1. Benin Pratap C, 2. A Immanuel Selvakumar, 3. S Paul Sathiyan, 4. Shine Let G

Karunya Institute of Technology and Sciences, India
ORCID: 1. 0000-0002-4717-9015; 2. 0000-0003-2637-4441; 3. 0000-0002-5993-0929; 4. 0000-0002-8800-3446

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Minimization of Torque Ripple in Induction Motor Drive by Optimal Harmonic Elimination

***Abstract**. Cascaded H-Bridge Multilevel Inverter (CH-MLI) is rich in output voltage harmonics. If MLI's poly-phase output voltage is fed directly as input to drive an induction motor, there is great change in the performance of the motor output. To reduce the lower order harmonics in CH-MLI, a novel selective harmonic elimination method is proposed in this paper. The proposed Cross-Entropy (CE) optimization is implemented to find the optimal switching angle of CH-MLI. The switching angles determined are generated by sinusoidal pulse width modulation in MATLAB based simulation. The performance of CE optimized 11-level CH-MLI connected to an induction motor drive is compared with existing optimization methods. The torque ripple and total harmonics distortion (THD) comparisons are studied. Moreover, Cross-Entropy optimization algorithm simulation results are found superior to the other algorithms in reducing the THD as well as a reduced torque ripple. Using CE optimization technique about 14.45% reduction in torque ripple is attained and 19.14% reduction in THD is found.*

***Streszczenie.** Kaskadowy wielopoziomowy falownik H-Bridge (CH-MLI) jest bogaty w harmoniczne napięcia wyjściowego. Jeśli wielofazowe napięcie wyjściowe MLI jest podawane bezpośrednio jako wejście do napędzania silnika indukcyjnego, następuje duża zmiana w wydajności mocy wyjściowej silnika. Aby zredukować harmoniczne niższego rzędu w CH-MLI, w niniejszym artykule zaproponowano nową metodę selektywnej eliminacji harmonicznych. Proponowana optymalizacja entropii krzyżowej (CE) jest wdrażana w celu znalezienia optymalnego kąta przełączania CH-MLI. Wyznaczone kąty przełączania są generowane przez sinusoidalną modulację szerokości impulsu w symulacji opartej na MATLAB. Wydajność 11-poziomowego CH-MLI zoptymalizowanego pod kątem CE, podłączonego do napędu silnika indukcyjnego, jest porównywana z istniejącymi metodami optymalizacji. Badane są porównania tętnienia momentu obrotowego i całkowitego zniekształcenia harmonicznego (THD). Co więcej, wyniki symulacji algorytmu optymalizacji krzyżowej entropii okazały się lepsze od innych algorytmów pod względem redukcji THD, a także zmniejszonego tętnienia momentu obrotowego. Przy użyciu techniki optymalizacji CE osiągnięto około 14,45% zmniejszenie tętnienia momentu obrotowego i 19,14% zmniejszenie THD. (**Minimalizacja tętnienia momentu obrotowego w napędzie silnika indukcyjnego poprzez optymalną eliminację harmonicznych**)*

Keywords: cascaded multilevel inverter; cross-entropy optimization; total harmonic distortion; selective harmonic elimination.
Słowa kluczowe: przekształtnik kaskadowy, tętnienia momentu obrotowego, silnik indukcyjny

Introduction

Multi-level inverters (MLI) have been a key factor in hybrid renewable energy power conversions. The energy converted from unstable renewable energy output alters the power quality. This causes issues in electrical network stability [1]. Multilevel voltage-source inverters are proving to be effective in rectifying these issues in low and medium power applications [2]. Due to its structure and capacitor voltages, the output stepped waveform is equivalent to a sinusoidal waveform without filter [3]. It is also preferred due to its cost-effectiveness. MLI is realized in three common topologies (1) Neutral point clamped (NPC) (2) cascaded H-Bridge (CH) (3) Flying capacitor (FC) [4]. Among these three, for renewable energy sources CHB gives a maximum output voltage and power level (13.8kV, 30MVA) due to its modular structure and it is more reliable [5].

Various methods such as sinusoidal pulse width modulation (SPWM), Space Vector Modulation (SVM) and other modulation techniques are used to reduce harmonics [6]. Selective harmonic elimination (SHE) and harmonic elimination pulse width modulation are discussed in the literature [7]. Finding switching angles by solving SHE equations is done by many heuristic algorithms [8]. There is limitation such as slow speed of convergence time. The reduction in torque ripple is directly calculated with respect to a 3ϕ induction motor. In this work, a metaheuristic algorithm known as cross-entropy algorithm is used to reduce the voltage harmonics of CH-MLI output and thereby reducing the torque ripple of an induction motor drive. This is achieved by eliminating the lower order harmonics by SHE in the output of a three-phase CH-MLI. Fig. 1 depicts the block diagram of CH-MLI fed 3ϕ induction motor drive. Here the pulse determination is done by the optimization technique and the switching angle determined is generated by SPWM and fed to the three-phase 11-level induction motor drive [9].

A structure of a three-phase 11-level cascaded H-Bridge inverter is shown in Fig. 2. 'M=2N+1' represents the number of output voltage levels. Here 'N' denotes the number of DC sources. Three different voltage levels generated by each H-bridge are given as $+V_{dc}/2$,$-V_{dc}/2$ and zero [10]. Each device conducts for one-half cycle. Fig. 3 gives the voltage waveform of individual H- Bridge and the sum of all H-bridges together as a stepped waveform.

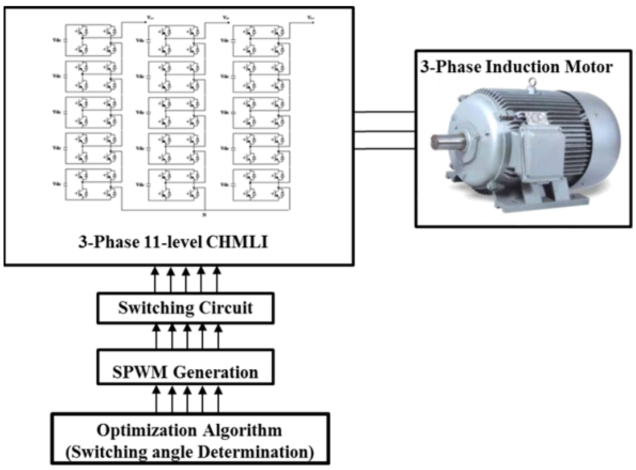

Fig.1. Block diagram of CH-MLI fed three-phase Induction Motor Drive

By proper optimizing the switching angles, the selective harmonics are eliminated. Even harmonics do not exist because of the quarter-wave symmetric pulse pattern. An 11-level inverter waveform is shown in Fig. 3. The parameters θ_1, θ_2, θ_3, θ_4 and θ_5 represent five switching angles. Five equal sources are considered (V_{dc1}, V_{dc2}, V_{dc3}, V_{dc4} and V_{dc5}) for ease of calculation, since the work objective is to check the harmonic content. If the DC sources ($V_{dc1}=V_{dc2}= V_{dc3}=V_{dc4}=V_{dc5}=V_{dc}$) considered are equal, Fourier series expansion of the generalized stepped voltage waveform is given in equation (1), consists of odd and half-wave symmetry.

(1) $V(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n\pi} \left[\sum_{i=1}^{S} c_i * \cos(n\theta_i)\right] \sin(n\omega t)$

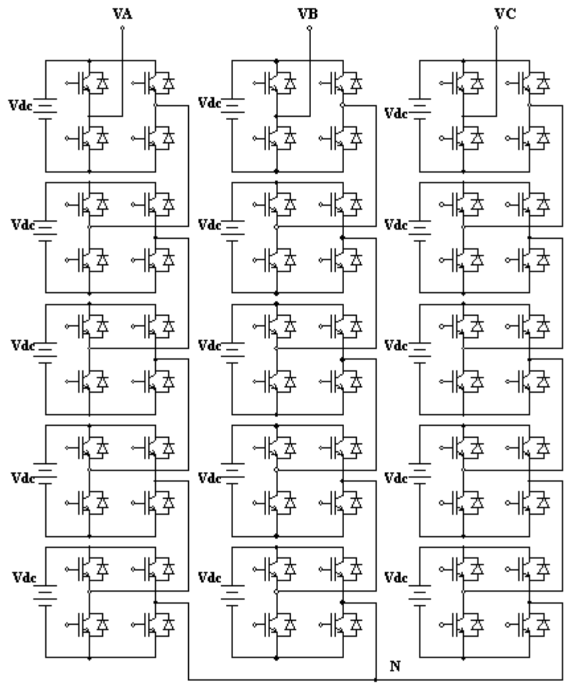

Fig. 2. Three-phase 11-level CH-MLI

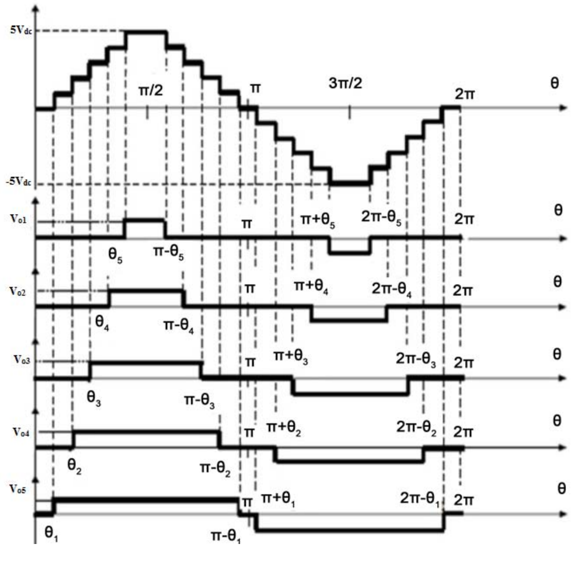

Fig.3. Output voltage of 11-level MLI

The angles satisfy the following conditions

$0 \le \theta_1 \le \theta_2 \le \theta_3 \le \theta_4 \; \ldots \le \theta_s \le \frac{\pi}{2}$

A fitness function to eliminate the lower order harmonics and to maximize the output is formulated and is given in equation (2).

(2) $\text{Minimize FF} = 100 * \frac{(V_1 d - V_1)^4}{V_1 d^4} + \left(\frac{50}{V_1}\right)^2 * \left\{\left(\frac{V_5}{5}\right)^2 + \left(\frac{V_7}{7}\right)^2 + \left(\frac{V_{11}}{11}\right)^2 + \left(\frac{V_{13}}{13}\right)^2\right\}$

Modulation index 'M' is the desired fundamental component's normalized value and is given by the equation (3).

(3) $M = \frac{\pi * H_1}{4SV_{dc}}$

Cross-Entropy Optimization

This optimization technique is to estimate the rare-event probabilities that use the cross-entropy or Kullback–Leibler divergence based on adaptive importance sampling procedure [11]. In cross-entropy optimization (CE), at each iteration a set of candidate solutions (population) is generated. Then the performance of each individual is measured on the basis of the fitness function. Top performing individuals are utilized in forming the Gaussian distribution for the next generation. This process is repeated for a specified number of iterations.

Step 1: Initialize number of population (n), number of top performing individuals nt (a small percentage of total population)

Step 2: Set the initial population numbers

Step 3: Calculate the mean (μp) and standard deviation (Σp) of the population

Step 4: Evaluate the performance of the individual members based on the fitness function

Step 5: Select the top 'nt' individuals and compute the mean (μt) and standard deviation (Σt)

Step 6: Based on μt and Σt of the top performing individuals, update μp and Σp for the whole population

Step 7: Generate the new population with the updated μp and Σp

Step 8: Repeat steps 4, 5, 6 and 7 until a stopping condition is reached.

Results and Discussion

The simulation model of a 3ϕ 11-level CH-MLI is developed with sinusoidal pulse width modulation technique. Then selective harmonic elimination of a MLI eliminating the lower order harmonics is estimated. The other optimization techniques present in the literature used for this estimation are Particle Swarm Optimization (PSO), Teaching Learning based Optimization (TLBO) and Chemical Reaction Optimization methods (CRO). Each optimization technique is run for 100 iterations and the attained switching angles are given in Table 1.

Table 1. Switching angles of PSO, TLBO, CR, CE

Optimization method	Switching Angle				
	θ_1	θ_2	θ_3	θ_4	θ_5
PSO	34.764	44.4186	54.568	65.4987	78.5016
TLBO	34.745	44.4295	54.545	65.4942	78.4713
CR	35.347	44.167	55.263	65.812	79.614
CE(Proposed)	32.589	45.7433	52.912	64.9486	76.3681

Each switching angles are analyzed with different modulation index and voltage. Fig. 4 clearly indicates that the root mean square error (RMSE) value of CE optimized switching angles gives the best results. As the RMSE and torque ripple are directly proportional the performance of the three-phase induction motor is compared with the THD of the MLI output voltage. However the modulation index corresponding to the minimum RMSE value is taken for analysis, as the minimum RMSE value gives the minimum torque ripple. Among the four, cross-entropy optimization is found to be a promising algorithm. Using cross-entropy optimization technique about 14.45% reduction in torque ripple is obtained, and 19.14% reduction in THD is obtained.

THD is based on the optimal switching angle of the multilevel inverter. The switching angles are fed to the MLI and the harmonic spectrum is obtained as shown in Table 2. It is shown that the cross-entropy based switching angles give optimized THD of 14.11%. The attained THD is much less than the phase voltage and this indicates that lower-order harmonics are eliminated.

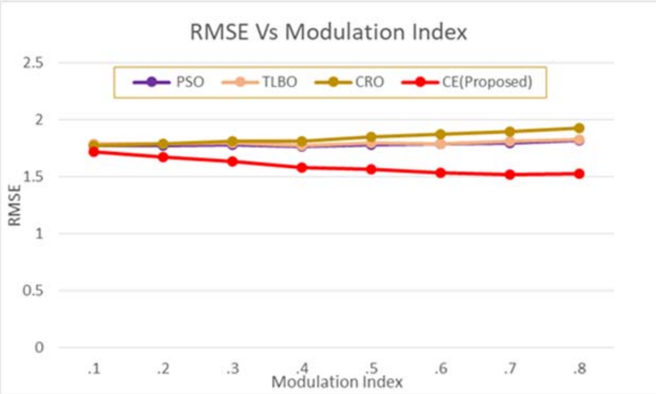

Fig. 4 RMSE Vs Modulation index

Table 2. RMSE and THD

Optimization method	RMSE	THD	Voltage Supplied
PSO	1.763729	15.97	114
TLBO	1.776289	15.93	114
CR	1.77776	17.45	114
CEO (Proposed)	1.520699	14.11	114

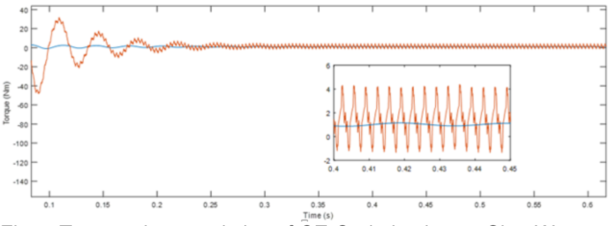

Fig. 5 Torque characteristics of CE Optimization vs Sine Wave

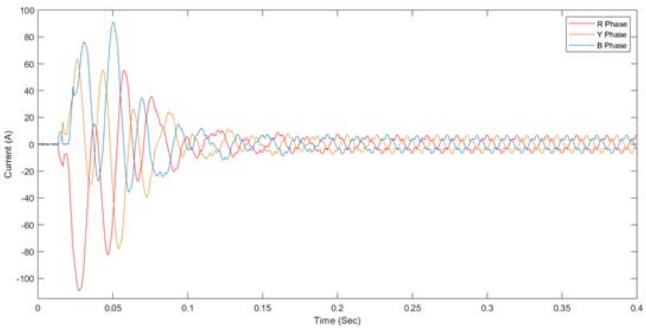

Fig. 6 a Phase Current

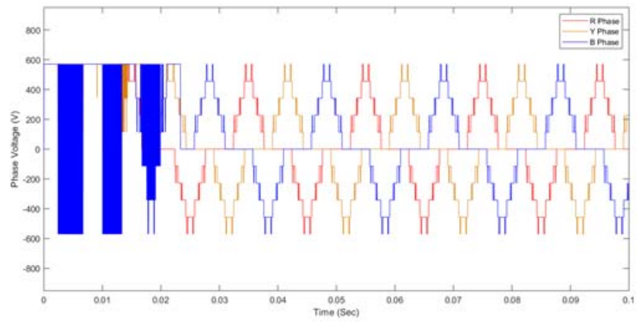

Fig. 6 b Phase Voltage

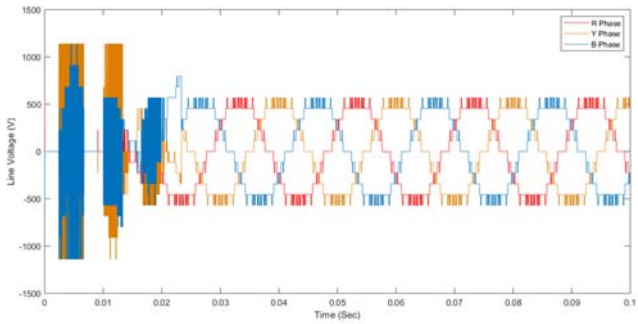

Fig. 6 c Line Voltage

The RMSE value is determined for modulation index between 0.2 to 0.8, and the minimum RMSE value is chosen. Fig. 5 shows the torque waveform of the switching angle obtained from CE Optimization.The CE optimized waveforms shows a better reduction in harmonics. The phase current, phase voltage and line current waveforms are depicted in the Fig. 6 with CE optimization algorithm.

Conclusion

In this paper, a cross-entropy optimization is proposed to find the enhanced switching angle which gives a reduced THD as well as minimizes torque ripple for a three-phase induction motor drive fed by an 11-level three-phase CH-MLI. CE optimization algorithm has been proved to eliminate selected lower order harmonics of CH-MLI by 14.45%. The convergence of the Cross-Entropy Optimization is better than the other evolutionary methods. The voltage harmonics minimization of about 19.14% is achieved, and a torque ripple minimization of 14.45% is achieved. The proposed method shows improvement in power quality and performance of the induction motor drive. The present study shows that CE is suitable for MLIs optimal switching angle determination for reduced THD and reduced torque fluctuation.

Authors. Benin Pratap C, A. Immanuel Selvakumar, S. Paul Sathiyan, Shine Let G, Karunya Institute of Technology and Sciences, Coimbatore, India-641114.
E-mail: pratapbenin@gmail.com, immanuel@karunya.edu, sathiyan@karunya.edu, shinelet@gmail.com

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