Particle Swarm Optimization to minimize THD in Multilevel Inverters

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Abstract: - This paper deals with the reduction of the harmonic content of the output voltage of a single-phase multi-level cascaded inverter which is optimized using the Particle Swarm Optimization (PSO) technique. The operating parameters of the inverter are modified, such as the number of stages, the voltage at the sources and the switching pattern to achieve a minimum configuration that satisfies a Total Harmonic Distortion (THD) of less than 5% and the less possible number of power semiconductor devices.

Key-Words: - THD, PSO, step modulation, SPWM, MCSPWM

1 Introduction

Multilevel inverters are an alternative to traditional two- level and three-level inverters [1]. The general concept involves a large number of switches based on power semiconductors that develop the conversion of the electrical energy provided by direct voltage sources (DC sources) into small steps, achieving a low-content harmonic AC waveform. In 1975 the first multi-level inverter circuit was patented [2]. Later, in the year 1980 the neutral-point clamped (NPC) inverter was registered [3]. In the mid-1990s a topology known as a Flying Capacitor Multilevel Inverter [4], [5] was introduced. This topology offers several advantages over the NPC inverter [6]. The cascade multilevel inverter with separate DC sources was patented in 1997 [7].

Among the most relevant works on the subject can be cited [6] and [8], where a comprehensive review of the state of the art of multilevel conversion is done. The different topologies are studied and the most important applications using this type of inverters. A very interesting work that reviews the topic of the simulation of multilevel inverters can be seen in [9]. Another significant contribution has been made in masters and doctoral theses focused on multilevel inverters [10-13].

The total harmonic distortion factor or THD, which is a measure of the harmonic content of the output waveform, is usually used to evaluate the power quality of the power inverter. The lower the THD, the better the signal quality, because in the inverter circuits the output waveform is generated by means of the switching of semiconductor devices, it is necessary to find the appropriate switching times to reduce the THD. The need to minimize THD makes the problem an optimization.

On the other hand, heuristic optimization techniques have emerged as an alternative to classical methods based on statistics. The main reason is that being inspired by natural processes are less affected by local maxima than traditional techniques. Important work has been developed in the use of particle swarm optimization (PSO) to find the appropriate switching angles in multilevel inverters [17-23].

2 Multilevel Inverters

Figure 1 shows the schematic diagram of a single-phase multi-level inverter with different number of levels. The switching devices are presented as ideal switches. The generation of the output waveform is achieved by an appropriate switching sequence of the DC voltage sources connected to the circuit. With a larger number of sources a higher number of inverter levels can be obtained.

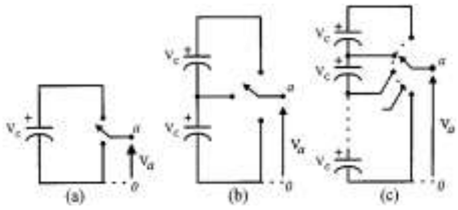


Fig. 1. Single-phase inverter (a) 2 levels, (b) 3 levels, (c) m levels.

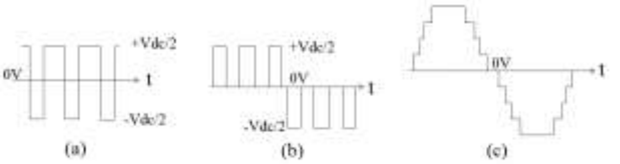


Fig. 2. Inverter output voltage (a) 2 levels, (b) 3 levels, (c) m levels.

As can be seen in Fig. 2, in a multilevel inverter it is desired to achieve a waveform most similar to a sine signal, in which, depending on the number of available DC sources, the distortion becomes much lower. Among its main advantages can be mentioned [6]:

The multilevel input voltage arrangement allows the inverter to be increased several times using the same switches as a conventional inverter.

The power of the inverters is increased by using higher voltages, without the need to increase the current, thus avoiding greater losses during the conduction, and consequently to improve the performance of the inverter.

Cascaded Multilevel Inverter

This topology is based on the serial connection of single-phase inverters with independent power supplies. Fig. 3 [17] shows the power circuit for a single-phase inverter with three H-bridges (stages).

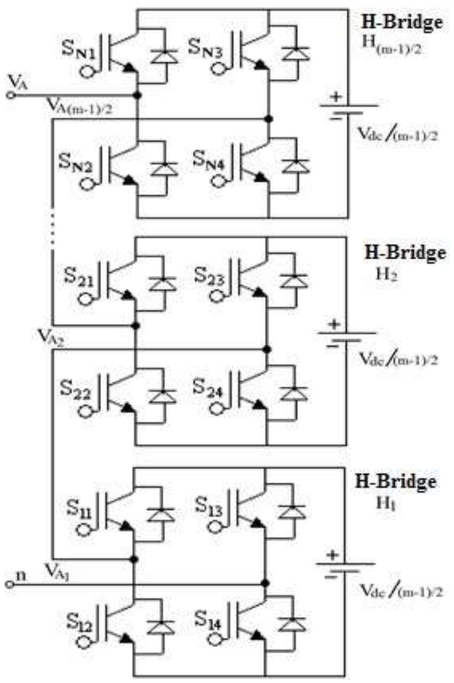


Fig. 3. Cascaded multilevel inverter

If all of the DC voltage sources in the inverter stages have the same value, the inverter is referred to as a "symmetrical cascade multilevel inverter".

In the case where the power supplies of the stages have different voltage values, this inverter is called "asymmetrical cascade multilevel inverter". Generally in this type of inverter, DC sources between H-bridges are related by an integer factor.

3 Commutation techniques

The main objectives of the switching strategies for CD / AC inverters are the regulation of the amplitude and frequency in the output voltage, in order to achieve the minimization of the harmonic content of the output voltage of the inverter.

The most frequently used technique in multilevel inverters is the step modulation, which aims to synthesize a stepped waveform much like a sine waveform with low harmonic content.

The generation of the output waveform is obtained from the appropriate switching of each stage, which sums up the different voltage levels generated by the circuit, as shown in Fig. 4 [17]:

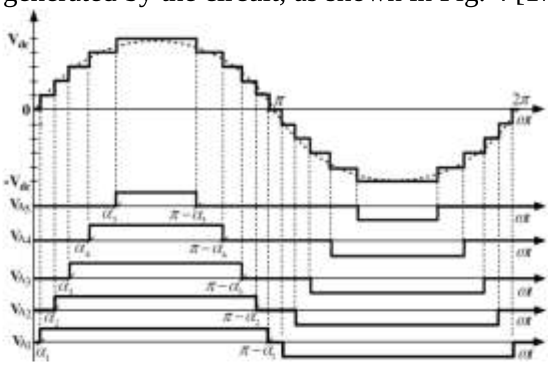


Fig. 4. Voltage output waveform of a multilevel symmetric inverter.

As shown in Fig. 4, by conveniently selecting the switching angles and it is possible to synthesize an output waveform close to a sine signal.

In order to improve the harmonic content of the output voltage of the multilevel inverter [24], it is possible to implement multiple carrier sine pulse width modulation (MC-SPWM). In this case, a sine reference signal is compared to several triangular carriers having the same frequency and phase, but with an offset to each other, depending on the desired number of inverter levels.

The signals obtained are used to switch semiconductor devices properly. An example for this type of modulation can be seen in Fig. 5 (a), while the typical output waveform for a 9-level inverter is shown in Fig. 5 (b).

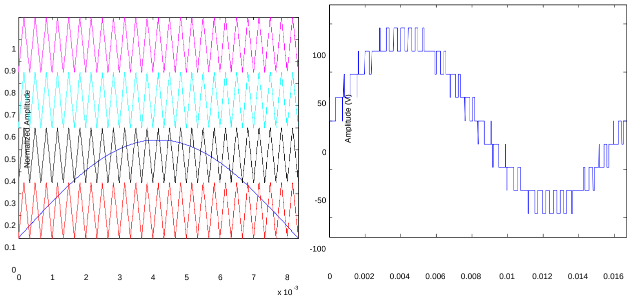


Fig. 5. (a) Multiples carriers modulation (MCSPWM) for a 9 levels inverter (b) voltage output waveform.

4 Particle Swarm Optimization

The Particle Swarm Optimization (PSO) algorithm was formulated by Edward and Kennedy in 1995 [14]. The algorithm was inspired by the social behavior of animals such as flocks of birds or schooling fish. This method of optimization is based on the premise that individuals living in a society have an opinion that is part of a set of beliefs (the search space) shared by all possible individuals. Each individual can modify his own opinion based on three factors:

Knowledge about the environment (fitness value).

Historical knowledge or previous experiences (memory).

Historical knowledge or past experiences of individuals in your neighborhood.

The PSO technique is similar to a genetic algorithm (AG) in the sense that it starts with a random initial population matrix. Unlike AG, PSO has no operators such as crossover and mutation. The rows in the matrix are called particles. These contain the variable values. Each particle moves on the cost surface with a given velocity. The particles update their speed and position based on the best local and global solutions, as well [15]:

$$v_{m,n}^{new} = v_{m,n}^{old} + \tau_1 \cdot r_1 \left(p_{m,n}^{lb} - p_{m,n}^{old} \right) + \tau_2 \cdot r_2 \left(p_{m,n}^{gb} - p_{m,n}^{old} \right) \quad (1)$$

$$p_{m,n}^{new} = p_{m,n}^{old} + v_{m,n}^{new} \quad (2)$$

Where:

$v_{m,n}$ is the particle velocity.

$p_{m,n}$ are the particles.

r_1, r_2 are random independent numbers.

τ_1, τ_2 are learning factors.

$p_{m,n}^{lb}$ the best local solution.

$p_{m,n}^{gb}$ the best global solution.

5 Optimization problem statement

Step modulation

The output voltage waveform is stepped waveform as Fig. 4 and can then be expressed as [16]:

$$v_{out} = \sum_{n=1}^{\infty} \frac{4V_{cd}}{n\pi} \left[\sum_{k=1}^{s} \cos\left(n\theta_k\right) \right] sen\left(n\omega t\right) \quad (3)$$

Where:

n is the odd harmonic order (1, 3, 5, 7, 9, …).

s is the inverter stages number.

k es a positive integer (1, 2, 3, 4, 5, …, s).

θ_k is the kth switching angle and must satisfy:

$$\theta_1 < \theta_2 < \cdots < \theta_s < \pi/2 \quad (4)$$

From (1), the amplitude of the odd harmonics, including the fundamental component can be expressed as:

$$a_n = \frac{4V_{cd}}{n\pi} \sum_{k=1}^{s} \cos\left(n\theta_k\right) \quad (5)$$

Expanding the above equation, we have:

$$a_n = \frac{4V_{cd}}{n\pi} \left[\cos\left(n\theta_1\right) + \cos\left(n\theta_2\right) + \cdots + \cos\left(n\theta_s\right) \right] \quad (6)$$

The switching angles $\{\theta_1, \theta_2, \theta_3, \cdots, \theta_s\}$ can be selected such that the total harmonic distortion of voltage is minimal. So the optimization problem can be considered as follows:

To minimize [24]:

$$THD\% = \sqrt{\left(\frac{1}{a_1^2}\right) \sum_{n=3}^{\infty} \left(a_n^2\right)} \cdot 100 \quad (7)$$

Where:

a_1 is the main harmonic amplitude.

a_n is the nth harmonic amplitude, for n odd.

Satisfying equation (6), subject to the following constraints:

$$a_1 = 169.7\,V \quad (8)$$

$$a_n = 0 \quad \text{For n>1 odd.} \quad (9)$$

$$0 < \theta_1 < \theta_2 < \cdots < \theta_s < \pi/2 . \quad (10)$$

MCSPWM Modulation

As described in section III, the SPWM modulation with multiple carriers consists of the comparison of a sine reference signal with a series of triangular carriers. From this comparison the switching signals of the inverter stages are generated. The value of the THD and the voltage of the fundamental component depend in this case on the modulation index (m), the number of pulses and the position of the pulses generated. These variables will act as particles in the PSO algorithm.

The modulation index is the ratio of amplitudes between the sine reference signal and the "sawtooth" type carriers. The number of pulses depends on the frequency of the carrier signals and the position of the pulse depends on the shape of the sawtooth signal. Fig. 6 shows three cases of the sawtooth waveform with which a different pulse position is obtained by varying the rise time (tr) and the down time (tf) of the triangular signal.

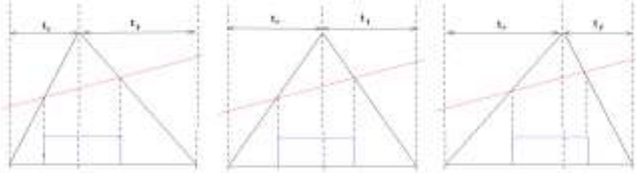


Fig. 6. Pulse position for the carrier signal with: tr=tf. tr>tf. and tr<tf.

The optimization problem can be considered as follows:

Minimizing:

$$THD\% = \sqrt{\left(\frac{1}{a_1^2}\right)\sum_{n=3}^{\infty}\left(a_n^2\right)}\cdot 100 \tag{11}$$

Constraints to:

a1=169.7 Vp; Fc ≤ 3 KHz; m≤1; width≤1.

Where a1 is the peak amplitude of the fundamental component, m is the modulation index, which depends on the amplitude of the reference sinusoidal signal. Fc is the frequency of the carrier signals and the width parameter corresponds to the symmetry of the sawtooth signal, i.e., the relationship between tr and tf. If tr = 0, width = 0, if tr = tf, width = 0.5 and if tf = 0, width = 1.

6 Prototype

The optimization algorithm PSO was developed in Matlab where simulations were carried out to obtain the optimized parameters depending on the type of modulation used. To verify the simulation results, a prototype of the multilevel inverter was implemented and the switching angles were programmed on a PIC18F4550 [25].

Fig. 7 shows the block diagram of the developed system. A data acquisition system based on the Agilent DSO3202-A digital oscilloscope has been used to perform the visualization and analysis of the waveform obtained, as well as the measurement of the THD value [26].

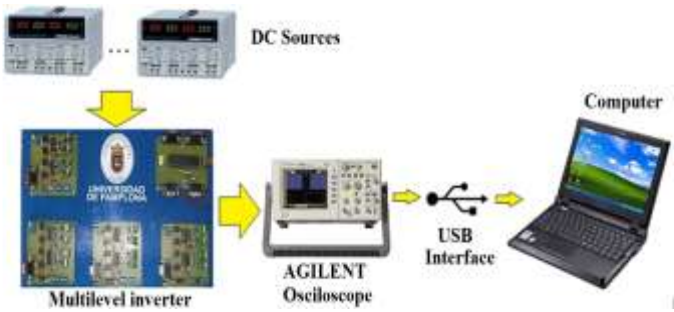


Fig. 7. Block diagram of the implemented system.

Step modulation

The PSO optimization algorithm must, in this case, be responsible for finding the optimal switching angles θ_k of the system of equations as described in Eq. 6. It minimizes the THD and allows to maintain constant the amplitude of the fundamental harmonic component to the desired output voltage.

The algorithms were written in MATLAB for both the fitness function and the PSO. The parameters used were:

Population size: 20.

Maximum number of iterations: 200.

Cognitive parameter: 1.

Social parameter: 3.

Fig. 8 shows the output voltage waveform of the asymmetric multilevel inverter with N=3 stages (15 levels). Fig. 9 shows the harmonic spectrum, while Fig. 10 shows the evolution of THD along the run of the PSO algorithm. Table 2 shows the results obtained:

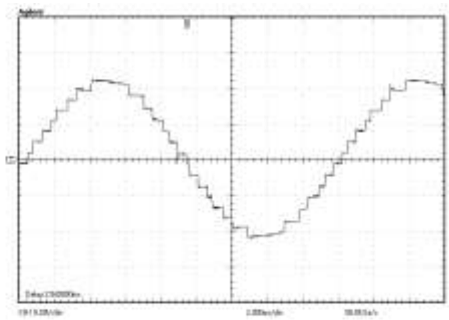


Fig. 8. Output voltage waveform with 3-stages asymmetrical step modulation.

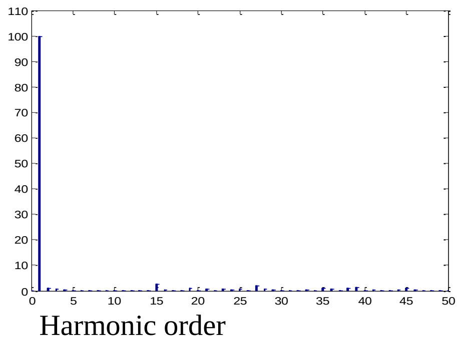


Fig. 9. Harmonic spectrum with 3-stages asymmetrical step modulation.

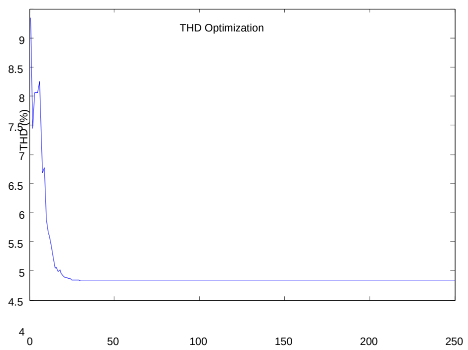


Fig. 10. THD vs. iteration

TABLE 1. Data for 3 stages.

DATA	VALUE
DC Sources	24V, 48V, 96V
Period	16,8ms
Frequency	59,7 Hz
RMS Voltage	121 V
THD	4.8 %

Fig. 11 shows the output voltage waveform of the asymmetric multilevel inverter with N=4 stages (31 levels). Fig. 12 shows the harmonic spectrum, while Fig. 13 shows the evolution of the THD along the run of the PSO algorithm. Table 2 shows the results obtained [27]:

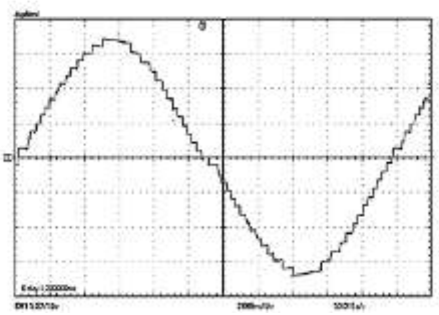
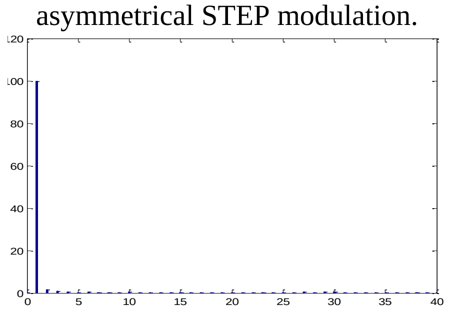


Fig. 11. Output voltage waveform with 4-stages asymmetrical STEP modulation.



Harmonic order

Fig. 12. Harmonic spectrum with 4-stages asymmetrical step modulation.

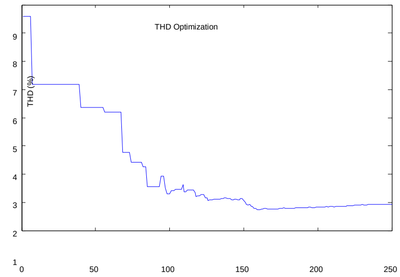


Fig. 13. THD vs. iteration

TABLE 2. Data for 4 stages.

DATA	VALUE
DC Sources	12V, 24V, 48V, 96V
Period	16.7 ms
Frequency	60.1 Hz
RMS Voltage	121 V
THD	2.26%

MC-SPWM modulation

As described in section V, the optimization problem consists of minimizing THD (<5%), keeping the fundamental component voltage constant at 169.7 V and ensuring that the devices switch at the lowest possible frequency [28], [29].

The PSO algorithm must then find the optimal values for the amplitude of the reference sine signal, the frequency of the triangular carriers and the shape remains the same. The PSO parameters were the same as those used with step modulation, except for the number of iterations that was set up to 50.

Fig. 13 shows the waveform of the output voltage of the multilevel inverter with MCSPWM 2-stage symmetrical modulation. Fig. 14 shows the spectrum of harmonics, while in Fig. 15 we see the evolution of the THD along the run of the PSO algorithm. Table 3 shows the results obtained at the output of the inverter.

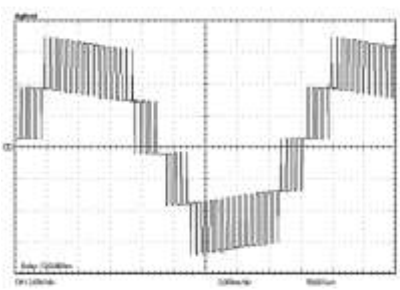


Fig. 13. Output waveform with 2-stage symmetrical MCSPWM modulation.

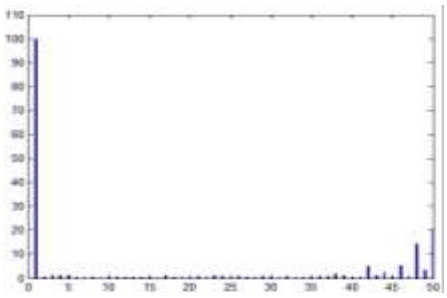


Fig. 14. Harmonic spectrum with 2-stages MCSPWM modulation.

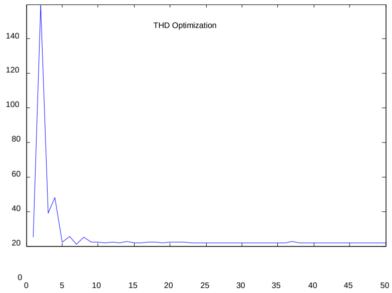


Fig. 15. THD vs. iteration.

TABLE 3. Data for 2 stages.

DATA	VALUE
DC Sources	96V
Period	16.9 ms
Frequency	59.17 Hz
RMS Voltage	120 V
THD	2.7 %

Fig. 16 shows the output voltage waveform of the 3-stage symmetric MC-SPWM modulated of the multilevel inverter. Fig. 17 shows the spectrum of harmonics, while Fig. 18 shows the evolution of the THD along the run of the PSO algorithm. Table 4 shows the results obtained at the output of the inverter.

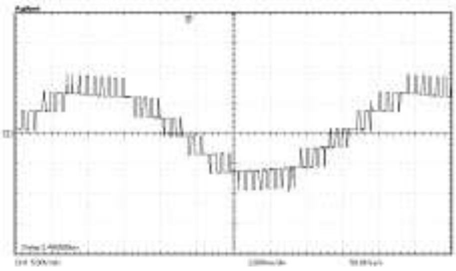


Fig. 16. Output waveform with 3-stage symmetrical MCSPWM modulation.

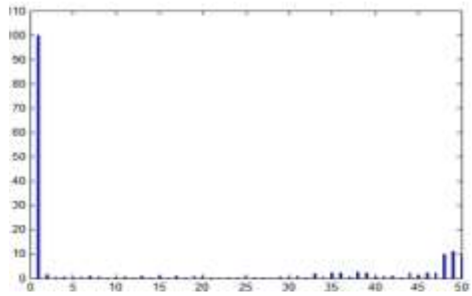


Fig. 17. Harmonic spectrum with 2-stage symmetrical MCSPWM modulation.

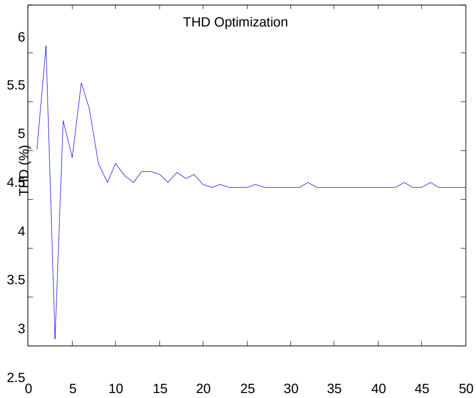


Fig. 18. THD vs. iteration.

TABLE 4. Data for 3 stages.

DATA	VALUE
DC Sources	72V
Period	16.6 ms
Frequency	60 Hz
RMS Voltage	121 V
THD	5.2%

7 Conclusion

The use of the PSO method allows that it is not necessary to approach the solution of a system of transcendental equations formally, since this programming algorithm explores in the search space from several points of solution and does not focus on finding "exact solutions" but the best solution to the problem.

As can be seen from the comparison of the results in Tables 1, 2, 3 and 4, the lowest THD was obtained with the optimized step modulation in asymmetric inverter configuration; however, this configuration requires values in the sources which may be impractical.

From Fig. 13 and Table 3 it is observed that the optimized two-stage MC-SPWM modulation achieves a THD value of 2.7% using half the number of semiconductors required for asymmetric step modulation. However, in this modulation, the semiconductor devices must switch to high frequency which can generate noise and losses by the effect of the switching.

It must be taken into account that the PSO is a meta-heuristic optimization method, each time that it is run can arrive at solutions slightly different but that satisfy the problem of minimization.

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