Analytical Loss Equations for Three Level Active Neutral Point Clamped Converters

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***Abstract*—This paper presents the analytical expressions that can be used to calculate conduction and switching losses in each device of an Active Neutral Point Clamped Converter. These expressions can be used to determine the losses in the individual components at different load current, power factor and modulation index to map the critical operation points while dimensioning the devices. The operation at nominal frequency and at dc current have been analyzed as the machine draws zero frequency current at startup. The validity of the expressions have been substantiated by simulation results and numerical calculation of the losses using datasheet parameters.**

***Index Terms*—Active Neutral Point Clamped Converter, Analytical loss calculation, Medium-voltage drives, Variable Speed Drives**

I. Introduction

For medium-voltage drives applications in industries, Neutral Point Clamped (NPC) converter has been the major workhorse since it was introduced in early 80's [1]. The NPC converter is best suited for many applications except few like pump storage hydropower plant, hoists, lifts and cranes where either very high starting torque is required or zero speed is maintained for significantly long duration. In such operating scenarios, the dc current loading stresses the inner semiconductor devices excessively because the conduction loss and switching loss both occurs at maximum current continuously. Therefore, it either needs to be over-sized or needs to be operated with lower dc current to protect the devices.

The above problem is eliminated in Active Neutral Point Clamped (ANPC) converter where additional switching devices are connected across the clamping diode and was first presented in [2], [3]. While designing such converters, the stress in all individual components of the converter is analyzed. This analysis requires the expressions to calculate the conduction and switching losses in each devices. Such expressions exist for two level three phase converters and three level NPC converters. In this paper, the analytical equations to calculate the losses in the semiconductor devices of ANPC converter with sinusoidal PWM modulation is presented. This method was first implemented for 2-level 3-phase converter in [4] and later for 3-level 3-phase Neutral Point Clamped (NPC) converter in [5]. This paper extends this concept for determining the analytical equations for calculation of conduction and switching losses in a 3-level 3-phase ANPC converter. These expressions will aid to fast and simplified way of loss analysis at various operating cases like at different load current, load power factor ($\cos\varphi$), modulation index (M) and fundamental frequency (f_n).

In medium voltage drives, normally the switching frequency is very low in the range of 200 – 500 Hz to avoid high switching loss in the devices [6]. Synchronous optimal modulation is used while switching at low frequency and the turn on and turn off current pulses differ from that in case of sinusoidal PWM modulation. The expressions for conduction loss and switching loss derived in this paper will not be accurate to high degree for synchronous optimal modulation case. But as the semiconductor device technology with wide band-gap devices like SiC MOSFETs and IGBTs are rapidly developing, the conventional PWM modulation techniques with high switching frequency can again be used. In that case, all these expressions will be precisely valid.

II. Converter Topology

A. Active Neutral Point Clamped (ANPC) Converter

The schematic of ANPC converter topology is presented in Fig. 1. The additional switches T_5 and T_6 across the clamping diodes D_5 and D_6 compared to the NPC converter provide parallel path for the current flow through the inner devices (D_5 & T_2 and D_6 & T_3) and hence reduce the losses in these devices.

The current through each devices of bridge leg "A" is presented in Fig. 2. The Level Shifted PWM Modulation strategy is used to control the switching devices. Looking into the symmetry of the position of the devices in a bridge leg and the current through them, the losses in the upper devices T_1, D_1, T_2, D_2, T_5 and D_5 of a bridge leg is same as that in the lower devices.

III. Analytical Loss Equations

A. Averaging Method

The current through the devices of an ANPC converter is a quite discontinuous current as shown in Fig. 2. The width of the microscopic pulses depend upon the carrier frequency (f_{sw}) and the amplitude of sinusoidal modulation index (m_a). Then number of pulses depends on the frequency modulation ratio (m_f) as in (1).

$$m_f = \frac{f_{sw}}{f_n} \tag{1}$$

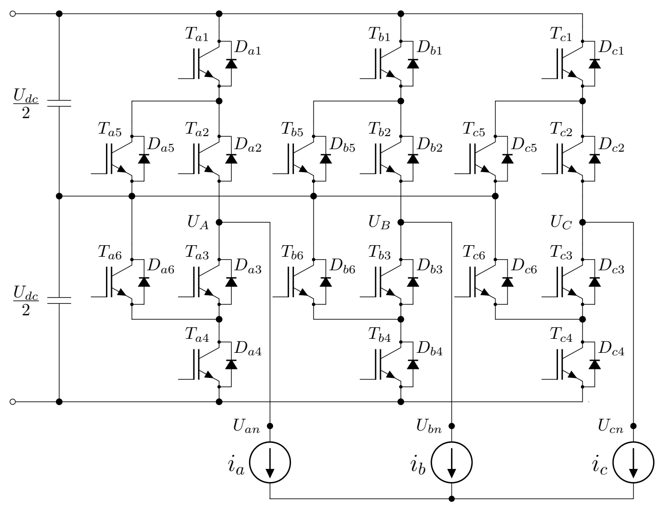

Fig. 1. Schematic of a 3-phase 3-level Active Neutral Point Clamped (ANPC) Converter configuration.

where, f_{sw} is the switching frequency or the frequency of the carrier waves (c_1 and c_2) shown in Fig. 2 and f_n is the frequency of fundamental component of the output voltage or current.

The averaging method samples the discontinuous current signals through the devices within a switching interval and transforms it into a continuous microscopic mean or rms signal. Therefore, the accuracy decreases as the switching frequency decreases. Mathematically, this method integrates the multiplication of m_a and the output current, e.g. i_a for phase "a" and takes the average of it over a cycle. The average of these microscopic currents over a fundamental cycle (T_p) is as presented in Fig. 3 [4].

The analytical equations to calculate average currents have been carried out with sinusoidal PWM modulation technique and the modulation signals are as in (2).

$$\begin{aligned} m_a &= M\cos(\omega t) \\ m_b &= M\cos(\omega t - 2\pi/3) \\ m_c &= M\cos(\omega t + 2\pi/3) \end{aligned} \tag{2}$$

The load is modelled as a pure sinusoidal current source and the phase angle (φ) is controlled w.r.t. the phase of the modulation signal m_a for phase "a" as in (3).

$$\begin{aligned} i_a &= \hat{I}_o\cos(\omega t + \varphi) \\ i_b &= \hat{I}_o\cos(\omega t + \varphi - 2\pi/3) \\ i_c &= \hat{I}_o\cos(\omega t + \varphi + 2\pi/3) \end{aligned} \tag{3}$$

where, i_a, i_b and i_c are the instantaneous output currents and $\hat{I}_o$ is the peak of the these currents.

B. Conduction Loss

The voltage drop across a semiconductor device during conduction period can be modelled as a forward voltage (U_{CE0}) and an Ohmic drop ($R_{CE,on}$) in series with that voltage as expressed in (4).

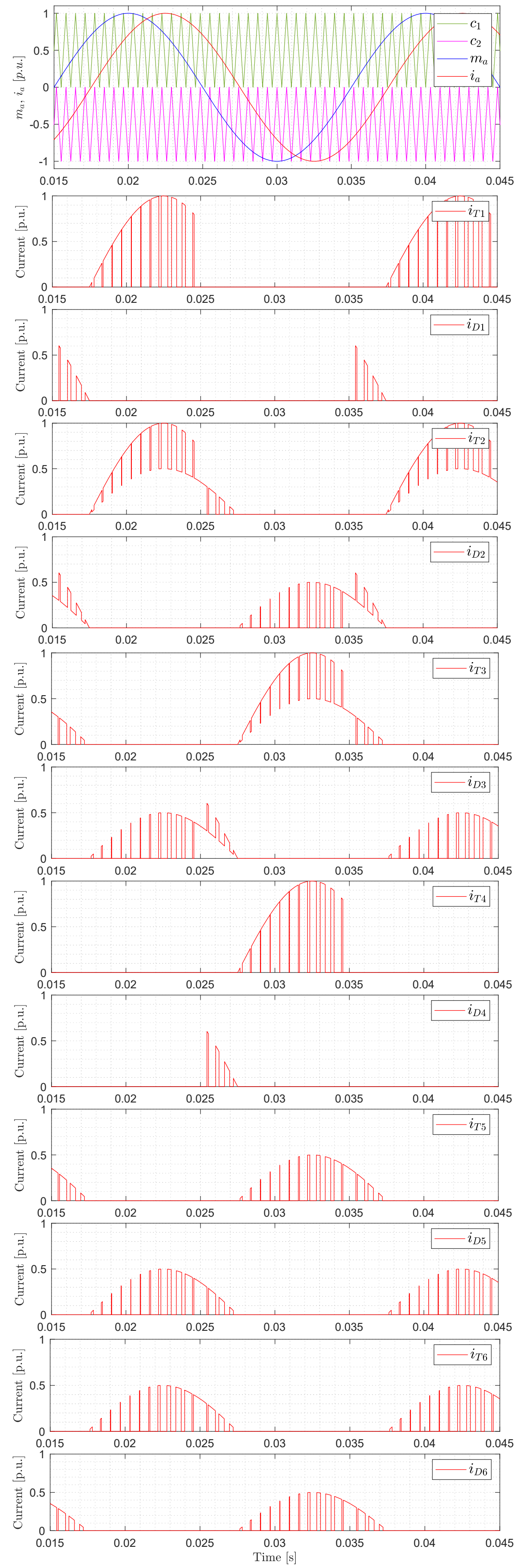

Fig. 2. Current through devices of Leg "A" at $f_{sw} = 1500\ Hz$, $\varphi = -\pi/4$.

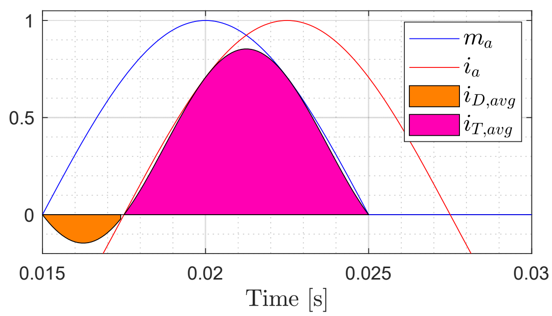

Fig. 3. Averaging method of PWM pulsed current through semiconductor devices in converter applications. The legends used are the modulation index (m_a), the converter output current (i_a), the area corresponding to average current through switch T_{a1} ($i_{T,avg}$) and the similar area through diode D_{a1} ($i_{D,avg}$). The current i_a is lagging the m_a by power factor angle $\varphi = -\pi/4$.

$$u_{CE} = U_{CE0} + R_{CE,on} \cdot i \tag{4}$$

The conduction loss is the product of the instantaneous current and the voltage drop across the device as expressed in (5).

$$P_{con,loss} = \frac{1}{T_p} \int (u_{CE} \cdot i)\, dt \tag{5}$$

Inserting (4) in (5) yields

$$P_{con,loss} = U_{CE0} \cdot I_{avg} + R_{CE,on} \cdot I^2_{rms} \tag{6}$$

where,

$$I_{avg} = \frac{1}{T_p} \int_0^{T_p} i dt \tag{7}$$

$$I^2_{rms} = \frac{1}{T_p} \int_0^{T_p} i^2 dt \tag{8}$$

According to (6), the conduction loss can be calculated using the average and rms value of the discontinuous current through the semiconductor devices over one period (T_p) of the fundamental current. The average and rms value of current through the devices T_1 and D_1 can be calculated using the method presented in Fig. 3. The integration is taken from $3\pi/2$ to $5\pi/2$ as the cosine wave has positive half-cycle between this interval.

$$\begin{aligned} I_{T1,avg} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2} m_a i_a d\omega t \\ &= \frac{M\hat{I}_o}{4} \cos\varphi + \frac{M\hat{I}_o}{4\pi} (\sin|\varphi| - |\varphi| \cos\varphi) \end{aligned} \tag{9}$$

$$\begin{aligned} I^2_{T1,rms} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2} m_a i_a^2 d\omega t \\ &= \frac{M\hat{I}_o^2}{6\pi} (1+\cos\varphi)^2 \end{aligned} \tag{10}$$

$$\begin{aligned} I_{D1,avg} &= \frac{1}{2\pi} \int_{3\pi/2}^{3\pi/2+\varphi} (-m_a i_a)\, d\omega t \\ &= \frac{M\hat{I}_o}{4\pi} [\sin|\varphi| - |\varphi| \cos\varphi] \end{aligned} \tag{11}$$

$$\begin{aligned} I^2_{D1,rms} &= \frac{1}{2\pi} \int_{3\pi/2}^{3\pi/2+\varphi} m_a i_a^2 d\omega t \\ &= \frac{M\hat{I}_o^2}{6\pi} (1-\cos\varphi)^2 \end{aligned} \tag{12}$$

The equations (5) – (8) can be used to calculate the average and rms current through the other devices as follows.

$$\begin{aligned} I_{T5,avg} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2+\varphi} \frac{1}{2} i_a d\omega t - \frac{1}{2} I_{T1,avg} - \frac{1}{2} I_{D1,avg} \\ &= \frac{\hat{I}_o}{2\pi} \left[1 - \frac{M}{2} \left(\sin|\varphi| + \left(\frac{\pi}{2} - |\varphi|\right) \cos\varphi\right)\right] \end{aligned} \tag{13}$$

$$\begin{aligned} I^2_{T5,rms} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2+\varphi} \frac{1}{4} i_a^2 d\omega t - \frac{1}{4} I^2_{T1,rms} - \frac{1}{4} I^2_{D1,rms} \\ &= \frac{\hat{I}_o^2}{16} \left[1 - \frac{4M}{3\pi} \left(1 + \cos^2\varphi\right)\right] \end{aligned} \tag{14}$$

$$\begin{aligned} I_{D5,avg} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2+\varphi} \frac{1}{2} i_a d\omega t - \frac{1}{2} I_{T1,avg} - \frac{1}{2} I_{D1,avg} \\ &= \frac{\hat{I}_o}{2\pi} \left[1 - \frac{M}{2} \left(\sin|\varphi| + \left(\frac{\pi}{2} - |\varphi|\right) \cos\varphi\right)\right] \end{aligned} \tag{15}$$

$$\begin{aligned} I^2_{D5,rms} &= \frac{1}{2\pi} \int_{3\pi/2+\varphi}^{5\pi/2+\varphi} \frac{1}{4} i_a^2 d\omega t - \frac{1}{4} I^2_{T1,rms} - \frac{1}{4} I^2_{D1,rms} \\ &= \frac{\hat{I}_o^2}{16} \left[1 - \frac{4M}{3\pi} \left(1 + \cos^2\varphi\right)\right] \end{aligned} \tag{16}$$

$$\begin{aligned} I_{T2,avg} &= I_{T1,avg} + I_{D5,avg} \\ &= \frac{\hat{I}_o}{2\pi} + \frac{M\hat{I}_o}{8} \cos\varphi \end{aligned} \tag{17}$$

$$\begin{aligned} I^2_{T2,rms} &= I^2_{T1,rms} + I^2_{D5,rms} \\ &= \frac{\hat{I}_o^2}{4} \left[\frac{1}{4} + \frac{M}{3\pi} \left(1 + \cos^2\varphi + 4\cos\varphi\right)\right] \end{aligned} \tag{18}$$

$$\begin{aligned} I_{D2,avg} &= I_{T5,avg} + I_{D1,avg} \\ &= \frac{\hat{I}_o}{2\pi} - \frac{M\hat{I}_o}{8} \cos\varphi \end{aligned} \tag{19}$$

$$\begin{aligned} I^2_{D2,rms} &= I^2_{T5,rms} + I^2_{D1,rms} \\ &= \frac{\hat{I}_o^2}{4} \left[\frac{1}{4} + \frac{M}{3\pi} \left(1 + \cos^2\varphi - 4\cos\varphi\right)\right] \end{aligned} \tag{20}$$

C. Switching Loss

The switching loss in the devices of a 3-level 3-phase ANPC converter does not depend on the modulation index as it does not influence the number of switchings over one cycle but the load power factor ($\cos\varphi$) does. The power factor other than unity makes the load current lead/lag the modulation index and the current is shared between the switches and the anti-parallel diodes across them.

The switching loss characteristics as the function of current, $e_{sw}(i)$, from an experimental result can be approximated as a quadratic function as expressed in (21).

$$e_{sw}(i) = k_{1,T} \cdot i + k_{2,T} \cdot i^2 \quad (21)$$

where, $k_{1,T}$ and $k_{2,T}$ are the curve fitting coefficients at the rated blocking voltage (U_{dc}^*) determined using the experimental results or manufacturer's datasheet. The same coefficients for diodes are $k_{1,D}$ and $k_{2,D}$.

Using these coefficients, the expressions for calculating the switching loss in each device can be formulated. The intervals in which the devices T_1 and D_1 switch are same as in case of calculation of average and rms current. Analytical equations for switching loss in these devices are:

$$\begin{aligned} P_{T1,sw} =& \frac{U_{dc}}{2U_{dc}^*}\frac{1}{2\pi}f_{sw}\int_{3\pi/2\ +\varphi}^{5\pi/2}\left(k_{1,T}i + k_{2,T}i^2\right)d\omega t \\ =& \frac{U_{dc}}{2U_{dc}^*}\frac{\hat{I}_o}{2\pi}f_{sw}\left[k_{1,T}\left(1+\cos\varphi\right)\right. \\ &\left. + \frac{\hat{I}_o}{2}k_{2,T}\left(\pi - |\varphi| + \frac{1}{2}\sin 2|\varphi|\right)\right] \end{aligned} \quad (22)$$

where, U_{dc} is the dc-link voltage as shown in Fig. 1 and U_{dc}^* is the rated blocking voltage of the device given in datasheet.

$$\begin{aligned} P_{D1,sw} =& \frac{U_{dc}}{2U_{dc}^*}\frac{1}{2\pi}f_{sw}\int_{3\pi/2}^{3\pi/2\ +\varphi}\left(k_{1,D}i + k_{2,D}i^2\right)d\omega t \\ =& \frac{U_{dc}}{2U_{dc}^*}\frac{\hat{I}_o}{2\pi}f_{sw}\left[k_{1,D}\left(1-\cos\varphi\right) + \frac{\hat{I}_o}{2}k_{2,D}\left(|\varphi| - \frac{1}{2}\sin 2|\varphi|\right)\right] \end{aligned} \quad (23)$$

In sinusoidal PWM modulation, the switch T_2 is continuously "ON" during the interval $3\pi/2$ to $5\pi/2$ ($t = 0.015s$ to $0.035s$ in Fig. 2). Therefore, T_2 will have switching loss only if the output current is leading or lagging the modulation signal, m_a, i.e. outside the aforementioned interval.

$$\begin{aligned} P_{T2,sw} =& \frac{U_{dc}}{2U_{dc}^*}\frac{1}{2\pi}f_{sw}\int_{5\pi/2}^{5\pi/2+\varphi}\left(k_{1,T}i + k_{2,T}i^2\right)d\omega t \\ =& \frac{U_{dc}}{2U_{dc}^*}\cdot\frac{\hat{I}_o}{2\pi}f_{sw}\left[k_{1,T}\left(1-\cos\varphi\right)\right. \\ &\left. + \frac{\hat{I}_o}{2}k_{2,T}\left(|\varphi| - \frac{1}{2}\sin 2|\varphi|\right)\right] \end{aligned} \quad (24)$$

$$\begin{aligned} P_{D5,sw} =& \frac{U_{dc}}{2U_{dc}^*}\frac{1}{2\pi}f_{sw}\int_{3\pi/2\ +\varphi}^{5\pi/2}\left(k_{1,D}i + k_{2,D}i^2\right)d\omega t \\ =& \frac{U_{dc}}{2U_{dc}^*}\frac{\hat{I}_o}{2\pi}f_{sw}\left[k_{1,D}\left(1+\cos\varphi\right)\right. \\ &\left. + \frac{\hat{I}_o}{2}k_{2,D}\left(\pi - |\varphi| + \frac{1}{2}\sin 2|\varphi|\right)\right] \end{aligned} \quad (25)$$

The diodes D_2 and D_5 have same switching pattern but in different half cycles, therefore, the switching loss over a cycle in these diodes are equal. The same applies for the switches T_2 and T_5.

D. Zero frequency or DC operation

1) Average and RMS current at DC current: At the startup of any machine connected at the output terminals of the converter, a constant torque (dc current) is applied and the duration depends upon the type of the load and the inertia of the machine and load. During this period, the applied voltage is very small to overcome only the drop across the stator resistance and the active converter components. Therefore, the modulation index (M) is kept very small. As shown in Fig. 4, for a positive current out of the converter, only the devices T_1, T_2 and D_5 in the upper half and the devices D_3 and T_6 in the lower half of the bridge leg conduct the current.

The current through switch T_2 commutates from $\hat{I}_o/2$ to $\hat{I}_o$ for an interval determined by modulation index. Similarly, the current through switch T_6 commutates from $\hat{I}_o/2$ to zero for the same interval. The devices D_5, T_6 and D_3 carry the same amount of current. Since the output current is dc, the average and rms current through the devices depend only on the modulation index (M) and the amplitude of output current ($\hat{I}_o$) as presented in Table I.

TABLE I
AVERAGE AND RMS CURRENT THROUGH THE DEVICES OF ANPC CONVERTER AT DC OPERATION.

Current	$\hat{I}_o \geq 0$	$\hat{I}_o < 0$
$I_{T1,avg}$	$M \cdot \hat{I}_o$	0
$I_{D1,avg}$	0	$M \cdot \hat{I}_o$
$I_{T2,avg}$	$(1+M) \cdot \frac{\hat{I}_o}{2}$	0
$I_{D2,avg}$	0	$(1+M) \cdot \frac{\hat{I}_o}{2}$
$I_{T5,avg}$	0	$(1-M) \cdot \frac{\hat{I}_o}{2}$
$I_{D5,avg}$	$(1-M) \cdot \frac{\hat{I}_o}{2}$	0
$I_{T1,rms}^2$	$M \cdot \hat{I}_o^2$	0
$I_{D1,rms}^2$	0	$M \cdot \hat{I}_o^2$
$I_{T2,rms}^2$	$(1+3M) \cdot \frac{\hat{I}_o^2}{4}$	0
$I_{D2,rms}^2$	0	$(1+3M) \cdot \frac{\hat{I}_o^2}{4}$
$I_{T5,rms}^2$	0	$(1-M) \cdot \frac{\hat{I}_o^2}{4}$
$I_{D5,rms}^2$	$(1-M) \cdot \frac{\hat{I}_o^2}{4}$	0

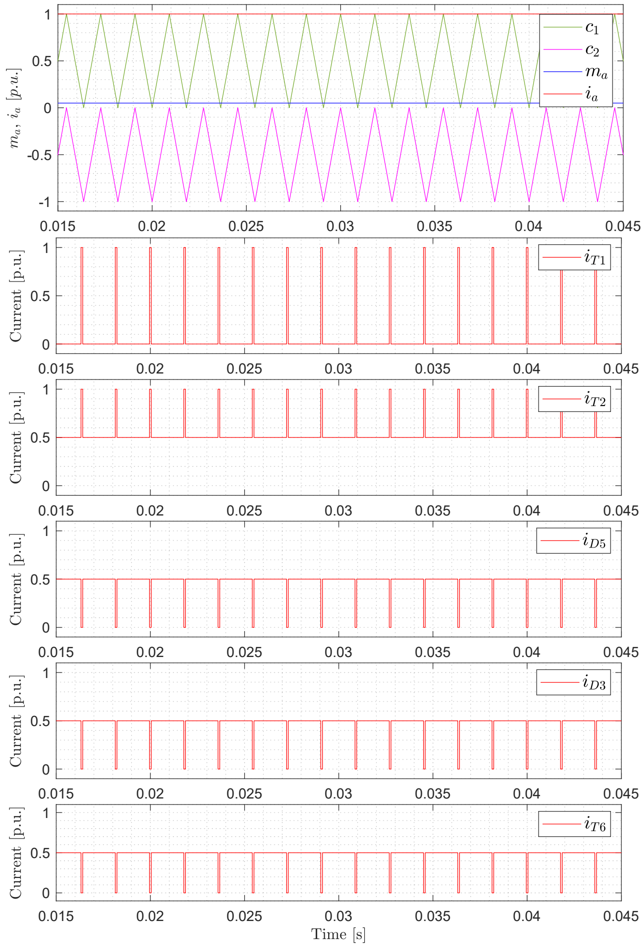

Fig. 4. Current through devices of Leg "A" at dc operation with $M = 0.05$, $f_{sw} = 500\ Hz$ and $\varphi = 0$.

The conduction loss at dc current is calculated by inserting the average and rms current expressions from Table I in (6).

2) Switching Loss at Positive output current: For bridge leg "A", the switches T_1, T_2 and T_6 and diodes D_3 and D_5 conduct the positive output current but only the devices T_1, D_3 and D_5 will incur the switching loss. There will be no switching loss in switches T_2 and T_6 because these devices are continuously "ON".

As the output current is constant, the switching loss in device T_1 is calculated by substituting the instantaneous value of current (i) in (21) with the output current ($\hat{I}_o$).

$$P_{T1,sw@f=0} = \frac{U_{dc}}{2U^*_{dc}} f_{sw} \left(k_{1,T} \hat{I}_o + k_{2,T} \hat{I}_o^2 \right) \tag{26}$$

$$P_{T2,T5,sw@f=0} = 0 \tag{27}$$

$$P_{D3,D5,sw@f=0} = \frac{U_{dc}}{2U^*_{dc}} f_{sw} \left(k_{1,D} \frac{\hat{I}_o}{2} + k_{2,D} \frac{\hat{I}_o^2}{4} \right) \tag{28}$$

IV. Simulation Results

A. Conduction Loss

The constituents of the conduction loss are the average and rms current and the device parameters as expressed in (6). The accuracy of the estimated conduction loss depends on the accuracy of the average and rms currents. Therefore, the expressions for calculation of these current are verified using Simulink with the converter configuration as shown in Fig. 1 and the result is presented in Table II.

TABLE II
Comparison of Analytical and Simulation Values of Average and RMS Currents Through Devices.

Device	T_1	D_1	T_2	D_2	T_5	D_5
$I_{avg,analytical}\ (A)$	25	0	28.42	3.42	3.42	3.42
$I_{avg,sim}\ (A)$	25.01	0	28.41	3.41	3.41	3.41
$Error\ (\%)$	-0.04	n/a	0.02	0.29	0.29	0.26
$I_{rms,analytical}\ (A)$	46.07	0	47.08	9.72	9.72	9.72
$I_{rms,sim}\ (A)$	46.0	0	47.03	9.62	9.62	9.80
$Error\ (\%)$	0.14	n/a	0.11	1.08	1.08	-0.84

The simulation is carried out with $\hat{I}_o = 100A$, $M = 1$ and $\varphi = 0$ at switching frequency (f_{sw}) = 500 Hz.

B. Switching Loss

The switching loss in the devices are analytically calculated using equations (22) – (25). The accuracy of these calculation are verified using the numerical calculation of loss at each turn-on and turn-off instances of the switch T1 over one cycle. The switching loss data of the selected switching device (Westcode T2960BB45E) is presented in Table III.

TABLE III
Switching Loss Data from IGBT (Westcode T2960BB45E) at 125°C [7].

$I_c(A)$	500	1000	1500	2000	2400	2800	3000
$E_{on}(J)$	2.9	5.0	7.0	8.75	10.0	11.0	11.5
$E_{off}(J)$	3.2	5.9	8.7	11.7	14.0	16.4	17.5

The variables used in the table are: collector current of IGBT, I_c; Turn-on energy loss, E_{on}; Turn-off energy loss, E_{off}.

From Table III, the curve fitting coefficients $k_{1,T}$ and $k_{2,T}$ of the switching loss (sum of turn-on and turn-off loss) as in (21) are as: $k_{1,T} = 0.0115 J/A$ and $k_{2,T} = -6.27 \cdot 10^{-7} J/A^2$.

The microscopic current pulses through the switch T_1 is shown in Fig. 5 and the switching loss at each turn-on and turn-off from the datasheet are listed in Table IV.

The sum of energy loss at all turn-on and turn-off instances is 97.82 $J/cycle$ which yields 4.89 kW at $f_n = 50\ Hz$.

The switching loss in the switch T_1 at $f_{sw} = 500\ Hz$ calculated using (22) is 4.80 kW which gives a very small error of 1.84 % w.r.t. the loss calculated using datasheet values.

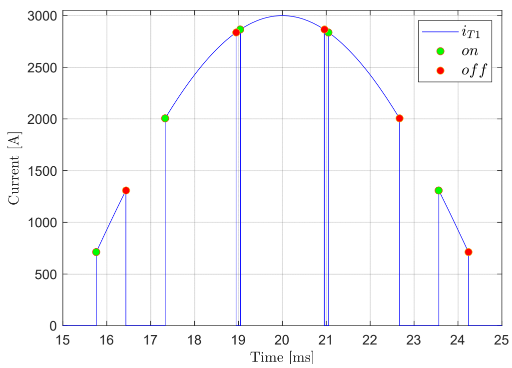

Fig. 5. Microscopic pulsed current through the switch T_1 at maximum rated current of the device $\hat{I}_o = 3000A$, $f_n = 50Hz$, $M = 1$, Power factor ($\cos\varphi$) = 1 and switching frequency (f_{sw}) = 500 Hz. The switching frequency is chosen only to achieve convenient number of pulses for numerical calculation of switching loss.

TABLE IV
NUMERICAL CALCULATION OF SWITCHING LOSS IN DEVICE T_1 OVER ONE FUNDAMENTAL CYCLE OF OUTPUT CURRENT FROM FIG.5.

i_{T1} (A)	713	2000	2864	2835	1304
E_{on} (J)	3.66	8.81	11.15	11.08	6.28
E_{off} (J)	4.21	11.72	16.70	16.54	7.67
E_{total} (J)	7.87	20.53	27.85	27.62	13.95

The numerically calculated switching loss is $97.82\ J/cycle$, i.e. $4.89\ kW$ at $f_n = 50Hz$. The analytically calculated switching loss using (22) is $4.80\ kW$.

C. Discussion on Switching Loss in Device T_1

The expressions derived in this paper can be used to calculate the conduction loss and switching loss in each device of an ANPC converter and the critical devices can be determined while designing the converter. The DC operation is the most critical for any type of converter as the conduction and switching losses are maximum at the same time for devices like D_5. ANPC converter has parallel devices to deal with such issues and is therefore, a better alternative for applications with high starting torque. But, this advantage can only be exploited if the switching loss in the device T_1 is lower than one-third of the total loss in this device.

This statement can be verified using the ratio of switching loss at dc operation as in (26) and the worst case loss at rated frequency operation with $\cos\varphi = 1$ as in (22).

$$\frac{P_{T1,sw@f=0}}{P_{T1,sw@f=f_n}} = \pi \cdot \frac{k_{1,T} + k_{2,T} \cdot \hat{I}_o}{k_{1,T} + \frac{\pi}{4} k_{2,T} \cdot \hat{I}_o} \qquad (29)$$

The coefficient $k_{2,T}$ is relatively very small compared to $k_{1,T}$ and can be neglected for approximate analysis. The ratio of the losses then becomes π. And, at dc operation even though there is very small conduction loss in T_1, the switching loss will increase by π times. To keep the total loss at dc operation less than or equal to the total loss at rated frequency operation, the switching loss must be less than $1/\pi$ times the total loss, i.e. around 32% of total loss.

V. CONCLUSION

The conduction and switching losses in each device of an ANPC converter can be calculated using analytical equations presented in this paper. These expressions can be used while dimensioning the semiconductor devices for an ANPC converter and to have an estimate of loss distribution across the devices without carrying out multiple simulation at various operating points. The constituents of the conduction loss are average and rms currents and the analytical equations have less than 2% error when the switching frequency is at least 10 times the fundamental frequency.

The equations for calculating the switching loss have also been validated by numerical calculations based on the loss characteristics presented in the datasheet of the device and shows a promising accuracy. The error is less than 2 % for switching frequency of 500 Hz.

The switching loss in the device T_1 is approximately 3 times higher at dc operation than the operation at nominal frequency. Therefore, the switching loss in this device must be less than 1/3 times the total loss to capitalize the advantage of ANPC converter configuration.

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