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Power Loss Calculation in 11-Level Cascaded H-Bridge Inverter using Harmony Search Optimized Switching Scheme

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Abstract**:** ***Power loss is the most significant parameter in power system analysis and its adequate calculation directly effects the economic and technical evaluation. This paper aims to propose a multi-objective optimization algorithm which optimizes dc source magnitudes and switching angles to yield minimum THD in cascaded multilevel inverters. The optimization algorithm uses metaheuristic approach, namely Harmony Search algorithm. The effectiveness of the multi-objective algorithm has been tested with 11-level Cascaded H-Bridge Inverter with optimized DC voltage sources using MATLAB/Simulink. As the main objective of this research paper is to analyze total power loss, calculations of power loss are simplified using approximation of curves from datasheet values and experimental measurements. The simulation results, obtained using multi-objective optimization method, have been compared with basic SPWM, optimal minimization of THD, and it is confirmed that the multilevel inverter fired using multi- objective optimization technique has reduced power loss and minimum THD for a wide operating range of multilevel inverter.***

Index Terms**:** ***Cascaded Multilevel inverter, Conduction Loss, Harmony Search Algorithm, Modulation Index, Pulse Width Modulation, Switching Loss, Total Harmonic Distortion.***

I. INTRODUCTION

The utilization of multilevel inverters at medium voltage and high power level has gained significance during previous years. Distinct combinations of power semiconductor switches can help in obtaining various different topologies of multilevel inverters for different applications [1]-[3]. Various literature works report efficient utilization of different topologies in various applications. However, out of three basic configurations, the cascaded H-bridge configuration has attracted the most reviewers due to its impressive features like modular structure, easy control and operation, adaptive to various modulation techniques [4], [5]. Cascaded H-Bridge Multilevel Inverter is basically a series/cascade combination of a number of H-bridge, that synthesize desired AC output voltage from several DC voltage connected at input of each H-bridge. As, each unit of H-bridge is supplied with its own isolated DC supply, the current in each unit and further in each power semiconductor switch of a particular unit is different from load current or source current. Thus, it becomes crucial to examine the behavior of power semiconductor switches and investigate power losses.

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Power loss is the most significant parameter in power system analysis and its adequate calculation directly effects the economic and technical evaluation [6], [7]. The power losses in a converter circuit comprises of conduction loss, switching loss, snubber loss, and off-state loss. But, as during the off state of the device, leakage current is negligibly small, so off state power loss can also be neglected. Also, snubber losses are negligible in IGBT's. Therefore, only switching losses and conduction losses are necessary to be considered [8], [9]. It is a quite challenging to perform the power loss analysis in multilevel inverters. Equally important is to control the power quality while adopting the modulation method for minimizing the power loss. Many reviewers have proposed SPWM based methods minimize harmonics and analyzed the total power loss in multilevel inverter. But as SPWM involves high switching frequency, thus power losses are high. Therefore, it is essential to optimize switching frequency for power loss reduction while minimizing THD [10]. Some methods involving optimization of switching angles for providing gating pulse to different switches of multilevel inverter are proposed which help in reducing the power losses to a greater extent, as the switching frequency is reduced significantly. Optimizing switching angles require use of some optimization algorithm, like Particle Swarming Optimization (PSO) [11]-[13], Genetic Algorithm (GA) [14], [15], BAT Inspired Algorithm, Evolution Algorithm, etc.

This research work presents a multi-objective optimization method which aims to minimize THD as well as optimize dc source voltages to give desired fundamental output voltage with better efficiency. Also, the optimized values of switching angles obtained from the proposed technique have values such that the power losses in the circuit are much more reduced than with single objective of minimizing THD. Optimization technique, Harmony Search is chosen as it is easy to implement and can be applied to higher order optimization problems. It has inherent feature of search efficiency and potential to avoid getting stuck at local minimum points. The algorithm efficiently reduces harmonic distortion and power loss analysis proves that the proposed method helps in significant reduction of power loss. Comparative analysis of power loss in MLI using PWM, OTHD and multi-objective optimization technique has been performed. Simulation results proved that multi-objective optimization technique has minimum power loss as well as the THD has been minimized with the desired value of fundamental voltage.

II. LITERATURE REVIEW

Various techniques have been proposed in literature to evaluate the power loss in multilevel inverters. Some methods perform calculation along with simulation of circuit while some require intense mathematical analysis and evaluation. Selection of modulation technique affects the harmonics and power loss in multilevel inverters. Like, in MLIs con- trolled using the traditional modulation method, carrier based pulse width modulation (PWM), and switching losses are most significant as they directly depend on switching frequency. But, reducing switching frequency is not possible without compromising the harmonic content of the voltage waveform, thus demanding the use of harmonic filters [16]. Space-vector modulation that operates with high switching frequency is also applied to multilevel inverter. They are efficient in reducing harmonics but cause high switching loss. A hybrid scheme [17] presents combination of carrier based space vector modulation and fundamental frequency modulation, to minimize switching losses with an improved harmonic performance. Compared to conventional CBSVM, it reduces 27% of power loss. In multilevel inverters operating at low switching frequency, conduction loss are a major part of the total power loss. But, as all semiconductor switches are gated with individual switching pulses, the amount of current flowing through them varies and hence the conduction loss in different switches also varies [18].

Also, estimation of switching and conduction times for each semiconductor switch is a slow and tedious process. Keeping numerous calculations in mind, some reviewers have suggested improving the power loss equations to simplify the task of power loss evaluation [19] .

Selective Harmonic Elimination (SHE) technique gives high output power quality because it uses low switching frequency, and thus gives reduced harmonic distortion. Many heuristic methods have been used to deal with the system of transcendental equations and optimize the switching instants so as to minimize harmonics while reducing the power loss. An optimization method has been proposed [20] using SHE where determination of switching angles is done using the application of Particle Swarming Optimization (PSO). But PSO tends to converge early at mid optimum points and takes time to converge in refined search stage. Another scheme where determination of switching angles is done using Genetic Algorithm (GA) is presented [21]. But the quality of solution deteriorates with increase in the level of inverter while using GA. A new heuristic method, Harmony Search is used in the multi-objective optimization because of its distinguishing features such as high rate of convergence and precision [22] . Also, the algorithm can be used with any level of multi-level inverter.

III. MULTI-OBJECTIVE OPTIMIZATION TECHNIQUE

Practically, MLIs are connected to solar power or photo-voltaic panels for getting DC input. And if the magnitude of DC source is decided according to the required fundamental output value, the efficiency of inverter is enhanced. As reviewed in literature, the researchers mainly focus on minimization of harmonics. But here in this paper, an optimization function has been developed with an objective to optimize switching angles as well as the input dc source magnitudes so as to achieve better power quality and efficiency. Some applications demand extending the operating range of multilevel inverter by varying the modulation index to get variable ac voltage. This method regulates the voltage levels of multilevel inverter by optimizing the dc source voltage magnitudes according to the desired modulation index.

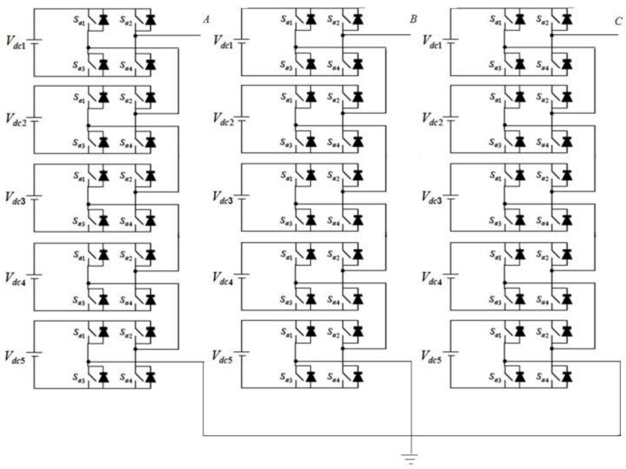

Fig. 1. Three-Phase 11- level Cascaded H Bridge Inverter

Now, for an 11-level Inverter shown in Figure 1 , switching angles α_1, α_2, α_3, α_4, α_5 and V_{dc1}, V_{dc2}, V_{dc3}, V_{dc4}, V_{dc5} are obtained for firing each H-bridge unit at desired switching instant with optimized output. As, the phase output voltage of multilevel inverter can be expressed in terms of Fourier series expansion:

$$V(t) = \sum_{n=1,3,5}^{\infty} \frac{4}{n\pi}(V_{dc1}\cos n\alpha_1 + V_{dc2}\cos n\alpha_2 + V_{dc3}\cos n\alpha_3 + V_{dc4}\cos n\alpha_4 + V_{dc5}\cos n\alpha_5)\sin n\omega t \tag{1}$$

where V_{dc1}, V_{dc2}, V_{dc3}, V_{dc4}, V_{dc5} are the output voltages of each H-bridge inverter units.

Since, we are considering line voltage and triplen harmonics are eliminated in line voltage. Thus, Total Harmonic Distortion of line voltage can be expressed as:

$$THD = \frac{\sqrt{\sum_{n=5,7,11..}^{\infty} V_n^2}}{V_1} \times 100 \tag{2}$$

The fundamental component can be written as:

$$V_1 = \frac{4}{\pi}(V_{dc1}\cos\alpha_1 + V_{dc2}\cos\alpha_2 + V_{dc3}\cos\alpha_3 + V_{dc4}\cos\alpha_4 + V_{dc5}\cos\alpha_5) \tag{3}$$

Now, the multi-objective function is developed and coded in MATLAB to give the desired results in form of switching angles to fire the switches of multilevel inverter

The condition for perfect waveform is that switching angles should be within zero and $\pi/2$..

$$\text{Objective} = w_1 \times THD + w_2 \times (\text{Voltage Deviation}) \quad (4)$$

Now, the Harmony Search Algorithm is implemented on the developed objective function to obtain best results. It employs two probabilities Harmonic Memory Considering Rate (HMCR) and Pitch Adjustment Rate (PAR) to update the solution till requirement is fulfilled. The technique proves to be successful in avoiding the output from getting stuck in some neighboring values, and thus results in best optimum solution, also known as global best solution.

IV. CALCULATION OF POWER LOSS

During operation of any power circuit which involves switching of power components, there are mainly four types of power losses, namely, conduction loss, switching loss, gate loss and off-state loss. The Gate loss and Off-state loss are minimal and normally neglected. Also, considering the total of the conduction and switching loss gives a good estimation of the total power loss in any power circuit. Thus, only switching loss and conduction loss are investigated for power loss analysis. Loss to be calculated can be classified as given in Fig.2.

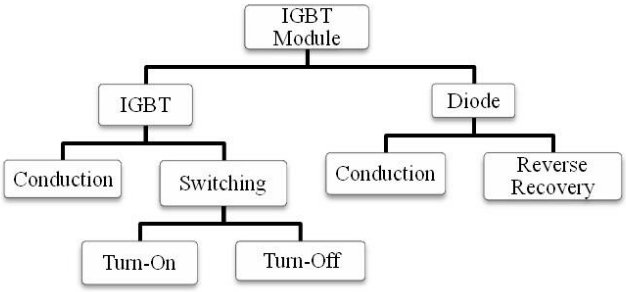

Fig. 2. Classification of Losses in IGBT Module

A. Conduction loss

The losses that appear during on-state or conduction of a device are termed as Conduction loss. Total conduction loss in the multilevel inverter is sum of real time loss of every component integrated over conduction period. So, the power loss can be represented by product of on-state saturation voltage V_{ON} and on-state current I_{ON}

$$P_{Conduction} = P_{Cond\,(IGBT)} + P_{Cond\,(Diode)}$$
$$P_{Conduction} = (V_{CE} \times I_C) + (V_D \times I_D) \quad (5)$$

Here, V_{CE} and V_D are functions of current flowing through the IGBT and diode. And I_C and I_D are taken as mean values of current. Now the value of V_{CE} and V_D can obtained from the V-I characteristic curve of IGBT and Diode. Now, by approximation of curves,

$$V_{CE} = -2 * 10^{-7} I_C^2 + 0.0018 I_C + 0.9661$$
$$V_D = -1 * 10^{-7} I_D^2 + 0.0012 I_D + 0.7796 \quad (6)$$

Conduction loss is also termed as on-state loss or steady state loss. They are independent of the switching frequency but depend on the duty cycle.

B. Switching loss

Switching loss appeared because the transitions from off-state to on-state and on-state to off-state do not occur immediately. During this transition, both current and voltage across the device are considerably high leading to high instantaneous power loss. These losses typically contribute a significant amount to the total system losses. As diode is considered to be an ideal switch, its turn-on loss is negligible. So, switching loss is total of IGBT turn-on loss, IGBT turn-off loss and Diode reverse recovery loss.

These losses can be computed from the switching energy equations which are function of switch current.

$$P_{Switching} = P_{Turn-ON} + P_{Turn-OFF} + P_{Rec.Diode}$$
$$P_{Switching} = (E_{Turn-ON} + E_{Turn-OFF}) * f_{sw\,(IGBT)} + (E_{Rec.Diode}) * f_{sw\,(Diode)} \quad (7)$$

Now, by approximation of curves,

$$E_{Turn-ON} = 8 * 10^{-7} I_C^2 - 0.0023 I_C + 4.016$$
$$E_{Turn-OFF} = 3 * 10^{-7} I_C^2 - 0.0011 I_C + 3.1584$$
$$E_{Rec.Diode} = 7 * 10^{-7} I_D^2 - 0.0039 I_D + 6.6546 \quad (8)$$

Switching losses can be easily estimated using these equations. These losses depend on the dc link voltage, load current, junction temperature and switching frequency. If the switching frequency is higher, then the losses will be higher.

V. SIMULATION AND RESULTS

For power loss investigation, an 11-level three-phase multi- level inverter in cascaded H-bridge configuration is modeled in MATLAB/Simulink environment. The H-bridges of multilevel inverter are supplied so as to give output of 430V, 10A when connected with a balanced load of 30Ω, 50mH as shown in Fig.3.

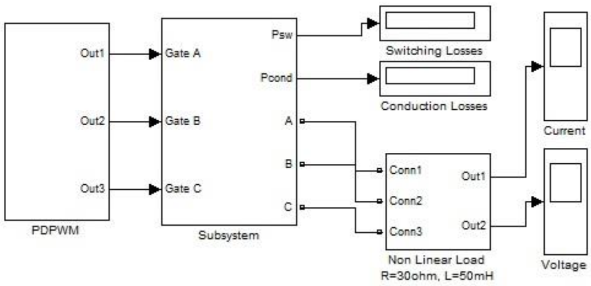

Fig. 3. MATLAB/Simulink of 11-level Cascaded H-Bridge Inverter

To evaluate the effectiveness of multi-objective optimization technique various simulations are carried out in MATLAB/Simulink. Power Loss Calculation and THD Analysis of 11-level Cascaded H-Bridge Inverter are done over a modulation range of 0.4 to 1.2 with an interval of 0.1 using SPWM and OTHD method. And the results are shown in Tables 1 and 2 . From the results, it is confirmed that switching losses are reduced by 54% approximately by using OTHD. It can also be observed that with SPWM, the desired fundamental output equals the desired voltage and the THD decreases with increase in modulation index but content of harmonics is not within acceptable range. However, using OTHD method decreases THD but fundamental is not equal to desired value. Power Losses have reduced to nearly half of the conventional technique. Also, conduction losses contribute only around 3-8% of total loss.

TABLE I: PERFORMANCE ANALYSIS OF MLI USING SPWM

M	Switching Loss (mW)	Conduction Loss (mW)	Total Loss (mW)	THD (%)	Fundamenta l Voltage (V)
0.4	2614	70.19	2684.2	17.79	169.1
0.5	2622	88.45	2710.5	13.38	211.3
0.6	2622	107.5	2729.5	11.26	254.8
0.7	2622	126.2	2748.2	9.09	297.0
0.8	2615	145.8	2760.8	8.34	340.8
0.9	2616	165.4	2781.4	7.61	383.7
1.0	2616	185.2	2801.2	7.01	426.8
1.1	2063	199.7	2262.7	6.96	456.2
1.2	1863	209.0	2072.0	7.06	472.7

TABLE II: PERFORMANCE ANALYSIS OF MLI USING OTHD

M	Switching Loss (mW)	Conduction Loss (mW)	Total Loss (mW)	THD (%)	Fundamenta l Voltage (V)
0.4	993.8	192.8	1186.6	5.89	442.8
0.5	993.8	192.8	1186.6	5.89	442.8
0.6	993.8	192.8	1186.6	5.89	442.8
0.7	993.8	192.8	1186.6	5.89	442.8
0.8	993.8	192.8	1186.6	5.89	442.8
0.9	993.8	192.8	1186.6	5.89	442.8
1.0	993.8	192.8	1186.6	5.89	442.8
1.1	1001	207.9	1208.9	6.13	471.4
1.2	1001	238.3	1239.3	6.66	519.1

When multi-objective optimization algorithm is executed, the optimized value of switching angles and magnitude of DC voltage input to be given to each H-bridge are obtained and shown in Table 3. Table 4 summarizes the performance of multilevel inverter using multi-objective optimization technique.The simulation results obtained, using multi-objective optimization technique, are compared with those obtained using traditional PWM method, and optimal minimization of THD method. The graphical comparison is done for Total losses, THD and Fundamental value shown in Fig. 4, 5 and 6.

From the graphical analysis, it can be clearly seen that the multi-objective optimization technique gives best results. Comparison shows that the power loss increase with increase in modulation index, and losses are further reduced by 2-10% with multi-objective optimization technique than OTHD method. Moreover, desired results can be obtained at any value of modulation index. By varying the value of modulation index, desired value of fundamental output can be achieved with THD in acceptable range.

TABLE III: PERFORMANCE OPTIMIZED SWITCHING ANGLES USING MULTI-OBJECTIVE OPTIMIZATION TECHNIQUE

M	α_1	α_2	α_3	α_4	α_5
0.4	12.68	36.28	56.31	62.47	83.98
0.5	10.03	34.43	39.70	59.89	81.72
0.6	9.06	32.67	40.35	59.28	80.24
0.7	5.39	34.54	45.02	74.85	85.04
0.8	3.35	13.36	34.03	40.04	82.08
0.9	7.30	20.09	33.39	46.61	60.35
1.0	6.60	14.42	26.74	39.61	59.61
1.1	6.58	14.46	26.43	38.92	59.44
1.2	6.83	14.76	25.98	39.68	59.73

M	V_{DC1}	V_{DC2}	V_{DC3}	V_{DC4}	V_{DC5}
0.4	38.94	36.25	36.05	38.30	37.08
0.5	45.73	35.57	44.76	45.86	38.08
0.6	57.56	40.36	56.63	43.7	36.41
0.7	66.4	71.87	72.08	45.68	43.06
0.8	57.6	68.47	60.21	52.23	41.17
0.9	79.41	75.26	59.00	35.62	46.44
1.0	74.12	68.30	69.90	58.40	52.65
1.1	84.43	78.67	72.21	62.91	56.34
1.2	84.57	83.38	87.08	69.26	65.25

TABLE IV: PERFORMANCE ANALYSIS OF MLI USING MULTI-OBJECTIVE OPTIMIZATION

M	Switching Loss (mW)	Conduction Loss (mW)	Total Loss (mW)	THD (%)	Fundamenta l Voltage (V)
0.4	1000	69.7	1069.7	8.43	169.6
0.5	993.7	89.35	1083.05	5.57	214
0.6	993.6	106.5	1100.1	5.42	253.4
0.7	999.6	124.8	1124.4	5.12	298.6
0.8	1001	149.7	1150.7	4.92	342.4
0.9	993.9	167.5	1161.4	4.84	383.6
1.0	974.4	187.8	1162.2	4.35	426.5
1.1	974.3	207.9	1182.2	4.39	470.7
1.2	994.1	225.8	1219.9	4.28	512.2

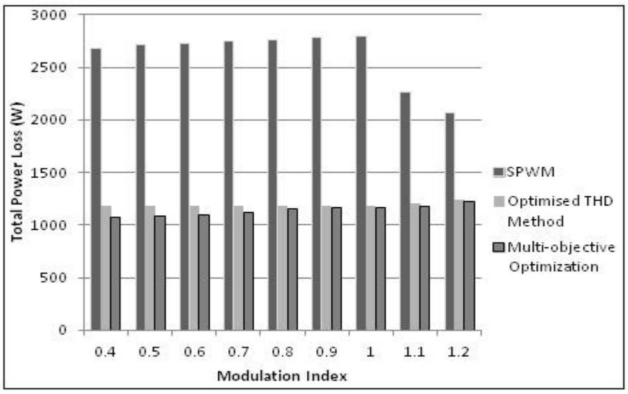

Fig. 4. Comparison of Total Power Loss at different modulation indices

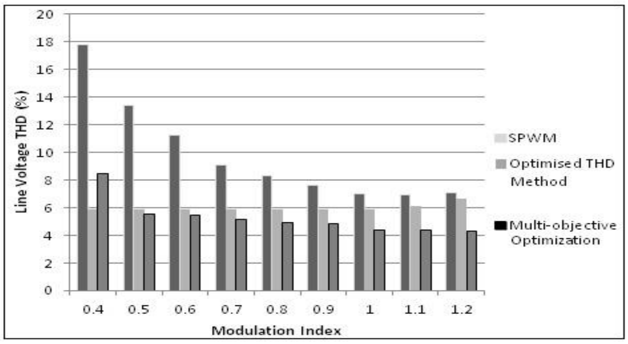

Fig. 5. Comparison of THD in Output Line Voltage at different modulation indices

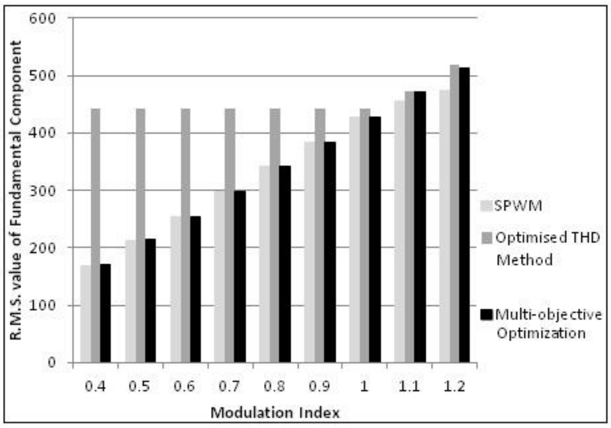

Fig. 6. Comparison of R.M.S. Value of fundamental component of Output Line Voltage at different modulation indices

VI. CONCLUSION

The multi-objective optimization efficiently solves for opti- mal switching angles for firing switches of multilevel inverter keeping the fundamental value of output voltage at desired value. Optimization is done using Harmony Search Algorithm, due to its distinguishing features like simplicity, better search efficiency and ability to avoid becoming trapped at local minima. The control signals given to multilevel inverter using optimized value of switching angles are proved to be very effective in reducing power loss and THD with optimized value of dc voltage sources at different value of modulation indexes. It was found that only about 3-8% of total power loss represent conduction loss. There is around 56 % reduction in power loss by using multi-objective optimization.

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