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RESEARCH ARTICLE OPEN ACCESS

IMPROVING INVERTER EFFICIENCY FOR ELECTRIC VEHICLES: EXPERIMENTAL VALIDATION OF THE NEURAL NETWORK-BASED SHE TECHNIQUE USING RT-LAB

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ABSTRACT

Inverters are essential for converting direct current to alternating current in electric vehicles, relying on pulse width modulation (PWM) for efficiency. This study presents a real-time Selective Harmonic Elimination PWM (SHE-PWM) algorithm using artificial neural networks, validated with the OP5600 RT LAB simulator. Unlike the traditional Newton-Raphson method, this approach employs a neural network trained on a database of pre-calculated switching angles, allowing for the precise elimination of specific harmonics while maintaining control of the signal's fundamental component. Although it offers similar accuracy to Newton-Raphson, the neural method provides significantly faster processing. MATLAB/Simulink simulations and experimental results on the RT-LAB simulator confirm the algorithm's capability to calculate optimal switching angles and produce high-performance PWM waveforms. The study highlights the neural network-based SHE technique's advantages, including its ability to model complex systems, robustness to noisy data, and versatility. This approach improves inverter performance and offers new optimization possibilities for various applications, including electric vehicles. The simulator results validate the alignment of real and simulated control signals.

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I. INTRODUCTION

In the field of electricity, power electronics is a vital domain that encompasses various activities such as the electrical grid, transportation (urban, railways, maritime...), renewable energy, and industry. Currently, energy has become one of the crucial aspects of human daily life. Therefore, it has become necessary to enhance the performance of power electronic devices. The latter can contribute to improving the quality of electrical signals [1],[2].

The aim of this work is to develop a new real-time PWM (Pulse Width Modulation) algorithm based on neural network principles, enabling the selective elimination of harmonics and control of the fundamental frequency.

In this context, the inverter powers the propulsion system, which is the heart of the Electric Vehicle (EV). This system consists of an electric actuator, a transmission device, and wheels. The drive, comprising the entire electric motor and static converters, coupled with electronic control, forms the core of the propulsion system in the EV.

The asynchronous motor can operate over a wide speed range with low torque ripples if coupled with appropriate control. Selective Harmonic Elimination (SHE) PWM is a technique used in electric vehicles. PWM control is frequently adapted to the static converters of electric vehicles. Several control methods have been developed with the goal of generating a sinusoidal voltage at the inverter output with minimal harmonics [3],[4].

According to the literature, there are several PWM control techniques that differ in how they define the switching instants of the switches. These include sampled sine waveform modulation and vector-based PWM control based on phase voltage dispersion, as well as SHE PWM [5],[6].. It is certain that choosing a better control strategy for an inverter feeding a three-phase cage induction machine significantly improves system performance [7],[8].

In the scope of our work, we will focus on the SHE PWM technique. Our objective is to implement neural network-based SHE-PWM control in real-time using RT-Lab, with control of the fundamental frequency and selective harmonic elimination. This application is intended for electric vehicles. The switching angles are calculated based on the principles of neural networks..

II. MATERIALS AND METHODS

II.1 USEFUL INVERTER

Figure 1 shows the classic two-stage inverter. It's composed of three transistor switching arms. Each arm is composed of two cells, each with a diode and a transistor that work in forced switching. [9],[10].

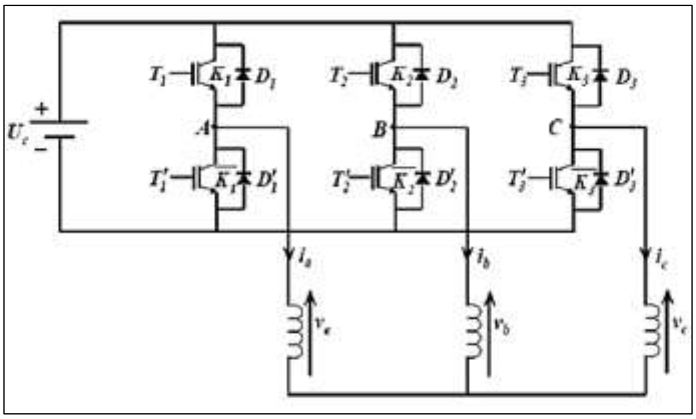

Figure 1: Schematic of the two-stage inverter.
Source : F.Z. Boudjella et al, (2022)

II.2 CONTROL STRATEGY

- Selective harmonic elimination technique SHE

Either the output voltage of the three-phase inverter at two periodic levels and with an amplitude equal to the unit, see Figure 2. [11],[12].

In this case, the output voltage $v(t)$ can be written in Fourier series:

$$v(t) = a_0 + \sum_{n=1}^{\infty}[a_n cos(nwt) + b_n sin(nwt)] \quad (1)$$

According to the properties of the voltage $v(t)$, (half-wave antisymmetric, quarter-wave symmetry), we find after simplification that:

$$a_0 = 0 a_n = 0 b_n = \frac{4}{n\pi}\left[1 + 2\sum_{k=1}^{k}(-1)^k \cos(n\alpha_k)\right] \quad (2)$$

Where, n, is an odd number, which must be different from a multiple of 3 for three-phase assemblies and k, represents the number of switches per quarter wave or the number of cuts per half-wave.

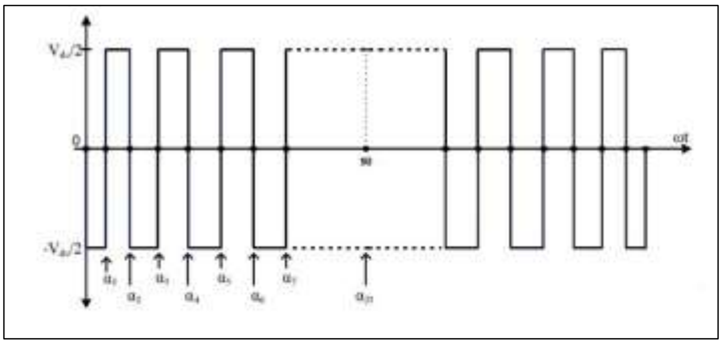

Figure 2: Form of a calculated PWM voltage.
Source: Authors, (2025)

Finally, the tension $v(t)$can be written as:

$$v(t) = \sum_{n=1}^{\infty}[b_n sin(nwt)] \quad (3)$$

The equation (3) has k unknown variables α1, α2, α3, ..., αk, called switching angles.

The values of these angles are calculated in order to assign a determined value to the fundamental a1 and to cancel the amplitudes an of the first (k -1) harmonics.

These equations are non-linear. The Newton-Raphson method will be used to solve this system of non-linear to unknown m equations [13].

The equation (4) is a system of non-linear m equations α1, ..., ..., αk. It is desired to assign a determined value im, called 'modulation index', to the amplitude a1 of the fundamental and to annul the amplitudes bn of the first (*k -1*) harmonics. A system of m non-linear equations to k unknown of the form is thus obtained:

$$\begin{aligned}
b(1) &= \frac{4}{\pi}[1 - 2\cos(\alpha 1) + 2\cos(\alpha 2) - \ldots - 2\cos(\alpha_{23})] - im\\
b(5) &= \frac{4}{5\pi}[1 - 2\cos(5\alpha 1) + 2\cos(5\alpha 2) - \ldots - 2\cos(5\alpha_{23})]\\
b(7) &= \frac{4}{7\pi}[1 - 2\cos(7\alpha 1) + 2\cos(7\alpha 2) - \cdots - 2\cos(7\alpha_{23})]\\
b(11) &= \frac{4}{11\pi}[1 - 2\cos(11\alpha 1) + 2\cos(11\alpha 2) - \cdots - 2\cos(11\alpha_{23})]\\
b(13) &= \frac{4}{13\pi}[1 - 2\cos(13\alpha 1) + 2\cos(13\alpha 2) - \cdots - 2\cos(13\alpha_{23})]\\
b(67) &= \frac{4}{67\pi}[1 - 2\cos(67\alpha 1) + 2\cos(67\alpha 2) - \cdots - 2\cos(67\alpha_{23})] \quad (4)
\end{aligned}$$

After solving the non-linear equations simultaneously, the switching angles can be obtained. For the entire modulation index range (im =0.02~1.15), the angle paths for the proposed switching pattern are shown in Figure 3:

The angles are calculated using a modified Newton-Raphson method, as detailed in our article [5]. This method enables commutation angles to be determined without the need for prior initial values.

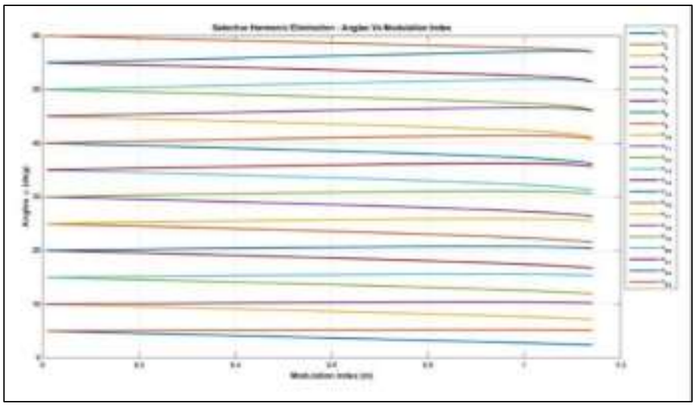

Figure 3: Trajectories of the 23 switching angles as a function of the modulation index for two-stage inverters.
Source : Authors, (2025).

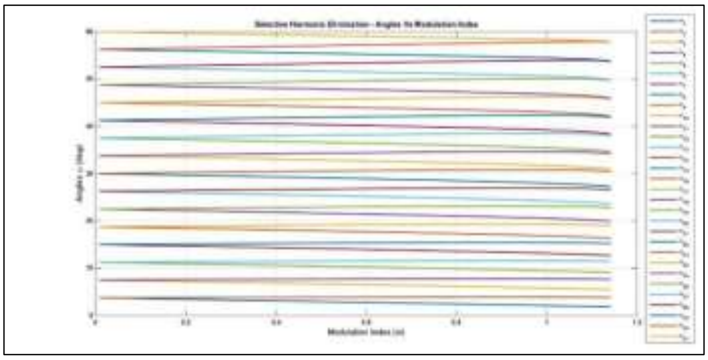

Figure 4: Trajectories of the 31 switching angles as a function of the modulation index for two-stage inverters.
Source: Authors, (2025)

II.3 ANN-BASED SHEPWM GENERATION

An Artificial Neural Network (ANN) stands as a potent instrument grounded in the patterns observed in biological neurons, effectively capturing the complexities of non-linear systems. Comprising interlinked neurons, this network facilitates communication through transmission of signals along weighted connections. These connection weights adapt through a learning process during training. The resultant output, denoted as yj, can be described as follows:

$$y_i = f(w_{ji} x_i) \quad (5)$$

The activation function is denoted as 'f', the input signal is represented as 'xi', and the connection weight is labeled as 'wji'. The expression for the error 'E', which is the sum of squared differences between the expected and obtained values of the output neurons, can be expressed as follows:

$$E = \frac{1}{2} \sum_j \left(y_{dj} - y_i\right)^2 \quad (6)$$

The passage in question deals with the use of a desired value "ydj" for output neuron j and the actual output "yj" of this neuron [14-16]. Various artificial neural network (ANN) architectures have been documented in the scientific literature. For this study, a specific type of neural network, known as a feedforward neural network, was used. The training process involves the application of the backpropagation learning algorithm. The activation functions used are sigmoidal for input and hidden layer neurons, and linear for output layer neurons. The architecture of the ANN used in this study is illustrated in Figure 5.

II.4 SYSTEM ARCHITECTURE

To simplify the architecture, we opt for a neural network consisting of an input layer, a hidden layer, and an output layer.

Figure 5: ANN Training.
Source: Authors, (2025)

The training process is shown in Figure 5, it stopped after 20 iterations for 23 angles and 207 iterations for 31 angles when the validation checks were carried out, the training performance is shown in Figure 6, the final regression was 99% as shown in Figure 7.

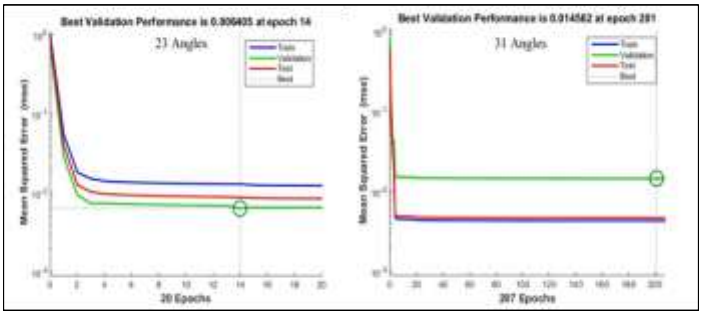

Figure 6: ANN Training performance.
Source: Authors, (2025)

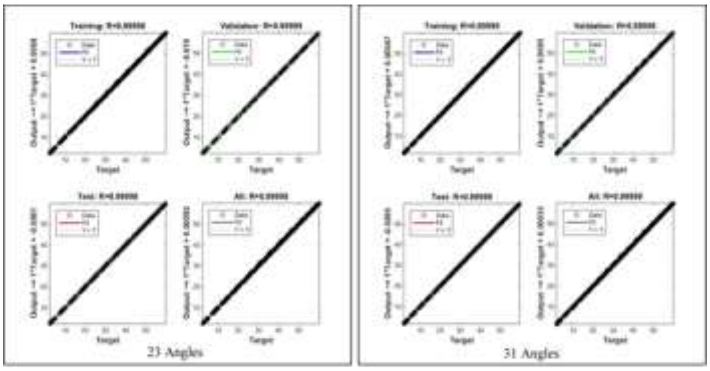

Figure 7: ANN Training regression.
Source: Authors, (2025)

Figure 8 shows the error between exact and approximate angles as a function of the modulation index “im”, covering a range of values from 0.02 to 1.15 for m = 23. In figure 9, the error is plotted as a function of the modulation index “im” for m = 31. This representation completes the analysis by allowing a comparison of errors for different values of m.

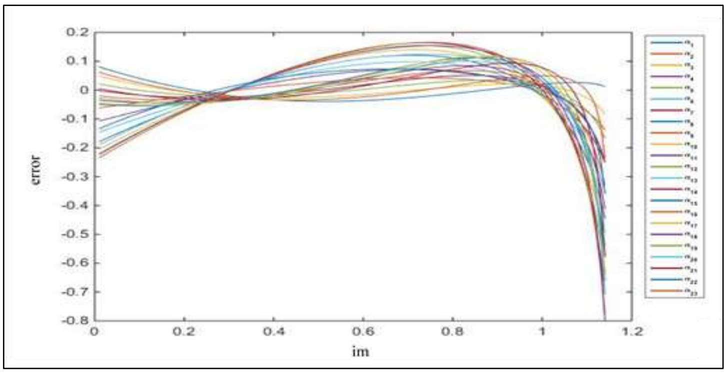

Figure 8: Variation in error between exact and ANNSHE angles over the entire range of im for m = 23.
Source: Authors, (2025)

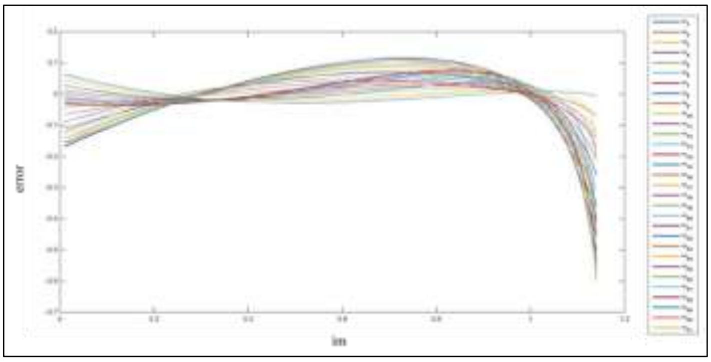

Figure 9: Variation in error between exact and ANNSHE angles over the entire range of im for m = 31.
Source: Authors, (2025)

III. RESULTS AND DISCUSSIONS

The Simulink diagram of the PWM technique is as follows:

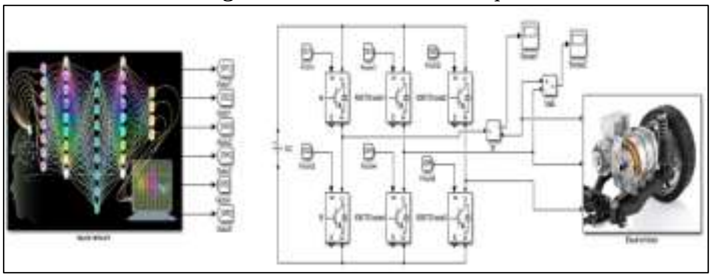

Figure 10: The Simulink diagram of the SHE-PWM technique
Source: Authors, (2025)

The following results are obtained for output voltage and current:

For voltage:

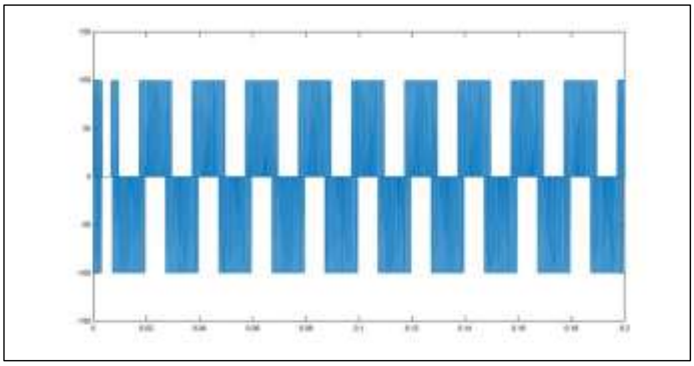

Figure 11: Voltage Waveform (M=0.1).
Source: Authors, (2025)

After analyzing the Total Harmonic Distortion (THD) of voltage and current, we observe the following figures:

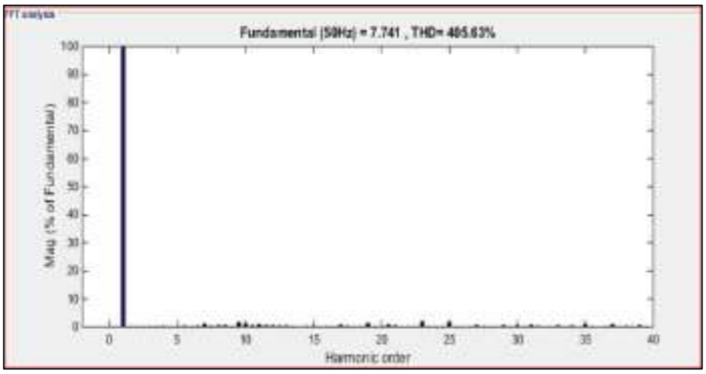

Figure 12: Output Voltage Harmonic Spectrum for m=0.1
Source: Authors, (2025)

For current:

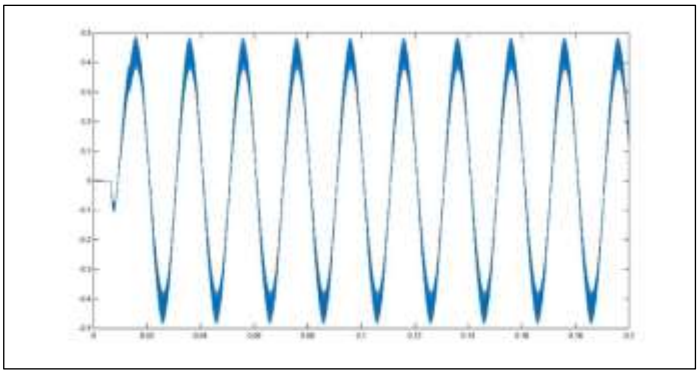

Figure 13 : Output Current Waveform Over Time (m=0.1)
Source: Authors, (2025)

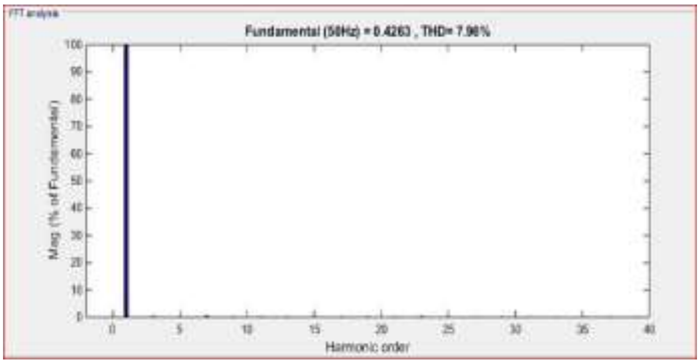

Figure 14: Output Current Harmonic Spectrum for m=0.1
Source: Authors, (2025)

Interpretation

According to the simulation results, it is evident that: as seen in Figure 7, the switching angles approximated by our neural network are very close to the exact angles, with a maximum error less than 0.0016 degrees.

Figure 12 demonstrates that the current waveform in the load closely resembles a sinusoidal shape. From Figure 13, it is evident that the selected current harmonics are eliminated, and the fundamental component is optimal. Therefore, we can conclude that our neural PWM algorithm exhibits high accuracy in computing switching angles and provides efficiency in eliminating desired harmonics.

The neural PWM control allows for:

- Ability to model complex structures and irregular data.
- Consideration of nonlinear relationships (interactions) between variables.
- Reasonable robustness to noisy data.
- Capability to model a wide range of diverse problems.

III.1 PRACTICAL IMPLEMENTATION THROUGH THE RT-LAB SIMULATOR

We introduce the control section into the RT-LAB software on the reference out block to obtain the following results [18]:

A. SHE PWM Control

The diagram of the PWM technique in RT-Lab is as follows:

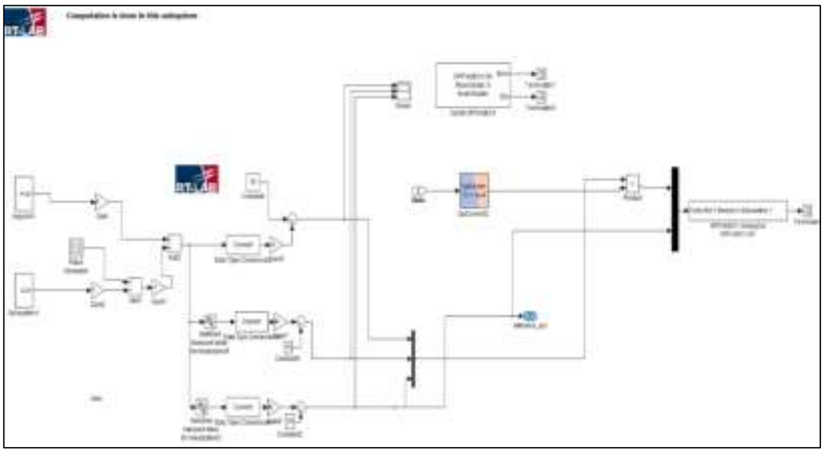

Figure 15: Block Diagram of Pre-calculated PWM Control using RT-Lab.
Source: Authors, (2025)

B. Architecture of the developed inverter

The block diagram of the inverter is shown in Figure 17. The power circuit switches are controlled by an OP5600 RT LAB simulator [19],[20]. The photo of the inverter is shown in Figure 18

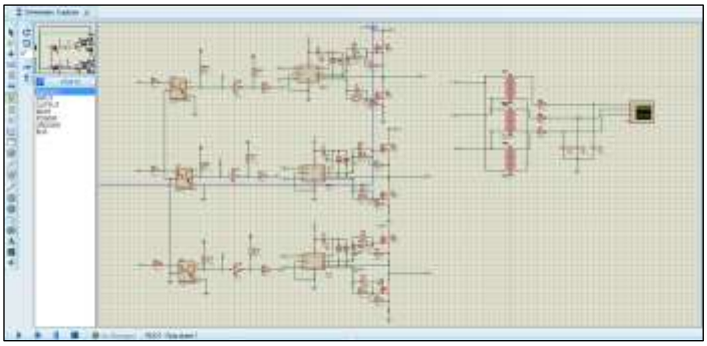

Figure 16: Power circuit of the inverter.
Source: Authors, (2025)

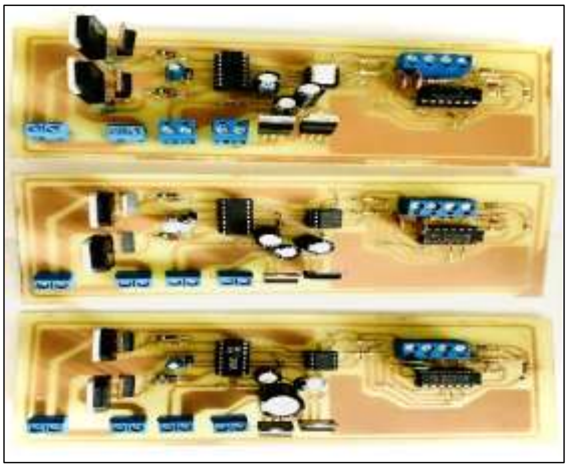

Figure 17: Photo of the inverter.
Source: Authors, (2025)

We present the voltage waveform for 23 angles at various frequencies and modulation indices.

For a modulation index im=0.1 and a frequency f=40:

❖ **Using a neural network**

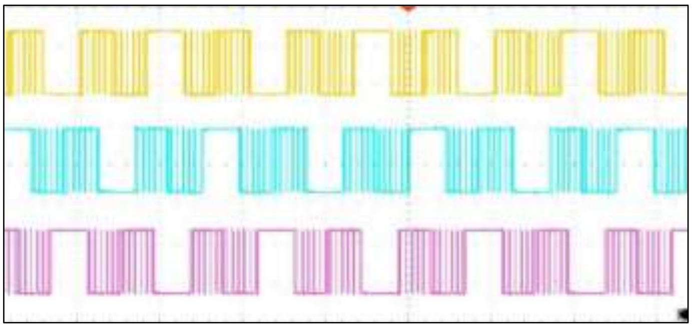

Figure 18: Voltage with Neural Network.
Source: Authors, (2025)

❖ **Using Newton-Raphson**

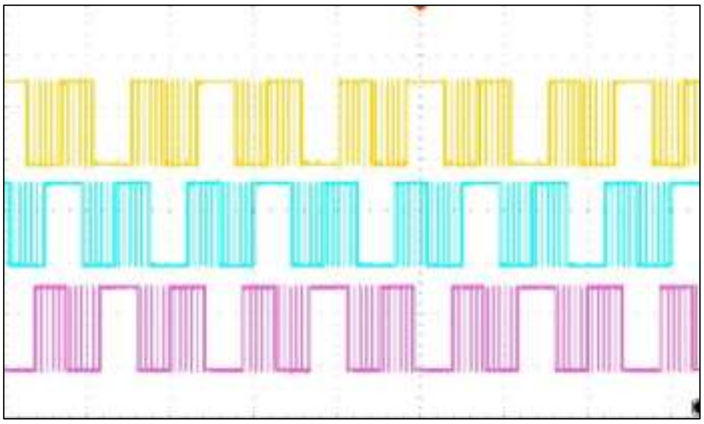

Figure: 19. Voltage with Newton-Raphson.
Source: Authors, (2025)

For a modulation index im=0.2 and a frequency f=20:

❖ **Using a neural network**

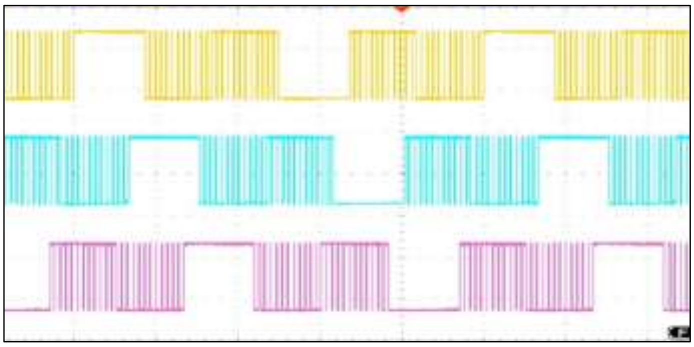

Figure 20 : Voltage with Neural Network.
Source: Authors, (2025)

❖ **Using Newton-Raphson**

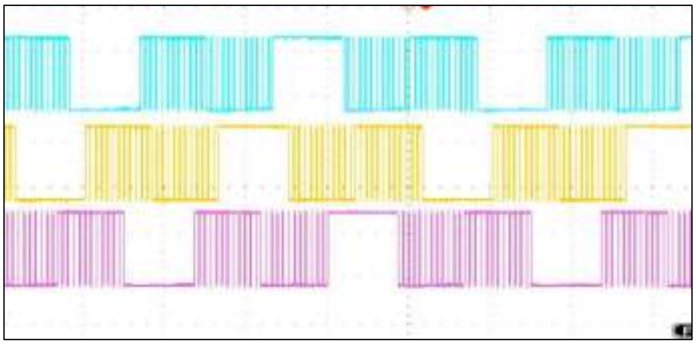

Figure 21 : Voltage with Newton-Raphson.
Source: Authors, (2025)

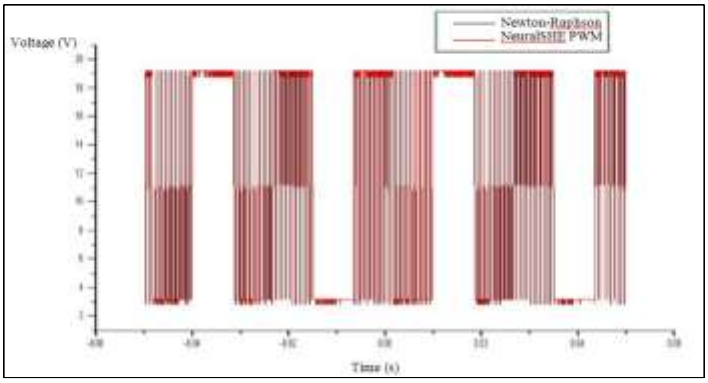

Figure 22: Comparative Study between SHE PWM Control (Newton-Raphson and NeuralSHE PWM).
Source: Authors, (2025)

For a modulation index im=0.1 and a frequency f=40, it is observed that the signals generated by both methods are identical with a small margin of error.

- **Interpretation of results**

The simulation results demonstrate that the signal quality improves as the modulation index increases, and the neural PWM control produces the same signal as the SHE PWM control.

It is noted that:

- The signals obtained using the RT-Lab Simulator for im = 0.2 and m = 23 (Figure 20 and 21) are identical to those obtained using Simulink MATLAB.

- The signals obtained using the RT-Lab Simulator for im = 0.1 and m = 23 (Figure 18 and 19) are identical to those obtained using Simulink MATLAB.

- There is a similarity between the control signals obtained using the RT-Lab Simulator for im = 0.1 (Figure 18 and 19) and im = 0.2 (Figure 20 and 21) compared to those obtained using Simulink MATLAB.

The RT-Lab simulator allows visualization of control signals on the oscilloscope, demonstrating the overlay between real signals and those obtained through simulation.

VI. CONCLUSION

In this work, we studied a selective harmonic elimination PWM control with fundamental control based on neural network theory, aiming to control a three-phase inverter for electric vehicles.

We modeled the three-phase asynchronous machine fed by an inverter, then presented various types of inverters and discussed different control strategies for these inverters. Based on the advantages and disadvantages of pre-calculated PWM control, it appeared to be the most suitable for varying the speed of asynchronous machines.

We solved the nonlinear equation system using MATLAB software with the Newton-Raphson method to calculate the switching angles of the inverter switches. Simulation results in MATLAB Simulink demonstrated the effectiveness of the control in eliminating desired harmonics. The drawback of this technique is the computation time for switching angles.

Artificial neural networks generate real-time switching angles for the switches. Simulations of this technique in MATLAB Simulink show the accuracy of calculating switching angles and efficiency in eliminating desired harmonics. Multiples of three harmonics are automatically eliminated in the case of phase-to-phase voltage.

The RT-Lab simulator was used to experimentally verify the generation of control signals. Simulation results show a similarity between the signals generated by the RT-Lab simulator and those obtained through Simulink MATLAB.

The results obtained from this research can significantly contribute to the advancement of electric vehicle technology and the broader field of power electronics. By optimizing the performance of three-phase inverters through selective harmonic elimination and precise control of the fundamental component, the proposed neural network-based PWM algorithm can lead to more efficient and reliable electric vehicle propulsion systems. This, in turn, can promote the widespread adoption of electric vehicles, reducing greenhouse gas emissions and mitigating the environmental impact of transportation.

Furthermore, the versatility of the neural network-based SHE technique opens up opportunities for its application in various other domains, such as renewable energy systems, industrial motor drives, and power quality improvement. The ability to model complex, non-linear systems and handle noisy data makes this approach attractive for a wide range of real-world scenarios.

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