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Calculation of Losses in VSC-HVDC based on MMC Topology

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Abstract

VSC technology is now well established in HVDC and is, in many respects, complementary to the older Line Commutated Converter (LCC) technology. Despite the various advantages of VSC technology, VSC HVDC stations have higher power losses than LCC stations. Although the relative advantages and disadvantages are well known within the industry, there have been very few attempts to quantify these factors on an objective basis. This paper describes methods to determine the operating losses of every component in the valve of VSC-HVDC system. The losses of the valve, including both conduction losses and switching losses, are treated in detail.

Keywords: Modular Multilevel Converter, HVDC, Losses, IGBT, Diode

I. INTRODUCTION

Voltage source converter based High-Voltage Direct Current (VSC-HVDC) transmission technology is becoming more important, both as a wide area controller to assist AC networks and as an enabling technology for large renewable energy farms (wind farms, solar farms). It is more and more noticeable because of the ability to feed passive (island) loads or into very weak AC systems, the smaller site footprint and the ability to control both active and reactive power [1]. Many researches indicated that the Modular Multilevel Converter (MMC) is particularly promising, with respect to efficiency, reliability and fault handling [1].

The Modular Multi-level Converter (MMC) and the Cascaded Two-Level (CTL) converter, have dramatically changed this situation by allowing the switching frequency to be reduced by an order of magnitude, while simultaneously achieving better harmonic performance than what is possible with two-level and three-level converters [2]. The Modular Multi-level Converter was originally proposed in 2001, and has the form shown in Fig. 2. It is composed of a set of submodules. The operation of these individual converters is coordinated by a central control to synthesize the AC and DC terminal voltages. The MMC has now been adopted widely for implementing multilevel power conversion for HVDC, having a number of advantages over previous methods [3].

However, the major disadvantage of VSC-HVDC compared with LCC HVDC has been the much higher power losses. The initial VSC-HVDC based on 2-level or 3-level converters structure rely on a relatively high IGBT switching frequency, typically 1-2 kHz, to obtain adequately low harmonic distortion. Therefore, the high switching frequency leads to very high switching losses in the IGBT's and freewheel diodes, while the conduction losses are also higher than for thyristor-based LCC HVDC systems [4]. As a result, the power losses of such VSC HVDC stations have been in the range of 2-4% per station, excluding the losses in the cable or line. This is much higher than for LCC stations, which are generally around 0.75% per station. In addition, the initial VSC-HVDC required significant screening and filtering to eliminate both airborne and conducted radio frequency interference.

As a result, the overall losses per VSC station now stand at around 1% per station: still higher than for LCC, but close enough for the two technologies to be able to compete in some applications. The evaluation of losses is needed for determining the component and equipment ratings and increase operation efficiency of transmission system by optimization design for devices that producing large losses. The intention of this paper is to present an analytical method for calculating the power losses of an MMC-based VSC HVDC converter.

II. ANALYSIS OF LOSSES OF CONVERTER

The MMC converter valves are composed of high power IGBT and anti-parallel free-wheeling diode (FWD) in the same semiconductor package to ensure current capability in the

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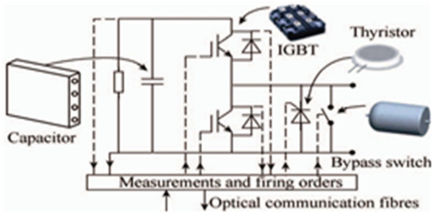

Fig. 1. Half Bridge Submodule.

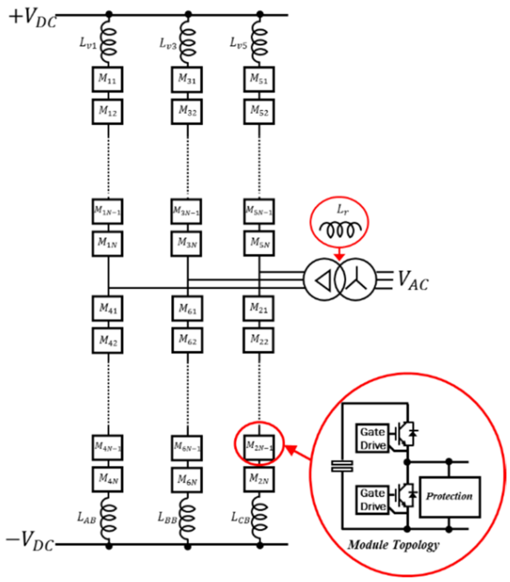

Fig. 2. MMC (Modular Multi-level Converter) Structure.

opposite direction and to prevent the application of reverse voltage. Furthermore, the valves must include the components that realize functions of voltage grading, monitor, control and heat sink, etc. So, a complete IGBT valve unit consists of an IGBT, a gate driver, a voltage grading circuit, a monitoring and protecting circuit, a current detecting circuit, as shown in Fig. 1 and Fig. 2.

The losses of IGBT submodule would be categorized into several groups as follows:

- P_{V1} IGBT conduction losses
- P_{V2} Diode conduction losses
- P_{V3} Other valve conduction losses
- P_{V4} DC voltage-dependent losses
- P_{V5} DC capacitor losses
- P_{V6} IGBT switching losses
- P_{V7} Diode turn-off losses
- P_{V8} Snubber losses
- P_{V9} Valve electronics power consumption

The dominant components of the valve losses are the semiconductor device conduction losses, P_{V1} and P_{V2}, and switching losses, P_{V6} and P_{V7}. Snubber losses (P_{V8}) can potentially be quite large in valves which use snubbers, but since most current VSC valves using IGBTs do not employ snubbers, this component can often be neglected. Before the loss calculation, the following assumptions have to be adopted:

- Neglect the switching time and dead-time

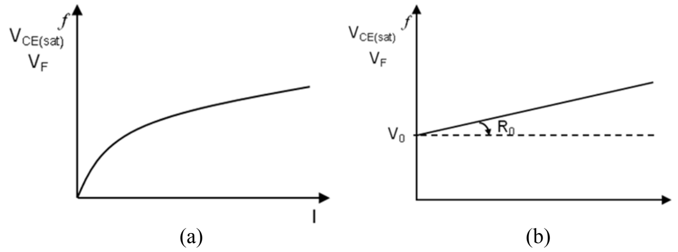

Fig. 3. Typical IGBT and Diode on-state characteristics. (a) Real, (b) piecewise-linear approximation.

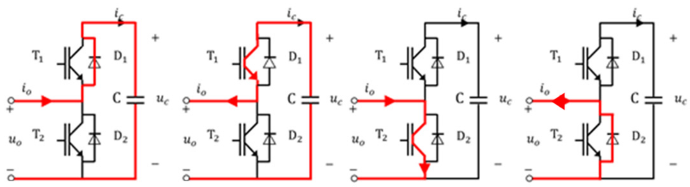

Fig. 4. Conduction condition of IGBT and FWD.

- Semiconductor Junction temperature keeps constant
- Converter operates in linear modulation
- Neglect the harmonious in the current of network
- Modulation frequency much larger than frequency of AC system

The relation between collector-emitter voltage of IGBT (forward voltage drop of FWD) and device current would be obtained by a linear equation based on the assumptions above.

A. Semiconductor conduction losses (P_{V1} and P_{V2} - IGBT and Diode Conduction Losses)

One of the most important components of the VSC valve losses is the conduction loss in the free-wheeling diodes and IGBTs. In the conducting state shown in Fig. 3, the semiconductor device has an on-state voltage which varies non-linearly with current and the on-state voltage is typically about 3 V at rated current.

The instantaneous power dissipation in the device is simply obtained by multiplying the on-state voltage by the current. This can then be averaged over a cycle to find the expected conduction losses in each device. It is possible to obtain a relatively accurate curve-fit to the on-state voltage as a function of current and thus approximate very accurately the characteristics shown on the left side of Fig. 3. In order to make the process of determining losses more transparent, an approximation is used whereby the on-state voltage is modelled as a piecewise-linear characteristic as shown in Fig. 3(b) and described in Eq. (1) and Eq. (2).

IGBT $$V_{ce(sat)}(I_T) = V_{0T} + R_{0T} \cdot I_T \tag{1}$$

Diode $$V_F(I_D) = V_{0D} + R_{0D} \cdot I_D \tag{2}$$

The time-averaged conduction losses can then be expressed in terms of the mean and RMS currents in each device:

IGBT $$P_{V1} = V_{0T} \cdot I_{Tav} + R_{0T} \cdot I_{Trms}^2 \quad (3)$$

Diode $$P_{V2} = V_{0D} \cdot I_{Dav} + R_{0D} \cdot I_{Drms}^2 \quad (4)$$

The above approximation allows the conduction losses to be determined simply from a knowledge of V_0 and R_0 for each type of IGBT device and from a knowledge of the mean and RMS currents in each device. The conduction losses, which is generated due to the volt drop across the IGBT or diode during conduction, is simply a product of the on-state voltage drop and the current in the IGBT device as is given in Eq. (5).

$$P_{cond} = \frac{1}{2\pi} \cdot \int_0^{2\pi} I_T(\omega t) \cdot V_{CE(sat)}(I_T) \cdot d(\omega t) \quad (5)$$

where $I_T(\omega t)$ represents the current in the device and $V_{CE(sat)}(I_T)$ the on-state volt drop across the device for a given current.

Eq. (5) is simplified by using a linear approximation for $V_{CE(sat)}(I_T)$, using a threshold value and a slope angle to model the relationship. Using this simplified relationship, Eq. (5) can be rewritten as follow:

$$P_{cond} = V_0 I_{av} + R_0 I_{rms}^2 \quad (6)$$

where V_0 is the threshold voltage for the approximation of the relationship shown in Fig. 3, and R_0 is the slope resistance shown in the same figure. Once V_0 and R_0 have been determined the average and rms current in the device are calculated. The average current is given as follows:

$$I_{av} = \frac{1}{2\pi} \int_0^{2\pi} I(\omega t)^2 \cdot d(\omega t) \quad (7)$$

The RMS current is given by:

$$I_{RMS} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} I(\omega t)^2 \cdot d(\omega t)} \quad (8)$$

In order to assess these values and obtain results, the conduction periods of each IGBT and diode in the sub-module needs to be considered. Using the above equations and Fig. 4, and considering the conduction periods, equations can be derived to describe the losses for each device. IGBT1 and D1 only conduct when the link is in output state, and IGBT2 and D2 only conduct when the link is bypassed. Also, using conduction criteria the appropriate limits can be selected in order to evaluate the integrals for the periods in which the components are conducting during a cycle.

Each converter arm contains series connected capacitors in which each can be either inserted or bypassed from the current path. Thus, the total arm voltage is synthesized by the summation of inserted capacitor voltages. The low-level control continuously generates the firing pulses for each individual submodule based on the required voltage level at each time step. In summary, the high-level control generates the reference signal for each converter arm and the low-level control decides how many submodules and which ones should be inserted.

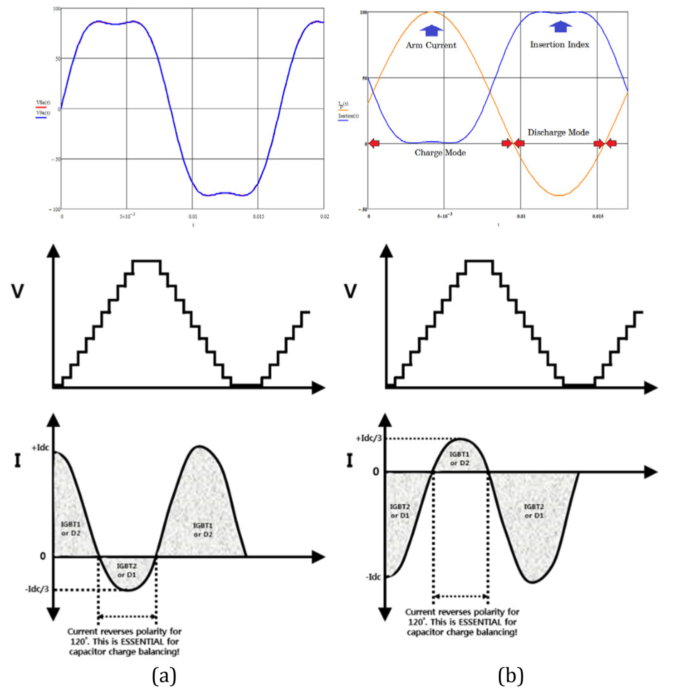

Fig. 5. Submodule Conduction Operation. (a) Rectifier Mode, (b) Inverter Mode.

There is a variety of combinations which can result in the required arm voltage level. Assuming identical capacitor voltage level for all submodules, the submodule selection scheme can be perceived as a scheme to select some items out of a collection. Therefore, the binomial coefficient gives the number of available combinations for each required voltage level. The binomial coefficient for the selection of n_{ref} out of N submodules is calculated as:

$$n_{ref} = \frac{N!}{n_{ref}!\,(N - n_{ref})!} \quad (9)$$

where N is the total number of submodule per arm and the insertion index, n_{ref} is a reference signal which equals the normalized required voltage level of each converter arm. The main objective of a submodule selection scheme is to insert the proper submodules, at proper time instants.

As stated above, the behavior of a given sub-module is hard to predict because of the way the capacitor balancing algorithm works. So, it is not possible to say with certainty in which periods of a cycle a sub-module will be in the output or bypassed states. However, with power loss calculations we are only interested in the average behavior rather than the instantaneous behavior. Since the number of sub-modules in a valve is very large, it is possible to use a statistical approach to calculate the average and RMS currents in each IGBT. This approach is based on determining the probability that a particular sub-module will be in the output state, as a function of time. $P_c(\omega t)$ is a term representing the probability that a sub-module is conducting, and therefore generating voltage. Hence at a given time in the cycle, each sub-module has an associated probability that it is conducting. In effect, $P_c(\omega t)$

is directly proportional to valve voltage. Fig. 5 shows the conduction period, the voltage and the current in the valve during rectifier and inverter operation. The point at which the current first passes the zero crossing can be calculated as:

$$\theta = cos^{-1}\left(-\frac{\lambda}{2}\right) \quad (10)$$

The modulation index, λ , is a quantity that describes the factor by which the peak AC voltage and DC voltage differ. This can be seen in the following equation:

$$\lambda = \frac{2}{V_{DC}} \cdot \left(V_{AC} \cdot \frac{\sqrt{2}}{\sqrt{3}}\right) \quad (11)$$

Therefore, the conduction loss is given as follow:

$$P_{con}(\omega t) = \frac{1}{2}(1 - \lambda \cdot cos(\omega t)) \quad (12)$$

Eq. (12) uses the fundamental voltage. This allows for the inclusion of third harmonic injection. Assuming unity power factor, with the current 180 degrees out of phase with the voltage the current becomes:

$$I(\omega t) = \frac{1}{3}\left(1 + \frac{2}{\lambda}cos(\omega t)\right) \quad (13)$$

For the upper components IGBT1 and D2, the general equation for the average and RMS current is as follow:

$$I_{av} = \frac{1}{2\pi}\int_{\omega t1}^{\omega t2} I(\omega t)P_c(\omega t) \cdot d(\omega t) \quad (14)$$

For the lower components IGBT2 and D1, to reflect the reversed voltage across the device, the equation becomes:

$$I_{av} = \frac{1}{2\pi}\int_{\omega t1}^{\omega t2} I(\omega t)(1 - P_c(\omega t)) \cdot d\omega t \quad (15)$$

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_{\omega t1}^{\omega t2} (I(\omega t))^2(1 - P_c(\omega t)) \cdot d\omega t} \quad (16)$$

The next step is to use Eq. (8) for $I(\omega t)$, and Fig. (12) for $P_{con}(\omega t)$ and evaluate the integrals for the following conduction periods. Using the equations given in Fig. 6 and combining with the original simplification given in Eq. (14) and Eq. (15), the losses due to conduction can be calculated. Therefore, assuming the same IGBT and diodes are used in both positions in the sub-module, the per-sub-module losses for P_{V1} and P_{V2} can be summarized as follows:

Rectifier Mode

$$\begin{aligned} &P_{V1} + P_{V2} \\ &= \frac{I_{DC}}{6\pi}\left[\left(2\theta - 2\pi + \frac{4}{\lambda}\sqrt{1 - \frac{\lambda^2}{4}}\right).V_{0D} + \left(2\theta + \frac{4}{\lambda}\sqrt{1 - \frac{\lambda^2}{4}}\right).V_{0T}\right] \\ &+ \frac{I_{DC}^2}{18\pi}\left[\left[\left(3 + \frac{3}{\lambda^2}\right).\pi - 4\theta - \left(\frac{16}{3\lambda} + \frac{2\lambda}{3}\right)\sqrt{1 - \frac{\lambda^2}{4}}\right].R_{0D}\right] \\ &+ \frac{I_{DC}^2}{18\pi}\left[\left[\left(\frac{2}{\lambda^2} - 1\right).\pi + 4\theta + \left(\frac{16}{3\lambda} + \frac{2\lambda}{3}\right)\sqrt{1 - \frac{\lambda^2}{4}}\right].R_{0T}\right] \end{aligned} \quad (17)$$

Inverter Mode

$$\begin{aligned} &P_{V1} + P_{V2} \\ &= \frac{I_{DC}}{6\pi}\left[\left(2\theta - 2\pi + \frac{4}{\lambda}\sqrt{1 - \frac{\lambda^2}{4}}\right).V_{0D} + \left(2\theta + \frac{4}{\lambda}\sqrt{1 - \frac{\lambda^2}{4}}\right).V_{0T}\right] \\ &+ \frac{I_{DC}^2}{18\pi}\left[\left[\left(3 + \frac{3}{\lambda^2}\right).\pi - 4\theta - \left(\frac{16}{3\lambda} + \frac{2\lambda}{3}\right)\sqrt{1 - \frac{\lambda^2}{4}}\right].R_{0D}\right] \\ &+ \frac{I_{DC}^2}{18\pi}\left[+\left[\left(\frac{2}{\lambda^2} - 1\right).\pi + 4\theta + \left(\frac{16}{3\lambda} + \frac{2\lambda}{3}\right)\sqrt{1 - \frac{\lambda^2}{4}}\right].R_{0T}\right] \end{aligned} \quad (18)$$

B. Semiconductor conduction losses (P_{V1} and P_{V2} – IGBT and Diode Conduction Losses)

Other valve conduction losses are due to the resistance of conducting components in the valve other than the IGBT's and diodes such as bus bars within the submodule and between sub-modules, and between tiers of the valve. In order to evaluate the losses from bus bar conduction within the valve, the arrangement of the current path needs to be understood.

Fig. 4 represents the current path through one valve. Each sub-module is connected to its neighbors using a copper linking piece. At the end of each module one of these links is used to connect to the module bus bar which results 9 bus bar links per module. For the Nordbalt project, which has 352 sub-modules per valve, these are arranged in 3 tiers of 14 or 15 modules. Each tier is then connected via a bus bar that runs up to the next tier, then the full length of the valve back to the other side of the tier. This arrangement minimizes the voltage stress and insulation requirement between tiers. Therefore, in order to calculate the total resistance of the bus bar arrangement, the number of modules per valve is multiplied by the required number of bus bar links per module. A value of 2 μΩ is used for the resistance of each bus bar link. This contribution is then added to the resistance of the external bus bars, which are copper tubing of outside diameter 160 mm and inside diameter of 140 mm. This provides the total resistance of the bus bar network. This is then added to the contribution of the bus bar inside each sub-module. This provides the value for R_S.

$$P_{V3} = I_{VRMS}^2 \cdot R_S \quad (19)$$

C. P_{V4} – DC Voltage Dependent Losses

The DC voltage-dependent losses are due to shunt resistive components in the valve. In the MMC converter, these are dominated by the 'bleed' resistors connected across each sub-module DC capacitor. In AREVA's design these are implemented as 2×330 kΩ resistors in parallel. In order to calculate the DC voltage dependent losses, the DC voltage is considered to be shared equally across all of the sub-module capacitors. The loss through the sub-module bleed resistors is considered as this voltage. In the case of this specific sub-module design, with equal R_1 and R_2, their total resistance is simply $R_1/2$. Hence, P_{V4} is given by:

$$P_{V4} = \frac{2}{R_1} \cdot \left(\frac{2 \cdot V_{DC}}{N_1}\right)^2 \tag{20}$$

D. P_{V5} – Losses in Sub-module Capacitors

Each sub-module capacitor carries a component of current, and as a consequence contributes towards losses. These come from both dielectric and ohmic losses in the capacitor. These have been treated by considering the equivalent series resistance R_{ESR} of the capacitor.

$$P_{V5} = N_t \cdot I_{cRMS}^2 \cdot R_{ESR} \tag{21}$$

where N_t is the number of levels, I_{cRMS} is the RMS current flowing in the capacitor, and R_{ESR} is the effective series resistance of the capacitor. I_{cRMS} can be found by summing vectorially the RMS currents in IGBT1 and D1, which upon simplification yields the following:

$$I_{cRMS} = \frac{Idc}{3 \cdot \sqrt{2}} \cdot \sqrt{\frac{2}{\lambda^2} - 1} \tag{22}$$

E. P_{V6} and P_{V7} – Switching Losses (Semiconductor switching lossess)

Every time an IGBT turns on or off, a small amount of energy is lost in the device, referred to as the switching energy. In addition, the turn-on of an IGBT is always accompanied by the turn-off of a diode elsewhere in the circuit. Diode turn-off also results in energy being lost. The IGBT turn-on and turn-off energies and the diode "recovery" energy are abbreviated E_{on}, E_{off} and E_{rec} respectively. They depend on several parameters of the converter but most importantly on the current in the device. The relationships between E_{on}, E_{off}, E_{rec}, and current may be conveniently represented as a linear relationship with current (IGBT switching energy) and a piece-wise linear representation (diode recovery energy):

IGBT turn-on $\quad E_{on} = k_{on} \cdot I_T$

IGBT turn-off $\quad E_{off} = k_{off} \cdot I_T$

Diode turn-off(rec) $\quad E_{rec} = k_{rec1} + k_{rec2} \cdot I_D$

If the waveform of the current in the valve can be represented mathematically and the switching instants occur regularly, predictable instants (as is the case for a two-level converter), it is quite simple to calculate the total switching losses in the semiconductors by simply summing the switching energies in each cycle and multiplying the result by the switching frequency. The MMC topology, however, is more complex and a direct analytical approach is difficult.

Along with conduction losses, the switching losses in IGBTs and diodes account for one of the major sources of loss within a VSC valve. During switching an IGBT device is subjected to both high current and high voltage simultaneously, and as a result the IGBT incurs a high-power dissipation for a short time. The turn on and turn off switching losses depend on the value of the collector current during the on-state and the collector-emitter voltage during the off-state.

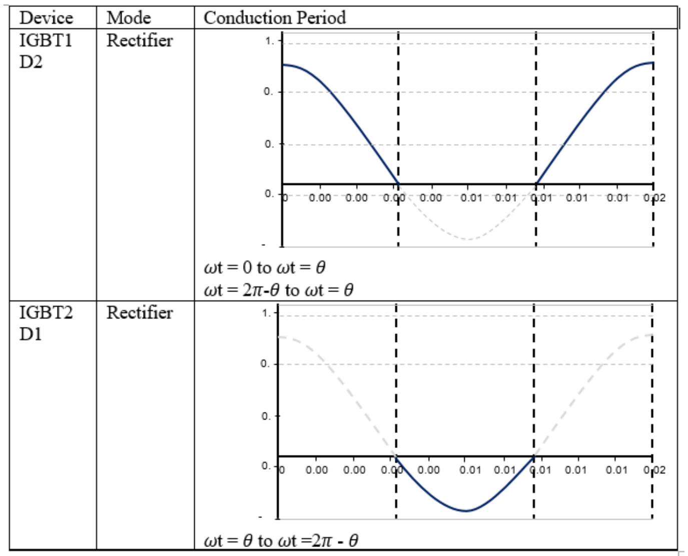

Fig. 6. IGBT and Diode Conduction Period.

$$P_{V6} = N_t \cdot f \cdot \sum (E_{on}(V, I) + E_{off}(V, I)) \tag{23}$$

For diodes the turn-on loss is negligible, the losses during turn-off are due to 'Reverse Recovered Charge', Q_{rr}, which passes through the diode after turn-off, in a similar way to a thyristor. The product of Q_{rr} and sub-module DC capacitor voltage gives rise to a turn –off loss E_{rec}.

$$P_{V7} = N_t \cdot f \cdot \sum_{cycle} E_{rec}(V, I) \tag{24}$$

As with conduction losses these relationships for E_{on}, E_{off} and E_{rec} are approximated as linear relationships varying with current. E_{on} and E_{off} are given as follow:

$$\begin{aligned} E_{on} &= k_{on} \cdot I \\ E_{off} &= k_{off} \cdot I \end{aligned} \tag{25}$$

For the diode this is modelled as a straight line plus intercept:

$$E_{rec} = k_{rec1} + k_{rec2} \cdot I \tag{26}$$

Therefore, if a switching event takes place at a point ωt, then the losses incurred are as follows:

IGBT $\quad E_{swT}(\omega t) = (k_{on} + k_{off}) \cdot I(\omega t) \quad (27)$

Diode $\quad E_{swD}(\omega t) = k_{rec1} + k_{rec2} \cdot I(\omega t) \quad (28)$

Table 1. Parameters used in Losses Calculation of VSC HVDC Station

Items	Symbol	Values
Rated IGBT Voltage	IGBT-V	3.3 kV
Rated IGBT Current	IGBT-I	1.2 kA
DC System Voltage	V_{DC}	293 kV
AC System Voltage	V_{AC}	306 kV
DC System Current	I_{DC}	711 A
Slope Resistance of IGBT	R_{0T}	2.00E-03 Ω
Slope Resistance of Diode	R_{0D}	1.75E-03 Ω
Threshold Voltage of IGBT	V_{0T}	1.3 V
Threshold Voltage of Diode	V_{0D}	1 V
IGBT Turn Off Losses Slope	K_{off}	1.83E-03
IGBT Turn On Losses Slope	K_{on}	1.67E-03
System Frequency	f	60 Hz
Diode Recovery Loss Threshold	K_{rec1}	0.35
Diode Recovery Loss Slope	K_{rec2}	7.08E04
Number of switching events per Fundamental Cycle	ns	3
Number of sub-module Levels	N_t	352
Effective Series Resistance of Sub-Module Capacitor	R_{ESR}	0.26 m Ω
Sub-module Resistor Values	R_1/R_2	330000 Ω

Table 2. Loss Calculation Result of VSC HVDC Station

	Station	
	Rectifier	
Per Unit Load	No Load	1 P.U.
AC Voltage Peak (kV)	306.43	306.43
Valve RMS Current (A)	0.00	711.50
DC Voltage (kV)	304.00	304.00
DC Current (A)	0.00	1211.00
Modulation Factor	0.82	0.82
Conduction Period (Degree)	114	114
System Frequency (Hz)	50.00	50.00
Maximum Number of Submodule (in Valve)	352.00	352.00
	Valve Losses (kW)	
Component (IEC62751-2 clause)	No Load	1 P.U.
$P_{V1}+P_{V2}$: IGBT and Diode Conduction Losses	0.00	739.401
P_{V3}: Other Valve Conduction	0.00	0.88
P_{V4}: DC Voltage Dependent	6.365	6.365
P_{V5}: DC Sub-module capacitor losses	0.00	14.56
$P_{V6}+P_{V7}$: IGBT and Diode Switching Losses	0.00	161.19
P_{V8}: Snubber losses	0.00	0.00
P_{V9}: Valve Electronic losses	3.52	3.52
PVT: Total Valve losses	9.88	925.9
Total Station Losses (352 x 2 x 3)	59.31	5555.5
% Loss of 700 MW	0.0085	0.79

Eq. (27) and (28) can be considered as the 'instantaneous switching loss' of the device. Although the instantaneous switching frequency will vary from cycle to cycle, the average switching frequency has been shown, by Matlab simulation, to be approximately 3 times fundamental, i.e n_s=3. For the purposes of the following analysis, switching events are assumed to be equally distributed throughout the power frequency cycle. The quantity f_s is defined as the average number of times that a sub-module will switch per radian. Hence:

$$f_s = \frac{n_s}{2 \cdot \pi} \tag{29}$$

Using this concept, we can calculate the average switching power of a particular device by multiplying the 'instantaneous switching loss' by the switching frequency f_s and integrating over a period during which the device in question is conducting, then multiplying by the system frequency. If we use simply the first half cycle, then we can simply multiply by twice the system frequency.

For example:

$$PsT1 = 2 \cdot f \cdot \int_0^{\theta} fs(\omega t) \cdot \left(k_{on} + k_{off}\right) \cdot I(\omega t) \cdot d\omega t \tag{30}$$

Following this process through, and substituting:

$$I(\omega t) = \frac{I_{dc}}{3}\left(1 + \frac{2}{\lambda} cos(\omega t)\right) \tag{31}$$

In case of negative current during the time in question:

$$I(\omega t) = -\frac{I_{dc}}{3}\left(1 + \frac{2}{\lambda} cos(\omega t)\right) \tag{32}$$

These are considered in conjunction with the appropriate conduction period for the device.

F. P_{V8} – Snubber Circuit Losses

The P_{V8} term represents the losses in the snubber circuit of a generic VSC valve. As this circuit is not present in many company's circuit topology, this loss is considered to be zero.

G. P_{V9} – Valve Electronic Losses

In order to calculate the total losses for the valve electronic losses, the energy consumption of each sub-module is simply multiplied by the number of sub-modules:

$$P_{V9} = N_t \cdot P_{GU} \tag{21}$$

III. CALCULATION OF LOSSES

The dominant components of the valve losses are the IGBT conduction losses P_{V1} and P_{V2} and switching losses P_{V6} and P_{V7} Snubber losses (P_{V8}) can potentially be quite large in valves which use snubbers, but since most current VSC valves using IGBTs do not employ snubbers, this component can often be neglected. As discussed above section, loss calculation considers the conduction losses for the other valve components. Here each module is considered to have 9 links, each contributing a 2 μΩ resistance. The external bus bars are considered to run the full length of the valve 3 times horizontally, and the height of 2 modules plus an insulator vertically. Therefore, this full length is used to calculate the resistance of the external bus bars. Consequently, the value of R_s per valve is 1.7 mΩ. In addition, the estimated consumption of each sub-module electronics package is considered to be below 10 W. Therefore, calculation of the losses due to the electronics levels is simply taken 10 W multiplied by the number of sub-modules in the converter. In no-load condition, where the converter is in a 'hot-standby' mode, that is where the system is in standby and not transmitting, no-load losses can be evaluated as the sums of the DC voltage-dependent losses, and the gate electronics losses.

Through tabulation of the results with respect to the system conditions at each station the following loss data is calculated in Table 2.

IV. CONCLUSIONS

This paper deals with the method of finding the loss of MMC HVDC system. The existing IEC specification does not provide an exact formula for the VSC HVDC system. In addition, since the MMC method deals with the NLM (Nearest Level Modulation) method and the various sorting methods for balancing the submodule, the method of obtaining loss is different for each company. However, in this paper, the loss is calculated based on the loss reduction and the TBS (Tolerance Band Sorting) method for the third harmonic injection. If the loss calculation method presented in this paper considers the error (probably within 5%) according to the sorting method, it will provide an accurate calculation within an error rate of 0.05%.

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