Application of Flexible OMTHD Technique to Cascaded Multi-level Inverter and the FPGA Based Implementation of Control System

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Abstract - *Generating controllable output voltage is a key factor in designing the motor speed control techniques. Providing desirable output voltage with less Total Harmonic Distortion (THD) is also necessary while utilizing renewable energy sources, configured to produce low voltage output. In this paper, a multi-objective optimization problem is performed to minimize THDs corresponding to desired output fundamental voltages simultaneously, while the output fundamental voltage is exactly produced as the required value. Both multi-objective genetic algorithm and a multi-objective approach to the Stochastic Fractal Search algorithm is utilized in two case studies. First, a common set of switching angles for a wide range of output fundamental voltages would be defined. Second, different sets of switching angles corresponding to low, medium and high values of output fundamental voltage would be determined. The results are compared to those obtained from THD minimization for the range of 0-1 P.U. as the benchmark. The results show better THD for the first case, similar to the benchmark. The experimental results are demonstrated on one phase seven and eleven-level inverter controlled by Xilinx SPARTAN3 FPGA (XC3S400-PQG208).*

Key Words: **Cascaded Multilevel Inverter, Total Harmonic Distortion, Multi-objective Optimization, Genetic Algorithm, Stochastic Fractal Search, OMTHD, Adjustable DC Voltage**

1. INTRODUCTION

In recent decades, many studies have been devoted to Cascaded Multilevel Inverters (CHB-MLI) due to their high voltage and high power applications such as high-voltage direct current (HVDC) [1], electrical drives [2], flexible ac transmission systems (FACTS) [3], [4] and renewable energy generation [5], [6], [7], [8], [9]. Due to the construction of a staircase output waveform by connecting H-Bridges, the CHB-MLI seems to be a practical configuration to achieve high-voltage output with reduced THD [10].

Several well-known switching strategies such as sinusoidal pulse width modulation (SPWM), space vector PWM (SVPWM) [11], selective harmonic elimination PWM (SHEPWM) [12], [13] and optimum minimization of the total harmonic distortion (OMTHD) [14], [15], [16] are commonly used for Cascaded Multilevel Inverters. Pre-calculating the parameters using the OMTHD modulation method is an efficient technique for generating the desired fundamental voltage, while reducing all harmonics as well as minimizing THD. The basic purpose of inverter control is adjustment of fundamental voltage to desired value [15]. In most applications, Cascaded Multi-level Inverters are needed to generate an adjustable output fundamental voltage say from 0 to 1 P.U, to cover the whole possible range of voltage. This issue is necessary for applications such as multi-level electrical drives, STATCOM, Dynamic Voltage Restores and renewable energy generation which may have variable values that could be regulated at the desired value through applying advanced controllers [16], [17], [18].

Several papers have worked on THD optimization under different operating conditions. Authors in [19] proposed an iterative-analytical method in order to minimize voltage THD and total loss of a power network. In [14], [15], [16] OMTHD method was applied to minimize THD for each level of the desired range while determining appropriate angles and DC voltages. In [14], a developed OMTHD concept has been introduced for THD minimization. Authors have tried to adjust fundamental voltage at a desired value. They added the absolute value of the error to the fitness function. This does not guarantee the fundamental voltage to be exactly regulated at the desired value. In [13] and [15] the fundamental voltage error multiplied by a weighting factor was also added to objective function, similar to [14]. Authors in [14] have developed their study in [15], [16]. They performed single objective GA to minimize THD for each value of fundamental voltage varied in the range of 0 to 1 P.U, separately and several single objective optimizations are performed. This increases the computational burden. In case of fewer parameters, the calculations would be less time consuming. So, in this paper the THD multi-objective optimization for various output voltages is examined while either the set of switching angles or DC voltages would be adjusted for different levels of output fundamental voltage. In this study, we introduce an inclusive survey in which, THD minimization problem is investigated for different output fundamental voltages simultaneously while various combination of switching angles and DC voltages have been proposed. A flexible OMTHD multi-objective problem is casted where the THD values corresponding to pre-defined output fundamental voltages are sought simultaneously. For this, two cases: I) a common set of switching angles and different sets of DC source voltages for output fundamental voltages in range of 0 to 1P.U. II) Different sets of switching angles and a common set of DC voltages for three predefined output fundamental voltage would be examined. The obtained results would be compared to those of base case where THD is minimized for each desired fundamental voltage separately.

Several optimization methods are used to solve nonlinear constrained or unconstrained problems [20], [21]. To handle the optimization problem, iterative and metaheuristic based optimization methods are commonly used [22]. The performance of the heuristic algorithms does not rely on the proper choose of initial values and they do not trap in local minima of the optimization problem [23]. GA is one of the methods that have been used in the literature [24]. In addition, particle swarm optimization [5], bacterial foraging algorithm [13] and so on have also been used. Moreover, in some references the authors have used GAMS in optimization problems [25]. Meanwhile, GA is widely used, since it offers a simple structure, and finds promising regions of search space quickly. Thus, it is used in this paper. In addition to GA, a multi-objective approach to the newly introduced algorithm SFS namely NR-SFS is presented for the first time and its results have been compared to multi-objective GA. SFS has been introduced recently for the first time. This algorithm has shown superiority to algorithms such as: PSO, MCS, GSA, CS and ABC in solving optimization problems in many fundamental and practical problems. Thus, in this paper, it has been selected as the optimization algorithm in finding the solutions to THD optimization problem.

2. Cascaded Multi-level inverter

The H-bridge topology often called cell, with four semiconductor switches is used to synthesize a three-level square-wave output voltage waveform. The 2k+1 level inverter consists of series connection of k H-bridges.

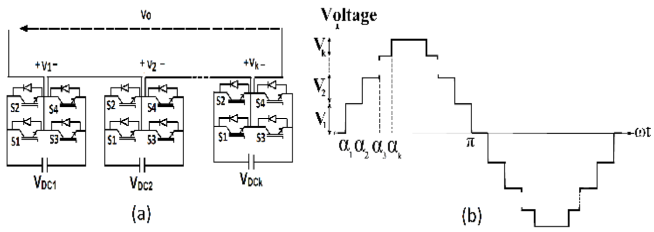

Fig -1: (a): The schematic, (b): typical stair case output voltage of CHB-MLI with k H-Bridges

The phase voltage of CHB-MLI is generally given as:

$$V_o = V_1 + V_2 + \ldots + V_k \tag{1}$$

The schematic of CHB-MLI and its typical cycle of the output waveform is illustrated in Fig -1. Some topologies use unequal DC voltage sources so as to be adjusted in order to meet special criteria like minimum THD or a large number of output voltage levels with minimum number of DC voltage sources.

The output voltage of CHB-MLI, is expressed in Fourier series expansion.

$$V(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} V_n \sin(n\omega t) \tag{2}$$

$$V_n = \begin{cases} \dfrac{4}{n\pi} \sum\limits_{k=1,2,\ldots}^{K} V_k \cos(n\alpha_k) & \text{n is odd} \\ 0 & \text{n is even} \end{cases} \tag{3}$$

α_k is the switching angle corresponding to kth H-Bridge. The phase voltage THD is represented as (4) which triple harmonics are neglected in calculating the line voltage THD for three-phase systems:

$$THD_P = \frac{\sqrt{\sum\limits_{n=3}^{\infty} V_n^{\,2}}}{V_f} \tag{4}$$

Vf is the fundamental voltage component as the voltage first order harmonic. The harmonics are most often considered up to a specified order to evaluate THD. Due to harmonics attenuation by increasing the order, THD is determined up to 31th harmonic in this paper.

3. Generalized formulation of OMTHD cases

In this paper, THD optimization problem is solved either for the THD of output line voltage called THD_L, or for the output phase voltage called THD_P using the OMTHD technique. The value of V_f is also considered as a separate constraint function. This makes our study different from the others in [14] which minimize the difference between fundamental component and its desired amount multiplied by a weighting factor as a part of the THD minimization objective function. This, does not ensure the exact control of the fundamental voltage at the desired level. The optimization problem solution must satisfy the following constraint:

$$\alpha_1 < \alpha_2 < \ldots < \alpha_k < \frac{\pi}{2} \tag{5}$$

$$V_{DC1}, V_{DC2}, \ldots, V_{DCk} > 0 \tag{6}$$

3.1 Benchmark case (BC)

An exclusive set of DC voltages and switching angles is determined for each Vf to minimize the THD as the objective function. Desired Vf is started from 0 and increased by steps of 0.01, to cover the range of 0 < Vf <1.

3.2 Common set of switching angles (CA)

In this case, a multi-objective optimization is performed so as to minimize THD for each desired fundamental voltage Vf. A common set of values of switching angles and different sets of values of DC voltage sources have to be identified.

3.3 Common set of DC voltage sources (CV)

In this case, multi-objective optimization problem is solved to determine a common set of values of DC voltage sources and three different sets of values of switching angles. 0.1 P.U, 0.5 P.U and 1 P.U was selected as values to the fundamental voltage, in order to represent low, medium and high output voltages.

4. Multi-objective optimization

In multi-objective problems where the objective functions are conflicting, each objective function may have a different individual optimal solution. So, to satisfy all objectives, a set of optimal solutions is required to be identified instead of one optimal solution. Most multi-objective optimization algorithms use the concept of dominance in their search. Definition of dominated points and non-dominated set are described in [27], [28]. One of the existing algorithms for multi-objective optimization is Non-dominated sorting method, which was introduced in [29]. In this method, the population is sorted according to non-domination concept and classifies the population into a number of mutually exclusive fronts [30]. In this paper, the ranking is performed based on non-domination sorting into each front, called Non-domination Ranking. Recently, a new optimization algorithm to solve both constrained and unconstrained global optimization problems based on Fractal concept was introduced by Salimi in [26], which is known as Stochastic Fractal Search algorithm, (SFS). Author in [26] proved that the proposed algorithm functionality in solving single objective optimization problems in many fundamental and practical problems in fields of machine learning, bioinformatics, image processing, outperforms some well-known algorithms. Thus, a multi-objective approach to SFS called Non-Dominated Ranking SFS (NR-SFS) [22], based on individual's non-domination mechanism is proposed this paper. Then, the algorithm is applied in per-forming THD multi-objective optimization in CHB-MLI.

5. Results and Discussion

BC: In this case, an individual set of switching angles and DC voltages is determined for each fundamental voltage, applying both GA and SFS. For the fairness of comparison, all the optimizations were initialized with same population size of and tested 10 times for each fundamental voltage value and the best answer was stored. The optimum THD_P and THD_L for seven-level inverter and eleven-level inverter are illustrated in Fig -2. Optimum switching angles and DC voltages are shown in Figs - 3 - 4.

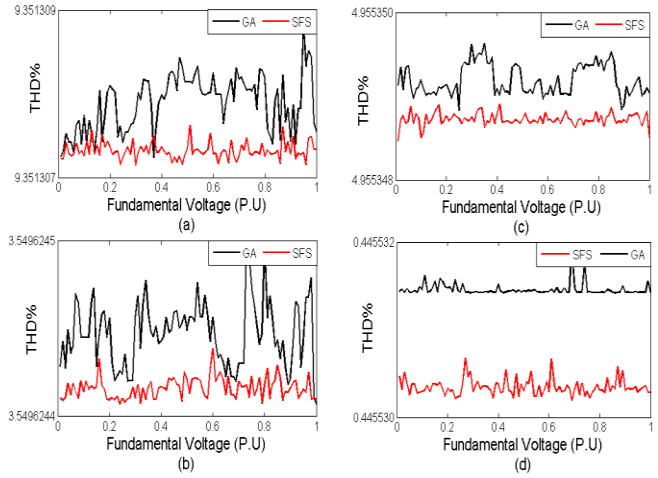

Fig - 2: Obtained THD against respective fundamental voltage for: (a) 7-level inverter THD_P, (b) 7-level inverter THD_L, (c) 11-level inverter THD_P, (a) 11-level inverter THD_L

Results for each case, as illustrated in Fig -2 show that the optimum THD for all fundamental voltages are approximately constant at a fixed value, with a little tolerance between 1e-7% to 1e-6% which is negligible. Fig -4 demonstrates same performance of BC as CA, so that, the optimum values of switching angles in BC are approximately constant for all fundamental voltages. Sets of switching angles are the same for any output fundamental voltage. So, the fundamental voltage could be controlled at the desired value through controlling DC voltage sources as described in Fig -4; Since the slope of the DC voltage waveform is constant, they could be calculated for each desired fundamental voltage. Photovoltaic systems can be used as adjustable DC sources and their control can be examined this way, provided that their operation point to be far from the short-circuit/maximum current region.

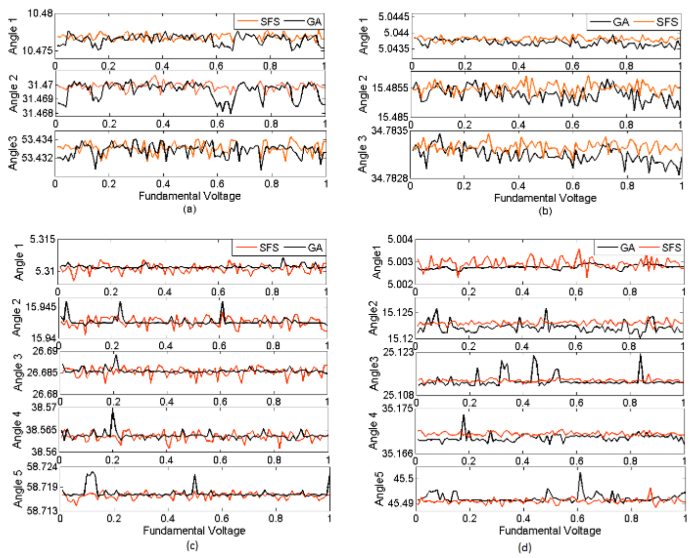

Fig - 3: Switching angle trajectories against respective fundamental voltage for seven-level inverter: (a) THD_P, (b) THD_L, eleven-level inverter: (c) THD_P, (d) THD_L

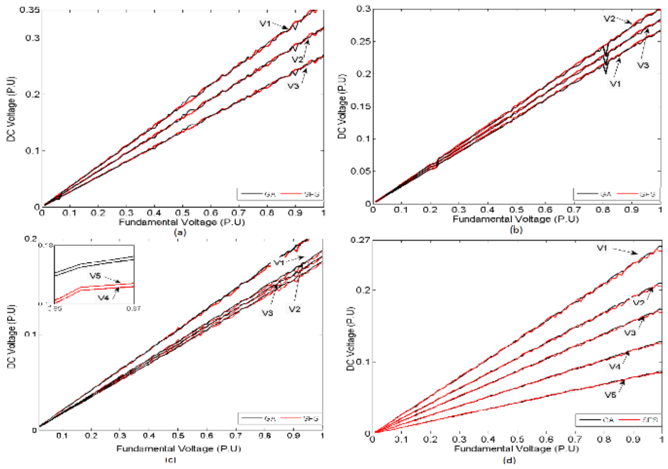

Fig - 4: Optimal DC voltages against respective fundamental voltage for seven-level inverter: (a) THD_P, (b) THD_L, eleven-level inverter: (c) THD_P, (d) THD_L

CV: Approaching low desired fundamental voltages, while obtaining the high ones simultaneously and trying to minimize the THD, makes it inevitable to find a trade of between the objectives. Hence, in this case, a multi-objective THD optimization based on OMTHD is performed. The output fundamental voltage range could be divided into three sub-ranges, namely: low, medium and high. In this paper, 0.1P.U, 0.5P.U and 1P.U have been selected as representative to fundamental voltage levels for these three mentioned sub-ranges.

Applying MOGA and NR-SFS, common DC voltages and exclusive switching angles are found for each fundamental voltage of 0.1P.U, 0.5P.U and 1P.U. For each case, optimization performed 5 times. Obtained non-dominated points of all 5 runs is demonstrated as pareto front for each algorithm. To facilitate comparison between MOGA and NR-SFS, obtained pareto fronts are demonstrated in same figures for each THD_P and THD_L of seven-level inverter and eleven-level inverter. Ultimately, pareto fronts of MOGA and NR-SFS have been compared and final non-dominated points have been introduced in Figs - 5-6. As anticipated, the CV results yield in higher THD than the BC and CA. On the other hand, although encompasses with higher THD, CV is more functional than the CA for low voltage outputs and the CV scheme with adjustable angels might be more reasonable for this specified case. Comparison between MOGA and NR-SFS shows that, although the MOGA gives more non-dominated points in its corresponding pareto front than the NR-SFS, most of them are dominated by NR-SFS solutions. Hence generally speaking, NR-SFS has more ratio of non-dominated points to all its obtained points. In addition, the more MOGA solutions violate 100% THD, which have to be considered as non-functional point. These results combined with less parameters to be addressed, makes the NR-SFS a straightforward algorithm in solving multi-objective optimizations. Thus, devoting more attention to this algorithm would be a worthy effort.

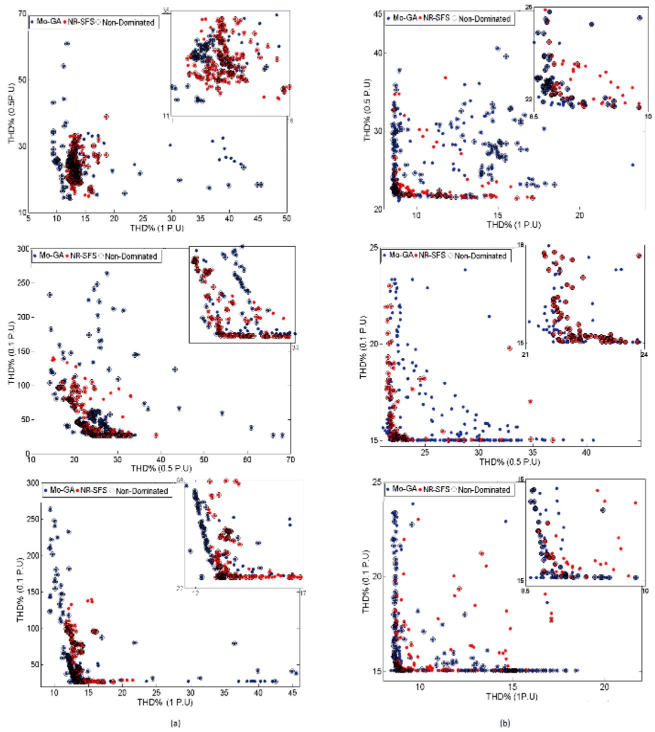

Fig -5: Pareto-Fronts for seven-level inverter, (a): THD_p, (b): THD_L

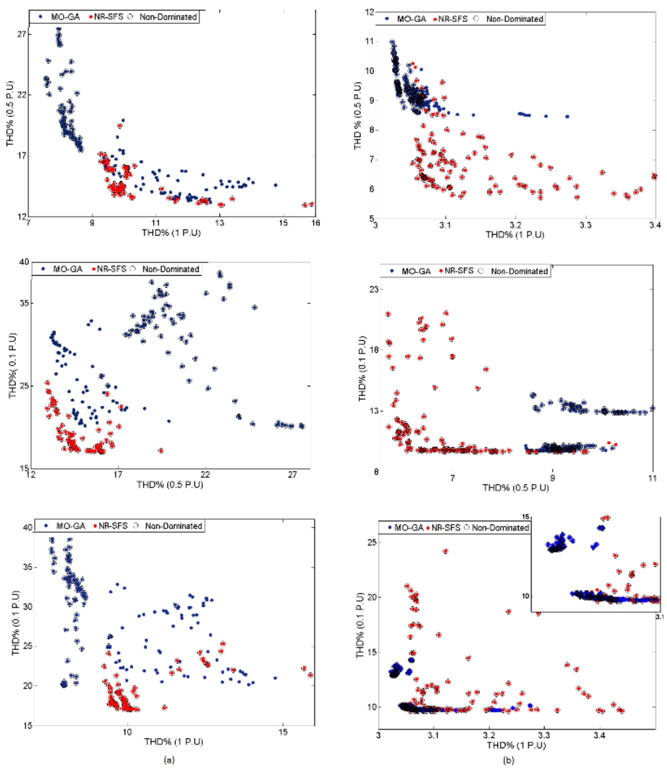

Fig - 6: Pareto-Fronts for eleven-level inverter, (a): THD_p, (b): THD_L

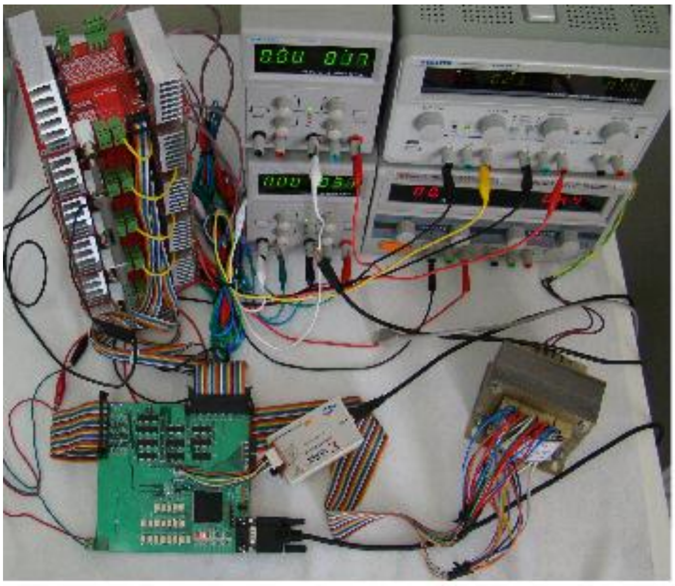

Fig - 7: Experimental set-up of eleven-level inverter

6. Experimental results

Fig -7 shows experimental set-up of a single phase eleven-level inverter. The frequency of the output is assumed to be 50 Hz. Switching angles are obtained offline by GA and SFS according to the results of CA as shown in Fig -3, for the representative output voltages of 0.1P.U, 0.5 P.U and 1P.U, considering the fundamental voltage of 10 volts. These amounts have been chosen for the sake of our laboratory experimental facilities. The ability to control angles and the On-Line switching parameters through graphical user interface (GUI) - that is written in Visual C# - is the other feature of this circuit. Owing to requirements of high accuracy in implementation of switching angles, a Xilinx SPARTAN3 FPGA (XC3S400-PQG208) is chosen. The angles through an interface platform are loaded from PC into FPGA. After protection and isolation, the switching signals are transferred to PMOS driver that is connected to PMOS gate. FPGA, the PMOS drivers and isolation circuits are placed on the controller board. Obtained switching angles have been applied to the inverter, and a GW- Instek 1072AU digital oscilloscope has been used to measure the voltage waveforms. The waveforms of the output voltages are shown in Figs - 8 and 9.

7. Conclusions

This paper, presents an inclusive survey in THD minimization of CHB-MLI with unequal DC voltages. Unequal DC voltages and switching angles could be selected to make output voltage as close as to the desired value with minimum THD. The configuration for the proposed concept is designed and simulated using MATLAB and implemented by HDL (Hardware Language) in FPGA. Optimum results, obtained applying GA and SFS, show the set switching angles for minimum THD are constant for any desired fundamental voltage value. Therefore, in the best case which yield in the least THD, the set switching angles maybe determined only once, while DC voltages have to be calculated for each fundamental voltage. This requires that DC sources be capable

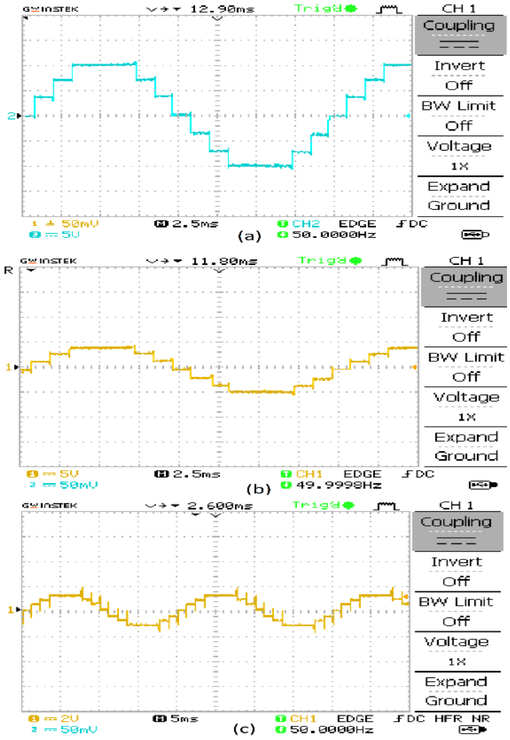

Fig - 8: Experimental Output phase voltage for the seven-level inverter, (a): V_f=1P.U, (b): V_f=0.5P.U, (c): V_f=0.1P.U

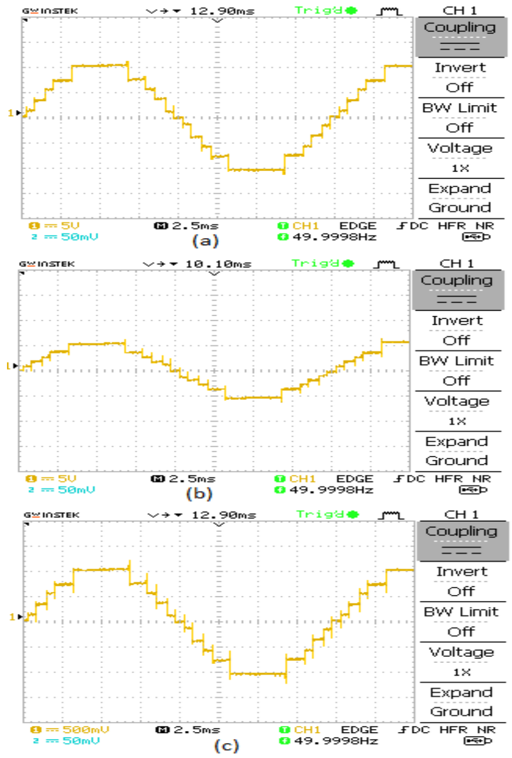

Fig - 9: Experimental Output phase voltage for the eleven-level inverter, (a): V_f=1P.U, (b): V_f=0.5P.U, (c): V_f=0.1P.U of being independently adjusted in a wide range. In order to determine optimal solutions in case of non-adjustable DC voltages, multi-objective THD optimization was performed applying both the multi-objective approach to the newly introduced algorithm SFS called NR-SFS and MOGA. Optimum set of DC voltages and adjustable switching angles for optimum THD in three desired fundamental voltages, was acquired. Comparisons show that OMTHD considering common set of voltage levels does not yield in the best answer, as in the case of common switching angles does. But it is a functional method to the systems with low output voltage. An optimal pareto front could be determined, this way and the designer would be capable of making the decision regarding to system considerations. A comparison between obtained pareto from MOGA and NR-SFS show that, NR-SFS algorithm results in solutions, which mostly dominates many of MOGA solutions.

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