Analytical Efficiency Evaluation of Modular Multilevel Converter for HVDC System

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ABSTRACT
Modular Multilevel Converter (MMC) is becoming a strong alternative converter for Voltage Source Converter (VSC) due to its control and flexibility. Considering the importance of the losses estimation in the design process, an analytical method is proposed to calculate the power losses in each switching device of a sub module of Modular Multilevel Converter (MMC). Average and root mean square of the sub module current is used to calculate the conversion losses (conduction and switching). The method is applied on a full bridge sub module topology. Then considering a case, with certain parameters a MATLAB program is developed to analyze the results for the proposed method.

General Terms
High Voltage Direct Current, Converters

Keywords
Modular Multilevel Converter (MMC), Conversion Losses, Full Bridge Sub Module, Efficiency, IGBTs, Free Wheeling Diodes

1. INTRODUCTION
In recent times, MMC has been widely accepted as the most concerned converter topology in the HVDC transmission system. It has features of low switching frequency, low converter losses and flexible control. MMC has a very complex topology structure, having large number of sub modules, resulting in the difficulty of stating the formulae for the losses. During the design stage of the MMC based HVDC system, the loss estimation stage is an important step, as it helps the designer to optimize the overall system performance, select the heat sinking equipment and cooling systems for the system. Therefore, it is important to make a research on the loss calculation method of MMC and state formulae for the losses.

In this paper, the structure of MMC based HVDC system is discussed. Then, an analytical method based on average current and root mean square (RMS) of the current passing through the sub module is presented to calculate the conversion losses in the switching devices of MMC. The method is applied considering the full bridge sub module topology. Then, considering a case with certain parameters, a MATLAB program is developed and the losses and efficiency curves for each switching device and sub module are obtained respectively. Also, those factors which affect the losses and efficiency of the sub module are discussed.

2. MMC BASED HVDC SYSTEM STRUCTURE
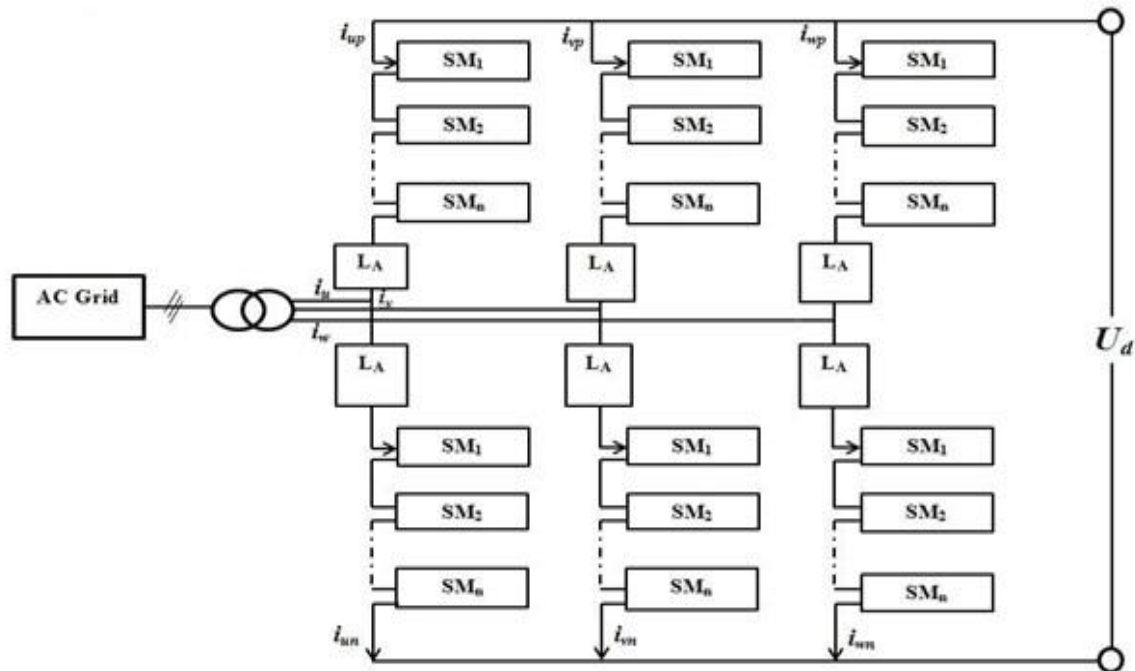Figure 1 shows the structure of MMC based HVDC system. The system consists of the following components:

Figure 1: MMC based HVDC System

1. *Coupling Transformer*
The coupling transformer changes the voltage level at the ac side to the level which is suitable for the MMC.

2. *AC Grid*
The AC grid is the part whose state is converted to DC.

3. *Arm Inductance*
Arm inductance serves multiple purposes; to limit the current during fault, as filter for ac current and to limit the circulating current among the legs which is of high harmonics.

4. *Sub Module*
A sub module or cell is a basic building block of the MMC. It is a two terminal device consisting of combination of IGBTs, diodes and capacitors used to generate the required voltage level.

5. *Arm*
A series connected sub modules and arm inductance forms an arm.

6. *Phase Leg*
Combination of two phase arms is known as phase leg.

2.1 Circuit Analysis
Figure 1 shows the structure of MMC based HVDC system. Assuming the losses of each phase is steady, for a three phase balance working condition. Then, only phase U is selected for the loss analysis. The current through the arm of phase U is:

$$I_{uu} = \frac{I_u}{2}\sin(\omega t + \varphi) + I_{ud} + I_{uz}\sin(2\omega t + \theta) \qquad (1)$$

$$I_{ul} = -\frac{I_u}{2}\sin(\omega t + \varphi) + I_{ud} + I_{uz}\sin(2\omega t + \theta) \qquad (2)$$

The terms I_{uu} and I_{ul} represent the current through the upper and lower arms respectively. In the above equations, I_u is the maximum value of the phase current. I_{ud} is the DC component in arm current, which is one third of the DC line current. The last element, I_{uz} is the circulating current having double line frequency. The fluctuation in the sub module's capacitor voltage results in the fluctuation of the arm voltage. This fluctuation produces the circulating current.

3. CONVERSION LOSSES
The conversion losses of MMC can be divided into two parts: [1, 2]

3.1 Conduction Losses
The on state voltages drop in the device produces the conduction losses. These losses are computed by averaging the conduction losses in each switching cycle [2] as shown in equation (3).

$$P_{con} = \frac{1}{T}\int_0^t V_f(\omega t)i(\omega t)d\,\omega t \qquad (3)$$

Where, P_{con} shows the conduction losses of the device $V_f(\omega t)$ shows the forward voltage drop of the device and $i(\omega t)$ represents the current flowing through the device during the conduction period. T is the switching period. The forward voltage drop is calculated by using the following equation:

$$V_f = V_{f0} + r_f i(\omega t) \qquad (4)$$

Where V_{f0} and r_f show the forward voltage drop of the device at no load and the device forward resistance respectively. The device's data sheet provided by the manufacturer is used to calculate V_{f0} and r_f. Substituting equation (4) into equation (3), results in equation (5).

$$P_{con} = V_f I_{av} + I_{rms}^2 r_f \qquad (5)$$

I_{av} is the average current flowing through the device while I_{rms} is the root mean square value of the current flowing through the device. These values of the current are calculated by using equation (6) and (7) respectively.

$$I_{av} = \frac{1}{T}\int_0^t i(\omega t)d\omega t \qquad (6)$$

$$I_{rms}^2 = \frac{1}{T}\int_0^t i^2(\omega t)d\omega t \qquad (7)$$

3.2 Switching Losses
The combination of turning on losses and turning off losses results in the switching losses of the device. These losses depend on the device characteristics, switching frequency and the current, which is flowing through the device [3]. Following relationship is used for the calculation of the switching losses of the device:

$$P_{sw} = \frac{f_s}{2\pi}\int_0^t ki(\omega t)d\omega t \qquad (8)$$

Where P_{sw} are the device switching losses, k is constant and is obtained from the switching energy graph of the device which is given in the data sheet. f_s is the switching frequency of the device.

4. CONVERSION LOSSES EVALUATIO OF FULL BRIDGE SUB MODULE
A full bridge sub module is shown in the Figure 2 this type of sub module topology consists of a dc capacitor and four power electronic switching devices. Each switching device consists of IGBT and free-wheeling diode. The terminal voltage of the sub module depends on the states of the four switches [4]. The terminal voltage of the sub module is either equal to capacitor voltage or zero or negative of the capacitor voltage. Table I shows the switching pattern and terminal voltage of the full bridge sub module. In this sub module topology two IGBTs in one pair cannot have on signal at the same time as it will result in short circuit condition.
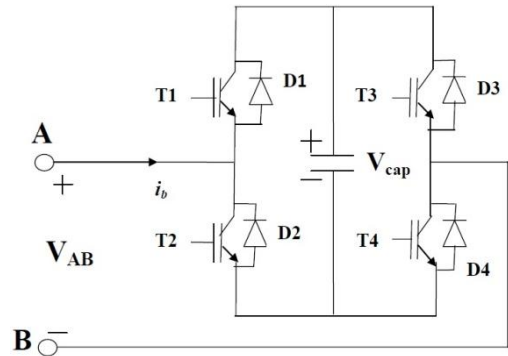

Figure 2: Full Bridge Sub Module

For the losses calculation, the current and voltage waveforms of the switching devices must be known. The current and voltage waveform of each switching device depends on the pulse waveform of the switching device. Also, if the phase current is assumed to be constant then the switching function can be replaced by the device duty cycle within the switching cycle. Considering Sinusoidal Pulse Width Modulation (SPWM), as the switching technique for the switching devices, the losses in each switching device is calculated.

Table 1. Switching States of IGBTs

IGBTs States				V_{AB}
T1	**T2**	**T3**	**T4**	
1	0	0	1	V_{cap}
1	0	1	0	0
0	1	0	1	0
0	1	1	0	$-V_{cap}$

Using i_b ; bridge current, to represent the current flowing through the full bridge sub module in the upper arm. This current is equal to the phase current flowing through the upper arm I_{uu}. Then, the duty cycles of the switching devices is:

$$D_{T1} = D_{D1} = D_{T4} = D_{D4} = M \sin \omega t \qquad (9)$$

$$D_{T1}^{'} = D_{D1}^{'} = D_{T3} = D_{D3} = 1 - M \sin \omega t \qquad (10)$$

$$D_{T2} = D_{D2} = D_{T4}^{'} = D_{D4}^{'} = 1 + M \sin \omega t \qquad (11)$$

$$D_{T2}^{'} = D_{D2}^{'} = D_{T3}^{'} = D_{D3}^{'} = -M \sin \omega t \qquad (12)$$

The average current and RMS currents for IGBTs, T1 to T4 for each switching period are calculated below by using equations (6) and (7) respectively. For the switching period of T1 and T4,

$$I_{T1} = \frac{1}{2\pi} \int_0^\pi I_{uu} D_{T1} d\omega t = \frac{1}{2\pi} \left[\frac{\pi}{4} MI_u \cos\varphi + 2MI_{ud} - 23MIuzsin\theta \right. \qquad (13)$$

$$I_{T4} = I_{T1} = \frac{1}{2\pi} \left[\frac{\pi}{4} MI_u \cos\varphi + 2MI_{ud} - \frac{2}{3} MI_{uz} \sin\theta \right] \qquad (14)$$

$$I_{rmsT\,1}^2 = \frac{1}{2\pi} \int_0^\pi I_{uu}^2 D_{T1} d\omega t = \frac{1}{2\pi} \left[\frac{I_{uu}^2}{4} M \left[1 + \frac{\cos 2\varphi}{3} \right] + 2I_{ud}^2 M + \right. Iuz2M1+cos2\theta15 \qquad (15)$$

$$I_{rmsT\,4}^2 = I_{rmsT\,1}^2 \qquad (16)$$

For the period when T1 and T3 are conducting,

$$I_{T1} = \frac{1}{2\pi} \int_0^\pi I_{uu} D_{T1}^{'} d\omega t = \frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 - \frac{\pi M}{4} \right) + \right. Iud\pi-2M+23MIuzsin\theta \qquad (17)$$

$$I_{T3} = -I_{T1} = -\frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 - \frac{\pi M}{4} \right) + I_{ud} (\pi - 2M) + 23MIuzsin\theta \qquad (18)$$

$$I_{rmsT\,1}^2 = \frac{1}{2\pi} \int_0^\pi I_{uu}^2 D_{T1}^{'} d\omega t = \frac{1}{2\pi} \left[\frac{I_u^2}{4} \left(\frac{\pi}{2} - M \left[1 + \frac{\cos 2\varphi}{3} \right] \right) + \right. Iud2\pi-2M+Iuz2\pi2-M1+cos2\theta15 \qquad (19)$$

$$I_{rmsT\,3}^2 = I_{rmsT\,1}^2 \qquad (20)$$

For the period T2 and T4 are in on-state,

$$I_{T4} = \frac{1}{2\pi} \int_0^\pi I_{uu} D_{T4}^{'} d\omega t = \frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 + \frac{\pi M}{4} \right) + \right. Iud\pi+2M-23MIuzsin\theta \qquad (21)$$

$$I_{T2} = -I_{T4} = -\frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 + \frac{\pi M}{4} \right) + I_{ud} (\pi + 2M) - 23MIuzsin\theta \qquad (22)$$

$$I_{rmsT\,4}^2 = \frac{1}{2\pi} \int_0^\pi I_{uu}^2 D_{T4}^{'} d\omega t = \frac{1}{2\pi} \left[\frac{I_u^2}{4} \left(\frac{\pi}{2} + M \left[1 + \frac{\cos 2\varphi}{3} \right] \right) + \right. I_{ud}^2 (\pi + 2M) + I_{uz}^2 \left(\frac{\pi}{2} + M \left[1 + \frac{\cos 2\theta}{15} \right] \right) \qquad (23)$$

$$I_{rmsT\,2}^2 = I_{rmsT\,4}^2 \qquad (24)$$

And for the T2 and T3 on-state period,

$$I_{T2} = \frac{1}{2\pi} \int_0^\pi I_{uu} D_{T2}^{'} d\omega t = \frac{1}{2\pi} \left[-\frac{\pi}{4} MI_u \cos\varphi - 2MI_{ud} + \right. 23MIuzsin\theta \qquad (25)$$

$$I_{T3} = I_{T2} = \frac{1}{2\pi} \left[-\frac{\pi}{4} MI_u \cos\varphi - 2MI_{ud} + \frac{2}{3} MI_{uz} \sin\theta \right] \qquad (26)$$

$$I_{rmsT\,2}^2 = \frac{1}{2\pi} \int_0^\pi I_{uu}^2 D_{T2}^{'} d\omega t = -\frac{1}{2\pi} \left[\frac{I_u^2}{4} M \left[1 + \frac{\cos 2\varphi}{3} \right] + \right. 2Iud2M+Iuz2M1+cos2\theta15 \qquad (27)$$

$$I_{rmsT\,2}^2 = I_{rmsT\,3}^2 \qquad (28)$$

The average value and RMS values of the current for the Diodes D1 to D4 for each switching period are calculated. For the period of D1 and D4 conduction, the average values of currents are,

$$I_{D1} = I_{D4} = -I_{T1} = -\frac{1}{2\pi} \left[\frac{\pi}{4} MI_u \cos\varphi + 2MI_{ud} - \right. 23MIuzsin\theta \qquad (29)$$

$$I_{rmsD\,1}^2 = I_{rmsD\,4}^2 = I_{rmsT1}^2 \qquad (30)$$

For the period when D1 and D3 are conducting,

$$I_{D1} = -I_{T1} = -\frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 - \frac{\pi M}{4} \right) + I_{ud} (\pi - 2M) + \right. 23MIuzsin\theta \qquad (31)$$

And

$$I_{D3} = I_{T1} = \frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 - \frac{\pi M}{4} \right) + I_{ud} (\pi - 2M) + \right. 23MIuzsin\theta \qquad (32)$$

$$I_{rmsD\,3}^2 = I_{rmsD\,1}^2 == I_{rmsT\,1}^2 \qquad (33)$$

Similarly, for the period of D2 and D4 conduction,

$$I_{D4} = -I_{T4} = -\frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 + \frac{\pi M}{4} \right) + I_{ud} (\pi + 2M) - \right. 23MIuzsin\theta \qquad (34)$$

$$I_{D2} = I_{T4} = \frac{1}{2\pi} \left[\frac{I_u}{2} \cos\varphi \left(1 + \frac{\pi M}{4} \right) + I_{ud} (\pi + 2M) - \right. 23MIuzsin\theta \qquad (35)$$

$$I_{rmsD\,4}^2 = I_{rmsD\,2}^2 = I_{rmsT\,4}^2 \qquad (36)$$

And for the period when D2 and D3 are conducting,

$$I_{D2} = I_{D3} = -I_{T2} = -\frac{1}{2\pi} \left[-\frac{\pi}{4} MI_u \cos\varphi - 2MI_{ud} + \right. 23MIuzsin\theta \qquad (37)$$

$$I_{rmsD\,3}^2 = I_{rmsD\,2}^2 = I_{rmsT\,2}^2 \qquad (38)$$

Switching losses for the transistors T1 to T4 are calculated using equation (8). Therefore,

$$P_{swT\,1} = \frac{f_s k}{2\pi} \int_0^t kI_{uu} (\omega t) d\omega t = \frac{f_s k}{2\pi} [I_m \cos\varphi + \pi I_{ud}] = P_{swT\,2} = P_{swT\,3} = P_{swT\,4} \qquad (39)$$

The diodes switching losses are not considered, as they are turned on and off very fast, hence, the losses are very small compared to IGBTs.

5. EFFICEINCY EVALUATION OF FULL BRIDGE SUB MODULE: CASE STUDY

Efficiency and losses evaluation of full bridge sub module is carried out by developing a program using MATLAB. The loss characteristic of full bridge sub module is studied for different values of modulation index, switching frequency and power angle. Table 2 shows the parameters used for the analysis.

Considering the conduction period when the voltage across the sub module is $+V_{cap}$, the losses and efficiency graphs are here discussed only. During other conduction periods the characteristics' graphs follow the same pattern. Figure3 and Figure4 show the average currents and conduction losses of diode D1and D4 for the stated period respectively. The conduction losses increase with the increase of power angle

and modulation index. The conduction losses reaches to maximum point at power angle 180°.

Table 2. Parameters Used for Analysis

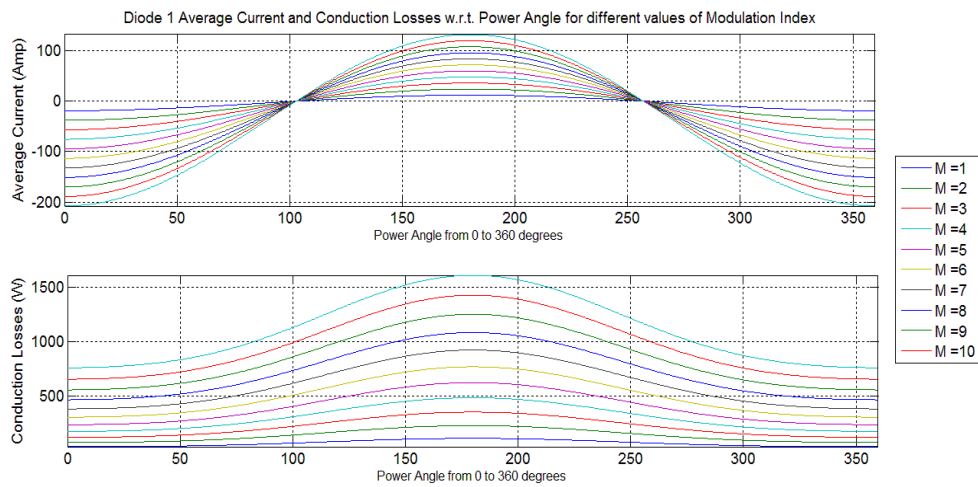| Parameter	Value
Rated MMC Capacity	200 MVA
Switching Frequency of each IGBT	300 Hz
Rated Frequency	60 Hz
IGBT Forward Resistance	3.5 mΩ
IGBT Threshold Voltage	3.5 V
Freewheeling Diode Forward Resistance	3.0 mΩ
Freewheeling Diode Forward Voltage	2.5 V

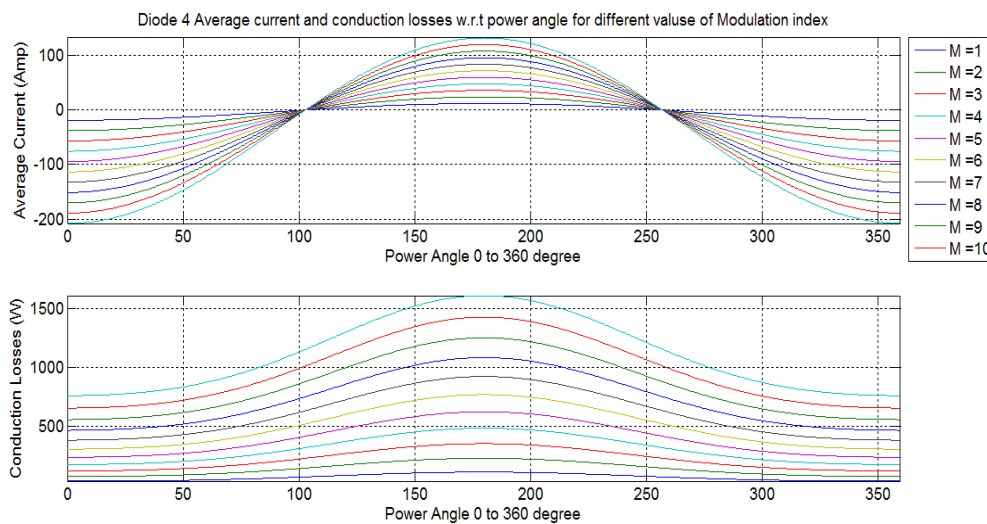**Figure 3: Diode D1 Average Current and Conduction Losses**

Figure 4: Diode D4 Average Current and Conduction Losses

Figure 5 and Figure 6 show the average currents, conduction losses and switching losses of IGBTs T1 and T4 respectively. In this case, the conduction losses decrease with the increase of power angle and reaches to minimum at angle of 180°.

While the switching losses increase with the increase in switching frequency and is at minimum value at an angle of 180°.
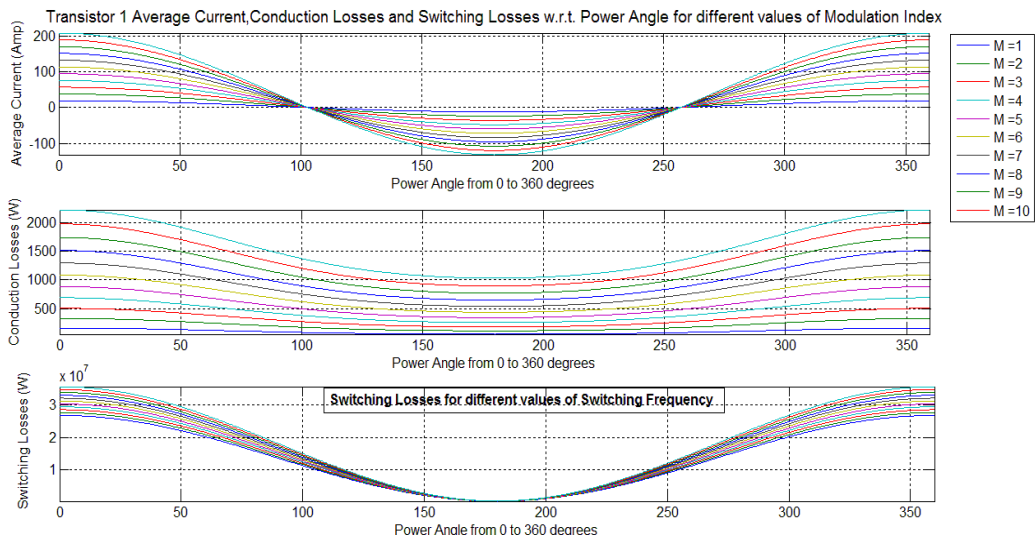
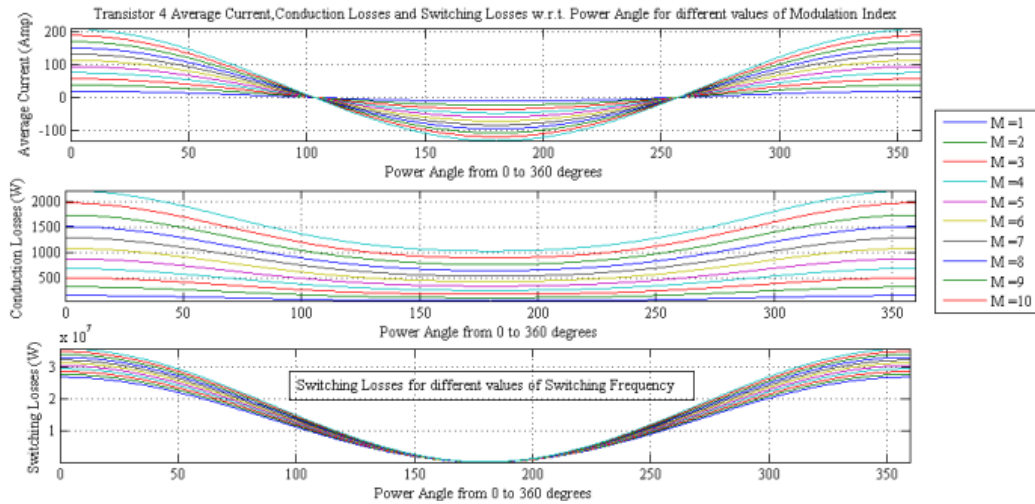**Figure 5: Transistor T1 Average Current, Conduction Losses and Switching Losses**

Figure 6: Transistor T4 Average Current, Conduction Losses and Switching Losses

The total power losses characteristic graph of full bridge sub module is shown in Figure 7. The losses increase with the increase in the power angle and modulation index. The losses are at the peak value at the power angle of 180°. The losses are dependent on power angle, modulation index and switching frequency. The increase in switching frequency also results in the increase of total power losses.

The efficiency of full bridge sub module for the particular case is described with the help of Figure 8 the efficiency of the sub module increases with the increase in the power angle, it has a maximum values at 180°. The increase in modulation index decreases the efficiency. While the switching frequency has the same effect on the efficiency as the modulation index has on it.

6. CONCLUSIONS

In this paper the loss characteristics of full bridge sub module were discussed in detail. The structure of MMC based HVDC system was discussed; also the types of losses in the converter were also discussed. An analytical method based on average and RMS values of current was presented. The losses equations were derived using the presented method. Finally, MATLAB based program was developed to analyze the losses and efficiency of the sub module.
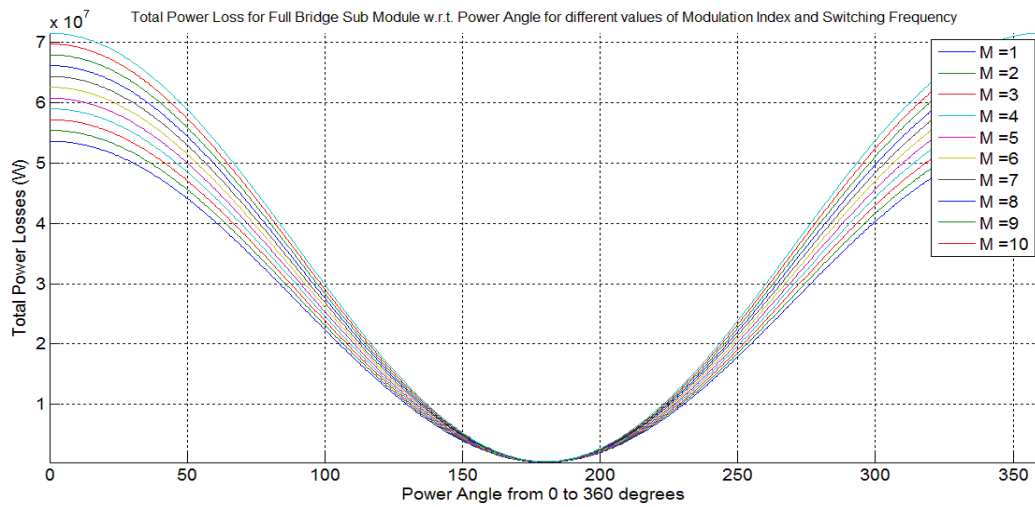
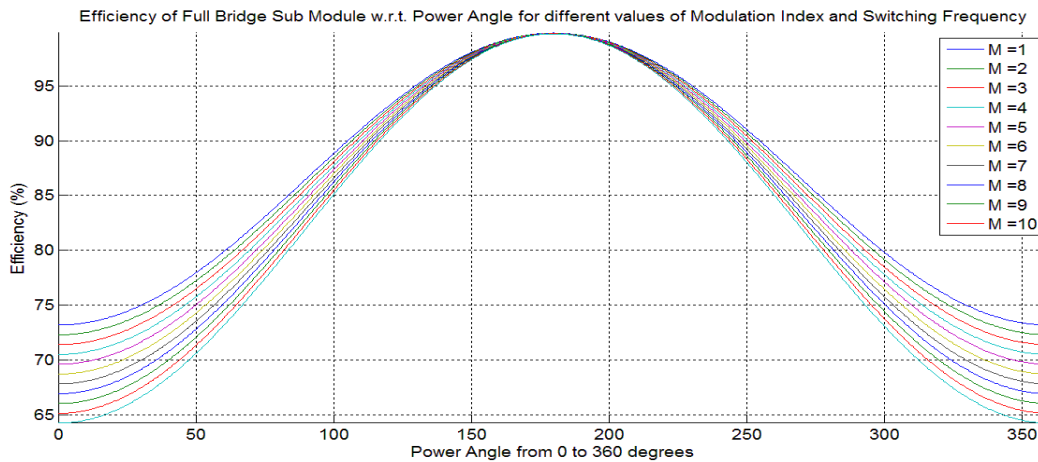**Figure 7: Total Power Losses of Full Bridge Sub Module**

Figure 8: Efficiency of Full Bridge Sub Module

The conclusions derived on the basis of the method presented are study as following:

1. The diodes conduction losses increase with the increase in the power angle but increase with the increase in the modulation index.

2. Increasing the power angle decreases the conduction losses and switching losses of the transistors; IGBTs. While the increase in the values of the modulation index results in increases of the conduction losses.

3. The switching frequency has a direct impact on the switching losses.

4. The transistors; IGBTs total losses are always greater than their respective diodes.

5. The total losses are dependent on the power angle, modulation index and switching frequency. Only the power angle has indirect impact on the total losses while the other two have direct impact.

6. The efficiency of the sub module is maximum at the power angle of 180°. While increase in the values of modulation index and switching frequency decreases the efficiency.

7. REFERENCES

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