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An analytical method for the loss calculation of an inverter with THPWM modulation technique

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ABSTRACT : *Hydro, wind and solar are the three main foundation belongs to renewable resource. Among these solar energy is considered as most reliable and continuous renewable energy consumed by photovoltaic array. Its profusion, omnipresent and easy existence are a strong competitor of fossil fuel. There exists various schemes for generating electric power from renewable energy resources in order to achieve the continuous power of constant magnitude as per demand and suitable such that it can be interconnected with a power grid without a step up transformer using as an isolated system, modular multilevel converter (MMC) known as H-bridge cascaded for Voltage Source Converter (VSC) has been established its bright footprint as a strong substitute converter due to its control and flexibility. In every electrical system, losses occurs due to heat dissipation. Therefore, losses cannot be avoided but can be reduced depends on design. Thus losses estimation in the design process is the technique to evaluate fundamental of the system efficiency evaluation for the converter, an analytical method is proposed in this paper to calculate the power losses in each switching device designed for third harmonics injected PWM modulation technique (THPWM) for H-bridge featured cascaded of modular multilevel converter (MMC) for 11KV micro grids.. The concept is presented through modeling and simulation in MATLAB/Simulation with reduced peak voltage of the sinusoidal waveform which causes less power loss for the system.*

KEYWORDS: *Photovoltaic (PV), H-bridge featured cascaded MMC, THPWM, heat dissipation, loss calculation*

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I. INTRODUCTION

Geothermal renewable energy and tidal renewable energy, are climate dependent, the power generated from them is of varying magnitude--even sometimes no power is generated at all. Except these two, renewable energy has been replaced on fossil fuel reducing global carbon emissions. The pace of investment on renewable energy has increased in such a way that the cost of technologies fall and efficiency continues to rise. (1)Growing price competitiveness (2) Long-term certainty (3) Energy security are the main three reasons of benefits of using renewable energies. In recent time, one fifth of the world's electricity is produced by renewable energy. In 2016, 160GW of clean energy installations globally which is 10% more than in 2015, costs almost a less quarter. The solar power gave the biggest boost, which is half of all new capacity, followed by wind power (one third), and hydropower (15%).

In this paper, the system is designed withPV array with MPPT, insulated gate bipolar transistor (IGBT) modules for H-bridge circuit along with its anti-parallel diodes. The power losses of IGBT devicesmainly contain conduction losses and switching losses. The losses of diode include the on-state losses or conduction, diode turn on losses and the diode reverse recovery losses. The diode turn on losses are so small that they can be ignored inthecalculation.The overall losses in multilevel converter depend on modulation schemes, operating level and intrinsic behavior of respective IGBTs. THPWM is used here for modulation with level shifted scheme

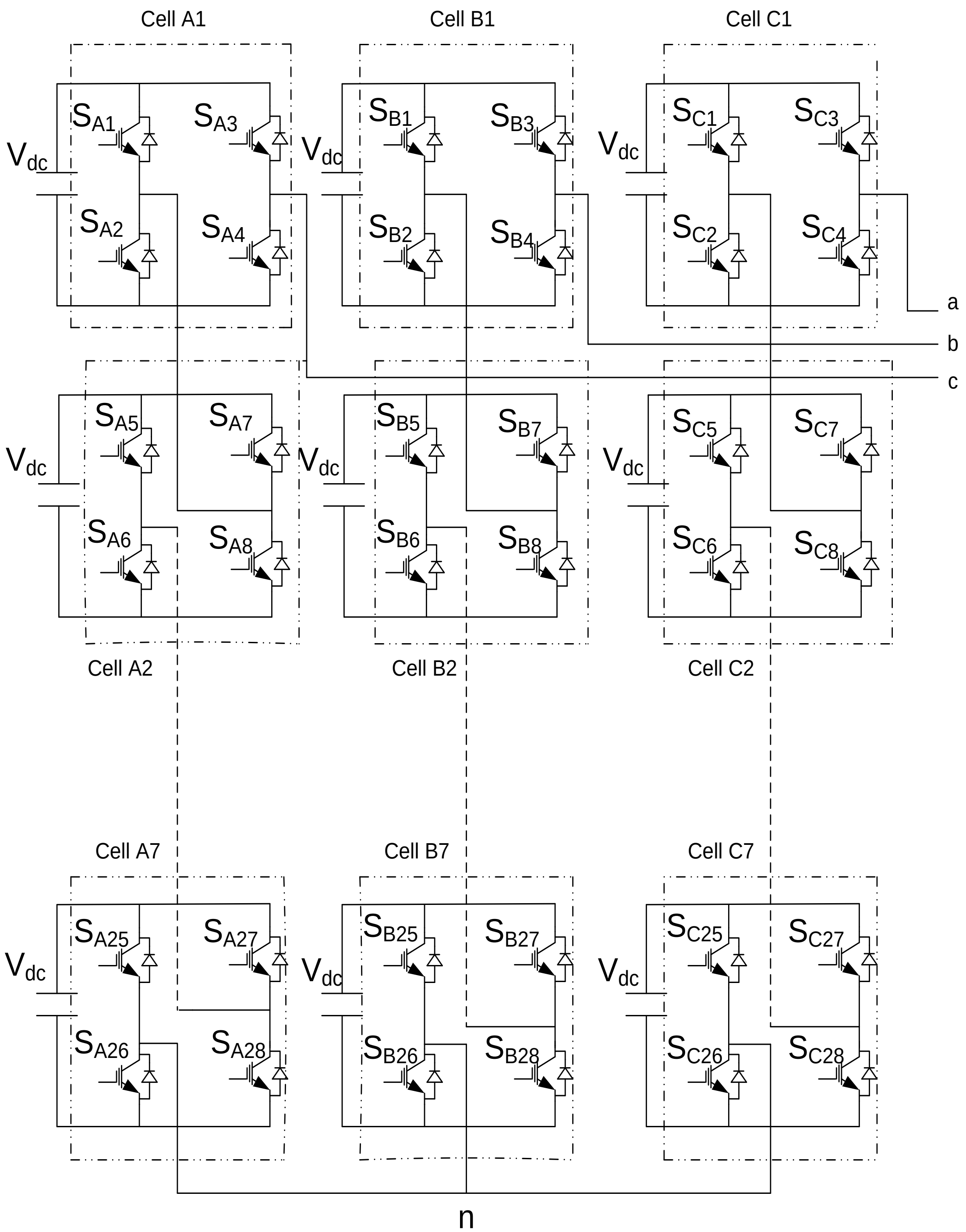


Fig. 1. Cascaded H-bridge mmc converter for three-phase 15-level system

which shows a better spectra property than the phase shifted scheme. Thus THD comes as 4% or slightly above. The overall losses in multilevel converter depend on modulation scheme, operating level and behavior of IGBTs. Selection of optimum level is based on control complexity, power loss and device voltage utilization factor, which should be more than 90%. Compared with different levels having different quantities of IGBTs, it can be shown that fifteen level multilevel converter is a better choice for selecting the levels used for multilevel converters.

II. LITERATURE REVIEW

An MMC control scheme controlling by individual sub module voltages, allows for maximum power point tracking of each photovoltaic array [5][6]. The loss estimation 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. The main factors affecting switching and conduction losses of converters are the individual current/voltage and the duty cycle of semiconductors [7].The energy dissipation at each switching event is proportional to the current level and the junction temperature at that instant. The maximum junction temperature of 125◦C is assumed for both conduction and switching loss calculation but in some experiment junction temperature is varied [9]. So, the switching power loss is extracted from the device data-sheet [10] for each current level at each switching instants. The switching loss calculation can be implemented in time-domain study utilizing the formulas [8].

It is very important to evaluate the losses in multilevel inverters as the power loss is considered a very important measure for cost, efficiency and reliability of the system. Loss evaluation in multilevel inverter is not an easy task and much more complicated because current differ in each power switch in the inverter. It is impossible to evaluate the instantaneous switching current of IGBT whereas in some experiments instantaneous switching current of IGBT has been taken for calculation [1][2] [3][4][5]. For calculation of average power loss current and voltage are multiplied as per the definition. As current is absurd to measure instantaneously, so instantaneous voltage is also impossible to measure. Thus average power loss is a challenging factor to measure. There are mainly two kinds of power losses such as conduction loss and switching loss. Average power loss has been calculated using device threshold voltage, diode conduction loss has not been obtained and finally conduction loss was not calculated with the total number of IGBT and diode [1]. The total switching frequency of IGBT and diode have been calculated using the value of datasheet [10] from the IGBT, no real time value has been used here for calculating the switching frequency [2]. The equation for collector-emitter voltage drop and the on-state forward voltage drop of diode were obtained by one dimensional equation using MATLAB and no specific company's diode has mentioned here for calculating any losses [1][3]. On the other hand, the equation of collector-emitter voltage drop and the on-state forward voltage drop have been obtained by 5^{th} order polynomial equation using MATLAB. A specific company's IGBT data sheet has been obtained for loss calculation because curve fitting equations are obtained as per the datasheet, so it must be mentioned a specific brand of IGBTs [2][4].The wave shape of average conduction loss and switching loss comes as scattered whereas average loss cannot come like that [1].

In this paper [3], the inverter was controlled using selective harmonic elimination. Genetic algorithm (GA) has been implemented successfully to solve for the switching angles. The process of genetic algorithm has been described theoretically by initialization of the population, evaluation of fitness function, selection, apply genetic operators and stopping criterion. However no numerical process has been analyzed and no equation derivation obtaining average power loss calculation for both conduction and switching losses has been shown. Also there are some figures explaining general GA algorithm flowchart, conduction losses block diagram, switching losses block diagram and basic flow model of applied methodology for losses calculation. But these figures does not explain any clear analysis for loss calculation. Moreover, MATLAB-SIMULINK is used for the modeling and simulation but no results and simulation figures have been given in the paper except 3 bar charts. All those above mentioned figures do not give any clear idea about loss calculation analytical method or any simulation results due to losses

In reference paper [4], a general scheme for calculating switching and conduction losses of power semiconductors in numerical circuits has been proposed based on online simulation. As per the reference paper [3], Selective Harmonic Elimination (SHE) technique is to be performed to determine the switching angles and Genetic Algorithm (GA) optimization method is used for solving the system of transcendental equations, no equation derivation of getting average power loss has been obtained. Only difference between reference [3] and reference [4] papers are to evaluate the conduction and switching losses, curve fitting equations are implemented to model the power switch mathematically as per the datasheet.

In reference paper [11], phase disposition pulse width modulation method is applied where the control strategy is selected based on some switching functions. No average power loss calculation has been obtained. The characteristic curves of IGBT and diode in different temperatures are shown here but no gray scale image processing curve using curve fitting tool has been shown. The two state voltage equations of collector-emitter voltage drop of IGBT and forward voltage drop of diode have been obtained. For calculating switching losses, here explaining that area under the power waveform is the switching energy at turn-on or turn-off transitions. However two unbounded graphs for IGBT and diode respectively are given to measure the areas of switching energies which are not possible. The average conduction loss and switching loss waveform in this paper is shown scattered. No numerical method as well as figure from MATLAB have been shown here for the loss calculation.

In this paper, conduction loss is counted for IGBT and its anti-parallel diodes. Moreover, switching loss is counted for IGBT turn on, IGBT turn off and diode turn off. Therefore the total conduction power loss will be the sum of total no of IGBTs and diodes used in the inverter. In addition, to evaluate switching loss, it must need to evaluate the instantaneous switching current. As said before, the IGBTs are fast switching in the inverter, few KHZ per second. So a precise and more effective way to measure the switching losses is to measure the rms and average current and then derive an equation for average switching losses using these currents accordingly.

III. MODEL FOR PROPOSED ANALYSIS

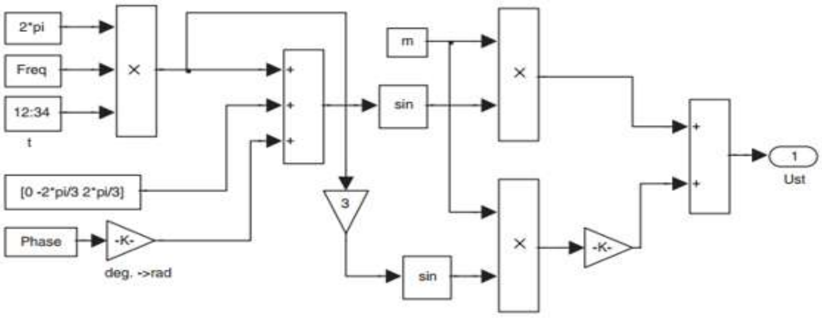


Fig .2. MATLAB/Simulink model to generate third-harmonic injected sinusoidal reference signals for 3-phase 15-level converter.

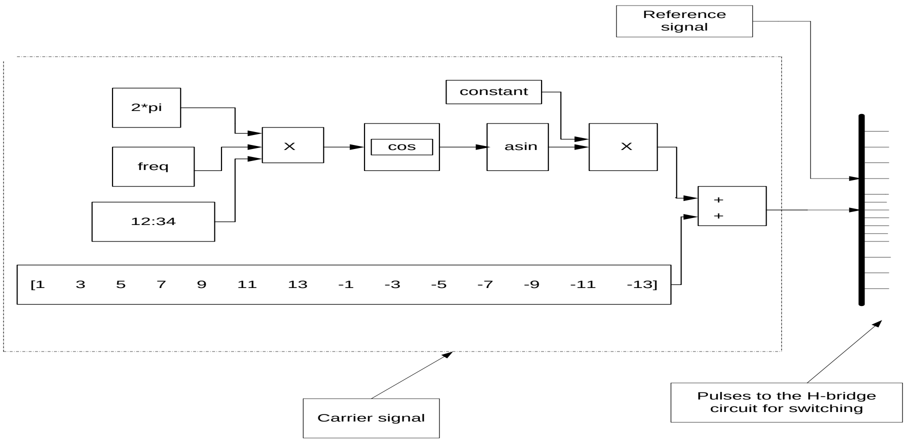


Fig. 3. MATLAB/Simulink model to generate carrier for 15-level converter

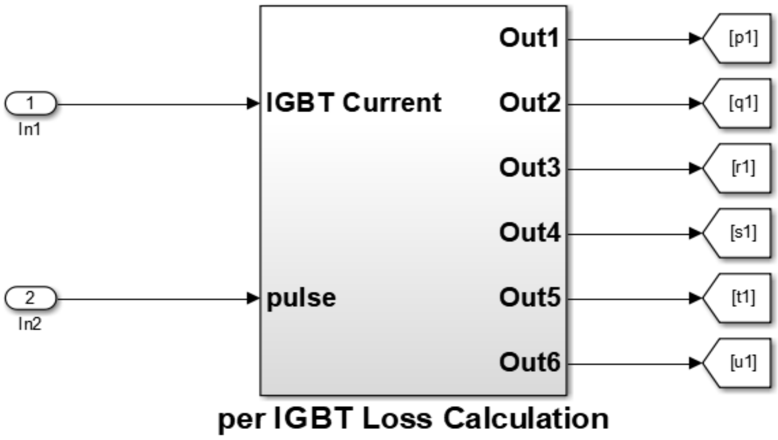


Fig .4.IGBT for loss calculation: p_1, q_1, r_1, s_1, t_1, u_1 are IGBT switching turn on loss, IGBT switching turn off loss, IGBT switching (total) loss, diode turn off loss, IGBT conduction loss and diode conduction loss respectively.

IV. LOSS ANALYTICAL METHOD

Power loss calculation due to Conduction: To evaluate the power losses due to conduction, a distinctive IGBT on-state characteristics has been obtained from the IGBT datasheet. Thus, form an equation of IGBT collector-emitter voltage drop (v_g) which has been approximated by

$v_g = v_g^0 + R_g.i_g$ (1)

v_g^0 is IGBT on-state zero current collector-emitter forward voltage drop and R_g is the collector-emitter on-state resistance. For the diodes conduction, v_d is the forward voltage drop, v_d^0 represents diode on-state zero current forward voltage drop and R_d is on-state resistance. The equation is given by

$v_d = v_d^0 + R_d.i_d$ (2)

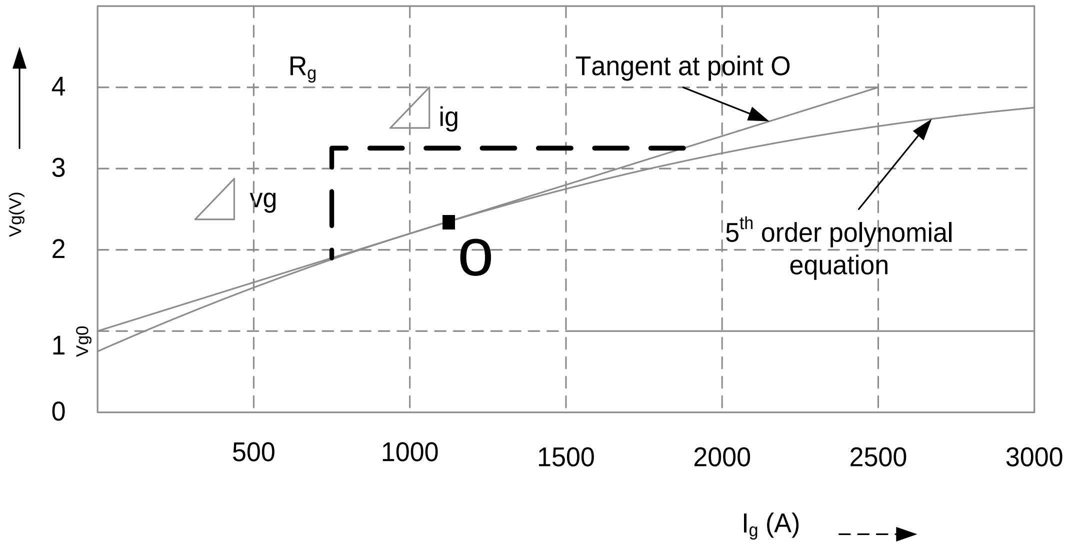


Fig .5. Obtaining v_{c0} and R_c from polynomial equation for IGBT.

By analyzing the process, the IGBT collector-emitter voltage drop (v_g) during conduction using image processing and the curve-fitting tool for the figure and got a 5th order polynomial equation of v_g from MATLAB which is shown below

$v_g = C_1 i_g^5 + C_2 i_g^4 + C_3 i_g^3 + C_4 i_g^2 + C_5 i_g + C_6$ (3)

The value of the co-efficient are found from the Simulink –
C_1 = 2.235 x 10 -17
C_2 = -1.996 x 10 -13
C_3 = 7.118 x 10 -10
C_4 = -1.294 x 10 -06
C_5 = 0.002105
C_6 = 0.6739

Let's draw a tangent on the curve at point O ($i_g^/, v_g^/$) Fig.5., thus the slope is calculated by

$m_g = \frac{dv_g}{di_g} = 5C_1 i_g^4 + 4C_2 i_g^3 + 3C_3 i_g^2 + 2C_4 i_g + C_5$ (4)

At $i_g = i_g^/$, $m_g = R_g$ from the voltage current plot of the polynomial equation after drawn the tangent, the zero-current collector-emitter forward voltage is,

$v_g^0 = v_g^/ - (m_g.i_g^/)$ (5)

Similarly, the diode on-state voltage is represented by the below polynomial equation,
$v_d = F_1 i_d^5 + F_2 i_d^4 + F_3 i_d^3 + F_4 i_d^2 + F_5 i_d + F_6$ (6)

The value of the co-efficient are-
F_1 = 3.298 x 10 -17

F_2 = -2.907 x 10 -13
F_3 = 9.866 x 10 -10
F_4 = -1.669 x 10 -06
F_5 = 0.001975
F_6 = 0.6265

Similarlyassume, point Q ($i_d^{/}, v_d^{/}$) considering fig.5.

$m_d = \frac{dv_d}{di_d} = R_d$ [where $i_d = i_d^{/}$] (7)

and $v_d^0 = v_d^{/} - (m_d.i_d^{/})$ (8)

The instantaneous IGBT conduction losses are

$P_g(t) = v_g\ (t).i_g(t)$

$= v_{g^0}(t).i_g(t) + R_g.i^2{}_g$ (9)

[Put the value of v_g from equation 3]

The average conduction power loss is

$$P_g = \frac{1}{2\pi}\int_0^{2\pi}[P_g\ (t)]d(\omega t) \quad (10)$$

$$= \frac{1}{2\pi}\int_0^{2\pi}[v_{g^0}(t).\,i_g(t) + R_g.\,i_g^2]d(\omega t)] \quad (11)$$

$$P_g = v_g^{\ 0}.I_{g(avg)} + R_g.I^2_{g(rms)} \quad (12)$$

$I_{g(avg)}$ and .$I^2_{g(rms)}$ are the IGBT's the average and rms currents. Similarly, the average diode conduction loss per phase can be written as

$P_d = v_d^{\ 0}.I_{d(avg)} + R_d.I^2_{d(rms)}$ (13)

The total conduction loss per phase with N no. of IGBT as well as diodes:

$P_{(g+d)} = \sum_{n=1}^{N}[\ P_g(no\ of\ IGBTs) + \ P_d\ (no\ of\ diodes)]$ (14)

IGBT Turn On and IGBT Turn Off switching losses:

To obtain switching losses means the moment of IGBT and its anti-parallel diode's instant switching time due to current which causes loss. Using image processing, a 5th order polynomial equation has been observed. The equation of power loss during IGBT ON and OFF are shown respectively.

$E_{ON\text{-}Time} = H_1 i_g^{\ 5} + H_2 i_g^{\ 4} + H_3 i_g^{\ 3} + H_4 i_g^{\ 2} + H_5 i_g + H_6$(15)

The value of the co-efficient are –
H_1 = -1.217 x 10 -25
H_2 = 8.32 x 10 -22
H_3 = 5.391 x 10 -11
H_4 = 2.552 x 10 -8
H_5 = 0.000738
H_6 = 0.09619

$E_{OFF\text{-}Time} = J_1 i_g^{\ 5} + J_2 i_g^{\ 4} + J_3 i_g^{\ 3} + J_4 i_g^{\ 2} + J_5 i_g + J_6$(16)

The value of the co-efficient are-
J_1 = 4.309 x 10 -19
J_2 = -3.189 x 10 -15
J_3 = 1.445 x 10 -10
J_4 = -6.775 x 10 -7
J_5 = 0.002042
J_6 = 0.2036

Polynomial equation of power loss due to Diode OFF

$E_{diode@Turn\ OFF} = K_1 i_d^{\ 5} + K_2 i_d^{\ 4} + K_3 i_d^{\ 3} + K_4 i_d^{\ 2} + K_5 i_d + K_6$ (17)

The value of the co-efficient are shown below:
K_1 = -2.34 x 10 -24
K_2 = 3.211 x 10 -20
K_3 = 5.448 x 10 -8
K_4 = -0.0004056
K_5 = 1.108
K_6 = 127.3

Therefore, the total power loss of IGBT Turn ON, Turn OFF and Diode OFF for the fundamental Time Period T_f can be written as follows respectively;

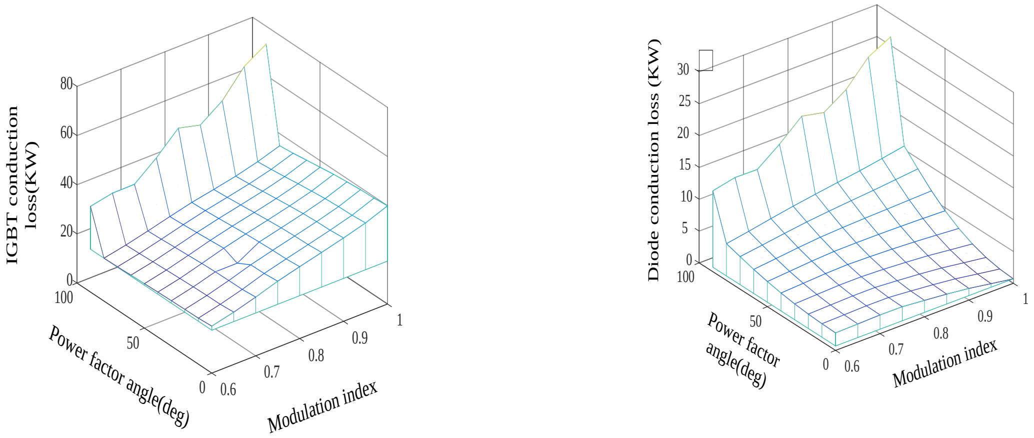
$$P_{IGBT\ (ON+OFF)} = \frac{1.\ V_{(min)}}{T_f.\ V_{(nom)}} \sum_{n=1}^{N} \left[E_{ON\ Time\ @T_n(i_g)} + E_{OFF\ Time\ @T_n(i_g)} \right] \quad (18)$$

$$P_{Diode\ (OFF)} = \frac{1.\ V_{(min)}}{T_f.\ V_{(nom)}} \sum_{n=1}^{N} \left[E_{diode\ @\ Turn\ OFF @T_n}.(i_d) \right] \quad (19)$$

Here $V_{(min)}$ and $V_{(nom)}$ are the minimum and nominal DC voltage of each H-bridge inverter cell

V. PERFORMANCE & RESULTS

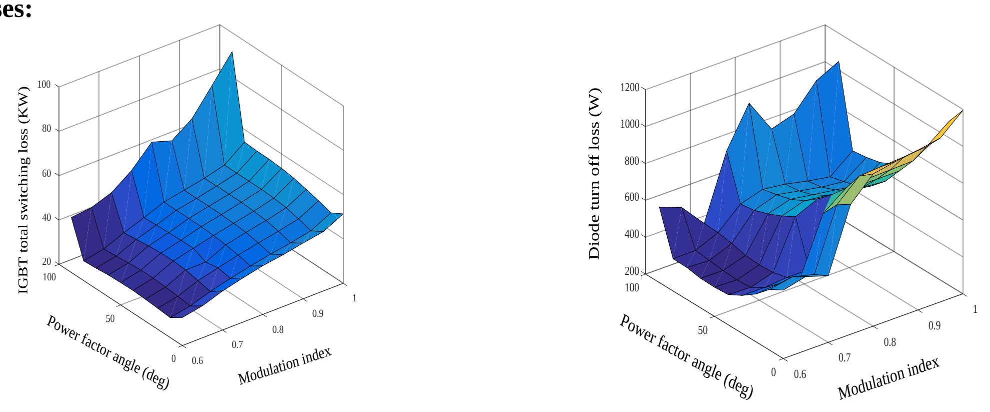
Conduction loss
IGBT conduction loss (KW):



(a) (b)

Fig.6. (a) IGBT conduction loss (KW) (b) Diode conduction loss (KW).

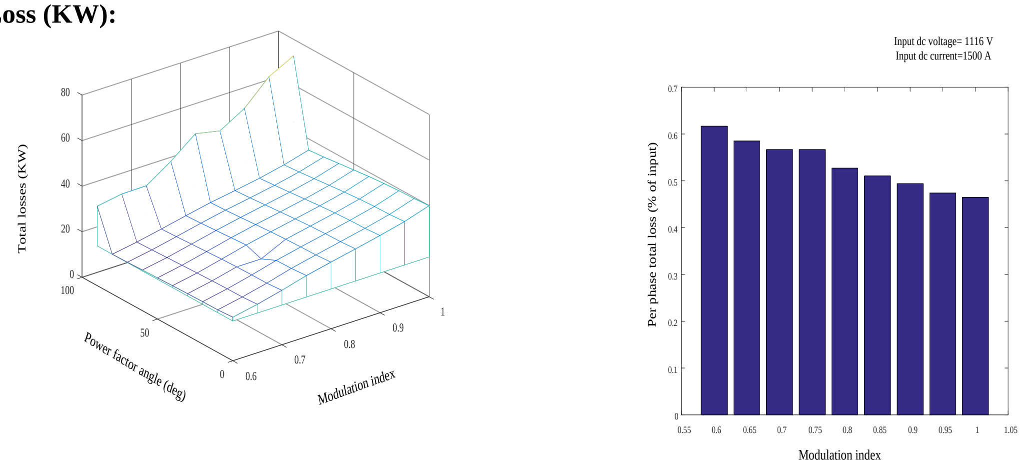
Switching losses:



(a) (b)

Fig .7. (a) IGBT switching loss (KW) (b) Diode Turn OFF loss (W)

Total Loss (KW):



(a) (b)

Fig.8.(a) Total loss (KW) (b) Per phase total loss (% of input) with respect to modulation index in a three-phase 15 level THSPWM.

Comparison of THD

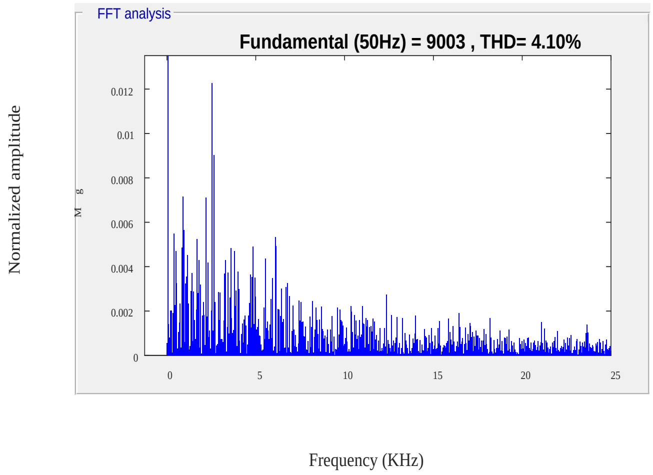
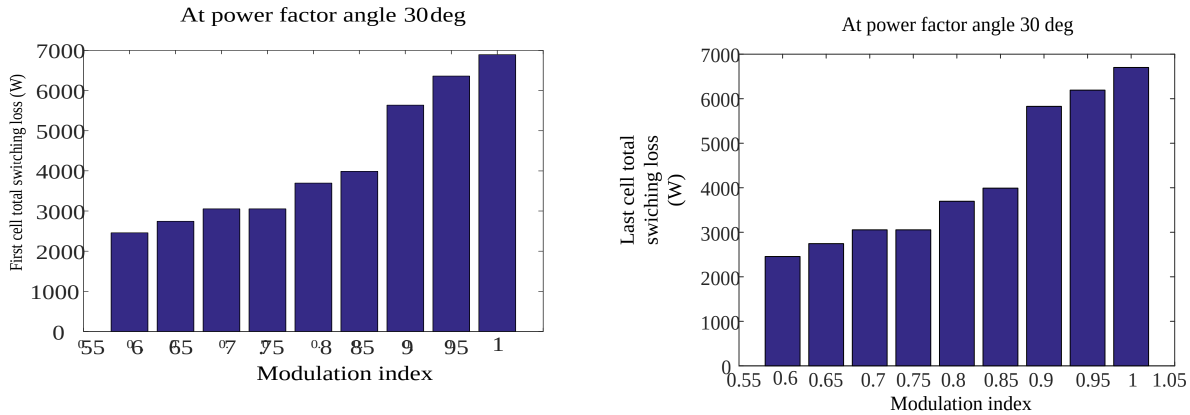
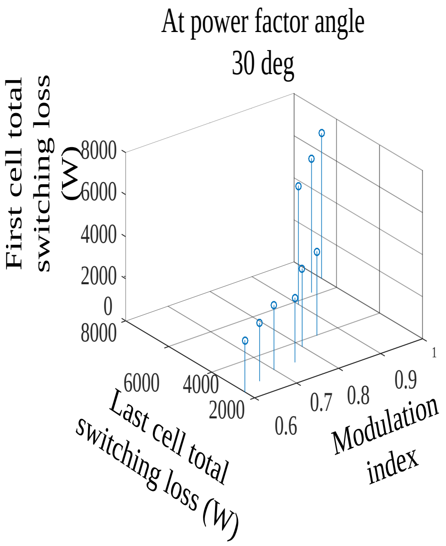


Fig.9.THD (%) with respect to modulation index.

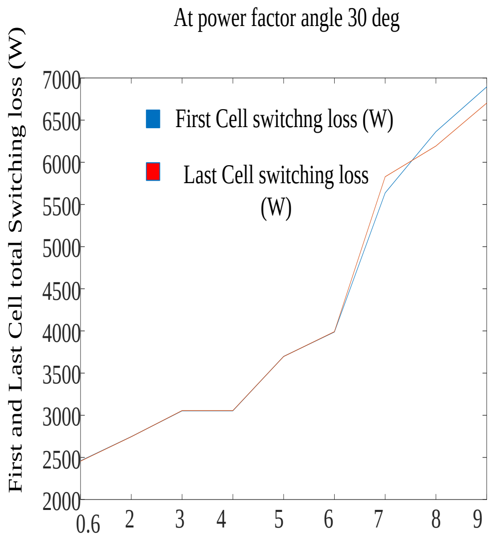
Losses in different area:



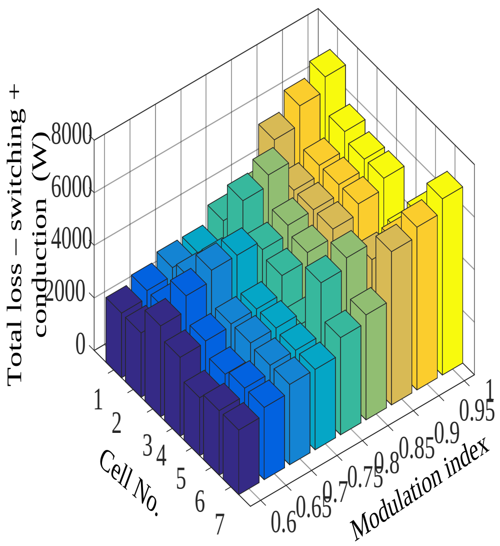
(a) (b)


At power factor angle
30 deg
First cell total switching loss (W)
Last cell total switching loss (W)
Modulation index

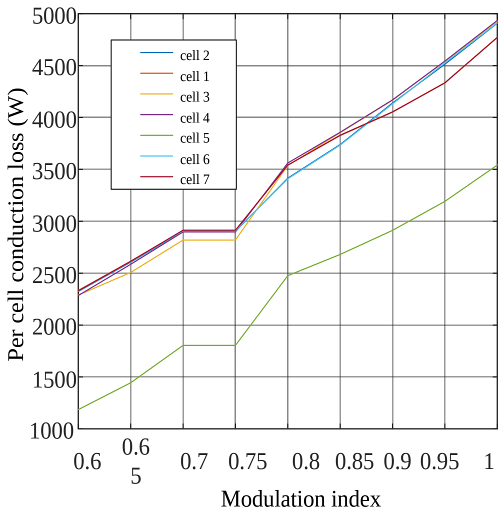
(c)


At power factor angle 30 deg
First Cell switchng loss (W)
Last Cell switching loss (W)
First and Last Cell total Switching loss (W)

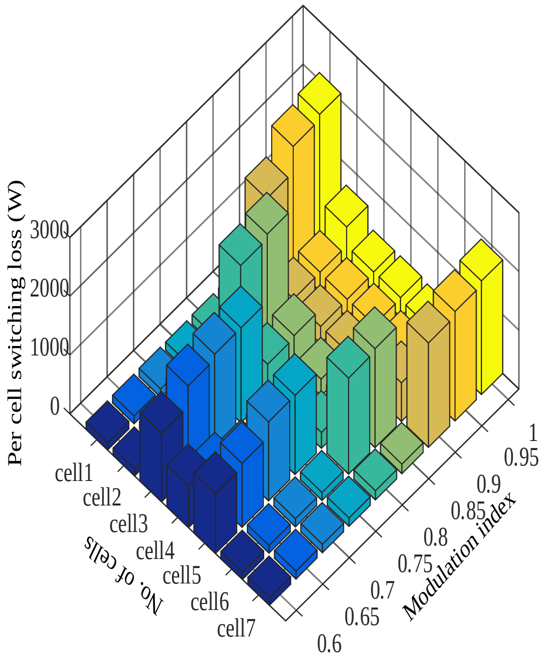
(d)


Total loss – switching + conduction (W)
Cell No.
Modulation index

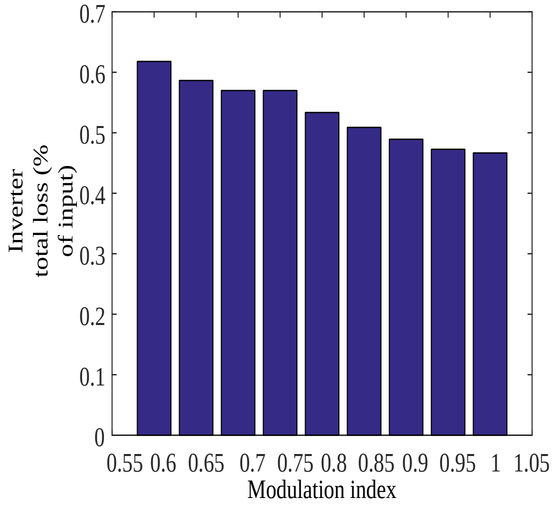
(e)


cell 2
cell 1
cell 3
cell 4
cell 5
cell 6
cell 7
Per cell conduction loss (W)
Modulation index

(f)

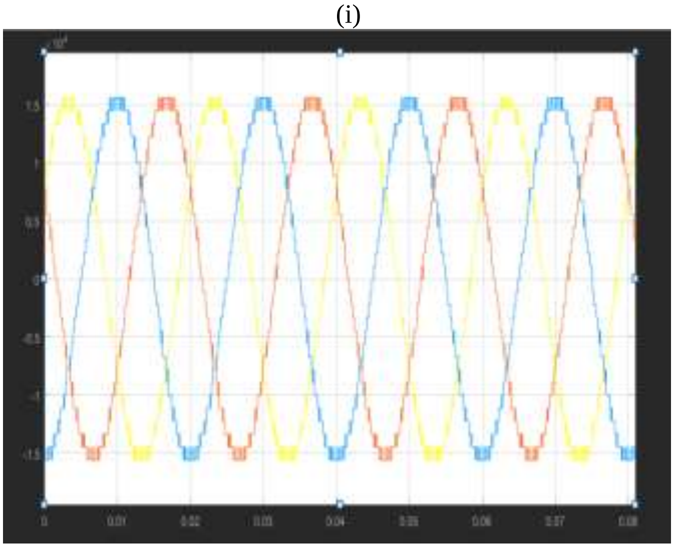


(g)



(h)

(i)



(i)

Fig.10. (a) First cell total switching loss (W) (b) Last cell total switching loss (W) (c) First cell total switching loss (W) (d) First and Last cell total switching loss (W) (e) Total loss (switching and conduction) (f) Per cell conduction loss (W) with respect to modulation index(g) Per cell switching loss (W) (h) Inverter total loss (% of input) (i) ac output signal of voltage and current.

VI. CONCLUSION

The proposed method is based on image processing, simulation and numeric approach. Rms current and average current have been obtained by putting ammeter, RMS and average blocks in MATLAB simulation. Practically rms current and average current can be obtained by putting only ammeter in series with IGBTs.

A high power loss means rise of temperature in higher switching frequency. It may have the risk of failure of IGBTs which will cause an uneconomical power conversion. So, in hardware basis, better cooling method as well as equation for cooling method can be developed for further work.

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