phase positive sequence active and reactive measurements. The losses in the VSC-HVDC system given in Table 4 could be used to validate the losses in the previous section using the analytical method.

8. Efficiency evaluation of the three-level VSC-HVDC system

The same system with the same parameters is used to evaluate the efficiency of the three-level VSC-HVDC system. In this case the switches of the three-level converter valve are reduced to half that of the two-level converter and composed of 53 series-connected 3.3 kV IGBTs switches with 15% redundancy to withstand 150 kV (the dc link voltage).

Using the similar operating conditions and parameters used in previous section with the two-level VSC-HVDC, the calculated losses using both the analytical and software measuring techniques are given in Table 5.

9. Conclusions

This paper introduced analytical mathematical method to calculate the operational losses in two and three level VSC-HVDC transmission systems and Software simulation is used to validate the result obtained. The results obtained demonstrate:

- The use of a NPC three-level converter reduces the conversion losses in the converter as the effective switching frequency per device is reduced to half compared to that in a two-level converter.
- The conversion losses represent around 63.74% of the total losses in two-level converter and 55.5% in three-level converter.
- The conversion losses can be reduced by using a higher multi-level approach.

References

[1] Bahrman MP, Johnson BK. The ABCs of HVDC transmission technologies. Power Energy Mag IEEE 2007;5:32–44.
[2] Hammons TJ et al. Role of HVDC transmission in future energy development. Power Eng Rev IEEE 2000;20:10–25.
[3] Meah Kala et al. A new simplified adaptive control scheme for multi-terminal HVDC transmission systems. Int J Electr Power Energy Syst 2010;32(4):243–53.
[4] Flourentzou N et al. VSC-based HVDC power transmission systems: an overview. IEEE Trans Power Electron 2009;24:592–602.
[5] Agelidis VG, et al. Recent advances in high-voltage direct-current power transmission systems. In: IEEE international conference on industrial technology 2006, ICIT 2006; 2006. p. 206–13.
[6] Latorre HF et al. Improvement of power system stability by using a VSC-HVDC. Int J Electr Power Energy Syst 2011;33(2):332–7.
[7] Senthil Kumae N et al. Impact of FACTS controllers on the stability of power connected with doubly fed induction generator. Int J Electr Power Energy Syst 2011;33(5):1172–84.
[8] Hui P, et al. Evaluation of losses in VSC-HVDC transmission system. In: Power and energy society general meeting – conversion and delivery of electrical energy in the 21st century, 2008 IEEE; 2008. p. 1–6.
[9] Ackermann T. Wind power in power system. John Wiley & Sons, Ltd.; 2005.
[10] Dahono PA et al. Analysis of conduction losses in inverters. Electr Power Appl IEE Proc 1995;142:225–32.
[11] Arrillage YHLLJ, Watson NR. Flexible power transmission systems – the HVDC options. John Wiley & Sons Publication; 2007.
[12] Cole S, Belmans R. Transmission of bulk power. Ind Electron Mag IEEE 2009;3:19–24.
[13] Ramadan HS et al. Performance enhancement and robustness assessment of VSC–HVDC transmission systems controllers under uncertainties. Int J Electr Power Energy Syst 2012;35(1):34–46.
[14] Blaabjerg F et al. Power losses in PWM-VSI inverter using NPT or PT IGBT devices. IEEE Trans Power Electron 1995;10:358–67.
[15] Tae-Jin K, et al. The analysis of conduction and switching losses in multi-level inverter system. In: Power electronics specialists conference, PESC. IEEE 32nd annual, vol. 3; 2001. p. 1363–8.
[16] Oh KS. Application note 9016: IGBT basics 1, FAIRCHILD Semiconductor, Rev. A2; Febuary 2001.
[17] Kolar JW et al. Influence of the modulation method on the conduction and switching losses of a PWM converter system. IEEE Trans Ind Appl 1991;27:1063–75.
[18] Zhang Yushu, et al. Voltage source converter in high voltage application: multilevel versus tow-level converets. In: Presented at the ACDC 2010, the 9th international conference on AC and DC power transmission, London, UK, October 2010.
[19] Yazdani A, Iravani R. Voltage-sourced converters in power systems: modeling control, and applications. Hoboken (New Jersey): John Wiley & Sons, Inc.; 2010.
[20] IEEE recommended practice for determination of power losses in high-voltage direct-current (HVDC) converter stations. IEEE Std. 1158-1991; 1992. p. 1.
[21] Barberis Negra N et al. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. Electr Power Syst Res 2006;76(11):916–27.