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Control of a Three-phase Induction Motor with an ANFIS based Modular Multilevel Inverter for Variable-speed Marine Water Pumping Applications

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Abstract: This research presents a ground breaking approach to optimizing marine water pumping systems by integrating an Adaptive Neuro-Fuzzy Inference System (ANFIS) with Solar Photovoltaic (PV) technology. The primary aim is to enhance system efficiency and performance by enabling precise variable-speed control of a three-phase induction motor. ANFIS dynamically adjusts a Modular Multilevel Inverter (MMI) to match changing solar irradiance and pumping demands, outperforming conventional Fuzzy Logic Control. Comprehensive investigations, including tests at three motor speeds, demonstrate superior adaptability. Simulations and experiments confirm the ANFIS-based strategy's potential for improved energy conversion, reduced consumption, and enhanced system reliability in marine water pumping. This study contributes significantly to renewable energy-driven water pumping technology, offering a refined control technique that optimizes energy use, and reduces Total Harmonic Distortions (THD), supports variable-speed operation, and ensures reliable marine water supply. The findings hold promise for sustainable water solutions in remote coastal regions, emphasizing the transformative potential of innovative control strategies in renewable energy applications.

Keywords: Total Harmonic Distortion (THD), Induction Motor (IM), Solar Photovoltaic (PV), Fuzzy Logic Control (FLC), Modular Multilevel Inverter (MMI), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Fuzzy Logic Control (FLC).

I. Introduction

Many people all around the world have worked hard to make the maritime and shipping industries more energy efficient and less polluting. The International Convention for the Prevention of Pollution from Ships (MARPOL) has put in place a set of regulations aimed at preventing unintentional sources of pollution in the marine ecosystem. These regulations must be rigorously followed to ensure environmental protection [1].As a contributor to global warming and greenhouse gas emissions, the shipping industry is responsible for around 3% of all CO2 discharges from diesel motors utilized in the marine sectors [3] [5]. Marine shipping diesel engines are responsible for emitting 2.8% carbon dioxide (CO_2), 15% nitrogen oxides (NO_X), and 13% sulphur oxides (SO_x), three of the most major pollutants contributing to air pollution.[7].

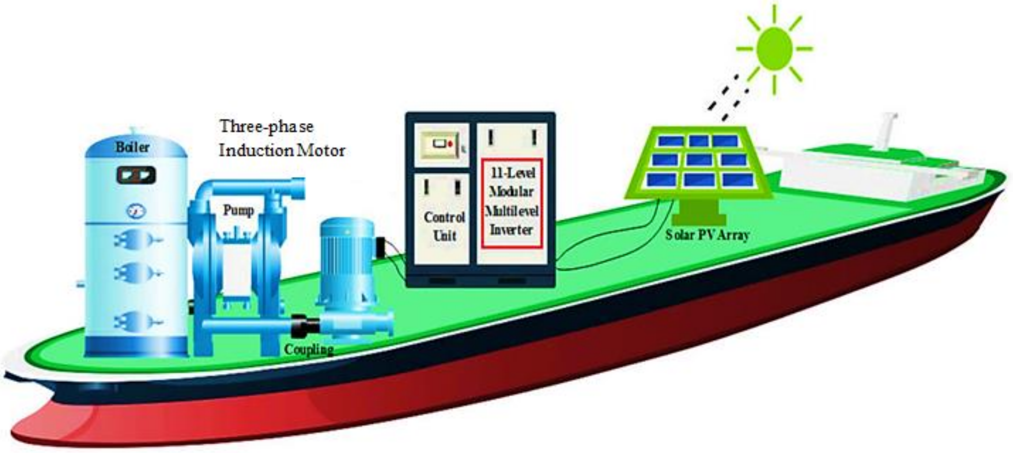


Figure1: This 11-level inverters suggested schematic [1].

This study discusses the need of using solar power in maritime applications to alleviate the global energy problem and reduce negative environmental effects. By reducing harmonics through intelligent management, it presents revolutionary modular inverter architecture for enhancing power quality in ships. Seawater cooling pumps' performance is improved by the inverter, which powers a variable-frequency motor. This research evaluates the efficacy of a Fuzzy Logic Control (FLC) and an Adaptive Neuro-Fuzzy Inference System (ANFIS) in controlling three-phase induction motor drives for marine water pumping with the goal of optimising the use of solar energy, as seen in (figure 1). Similar examination of the two control systems is given in the study, with a focus of enhancing the quality of power, utilizing a real-time implementation.

II. Operation Strategy and System Configuration

The modular multilevel inverter and associated water pump's power requirements are met by the PV array; this guarantees the system's capacity to function by having a maximum power output of 150W under Standard Test Conditions (STC) of (1000W/m2) and 25°C. [6][7]

A. Designing the PV Array

To be able to generate a 10W solar PV module, 36 cells are needed connected in series (36 cells x 0.588 V = 21.6 V_{oc}). Maximum power (P_{max}) is equivalent to 10W_p, V_{oc} is equal to 21.6V, and I_{sc} is equal to 0.659 A. V_{mp} = 17 V and Imp = 0.588 A respectively, are the max voltage and current of a module ($P_{max} = V_{mp} \text{ x } I_{mp}$ = 17 x 0.588 = 9.96 W). The input source is a 20W solar module with 72 cells connected in series. Maximum power (P_{max}) is 20W_p, V_{oc} is 21.5V, and I_{sc} is 1.24 A according to the specifications. The module's maximum voltage and current ratings are 17.5V and 1.143A ($P_{max} = V_{mp} \text{ x } I_{mp}$ = 17.1x1.14 = 19.38W). [10In order to achieve a maximum power capacity of 150W (5x10 = 50 W, 5x20 = 100 W) at STC, the aforementioned two power evaluations of 10W and 20W are associated in series and equal.The equation (1) present solar cell equation contains four indeterminate restrictions (I_L, I_0, R_s, and ∝) that must be overcome in order to achieve the PV cell's V-I properties. [3][5]

$$I = I_L - I_D = I_L - I_O e^{\left(\frac{V+iRs}{\propto}\right)} - 1 \tag{1}$$

B. DC-DC Converter Design

As part of the solar photovoltaic conversion system, an intermediate DC-DC converter is set at full power in order to provide symmetric input to MMI.[15] A DC-DC boost up converter's duty cycle is related to the input voltage and output voltage as shown by the equation (2).

$$V_{out} = \frac{V_{IN}}{1-D} \tag{2}$$

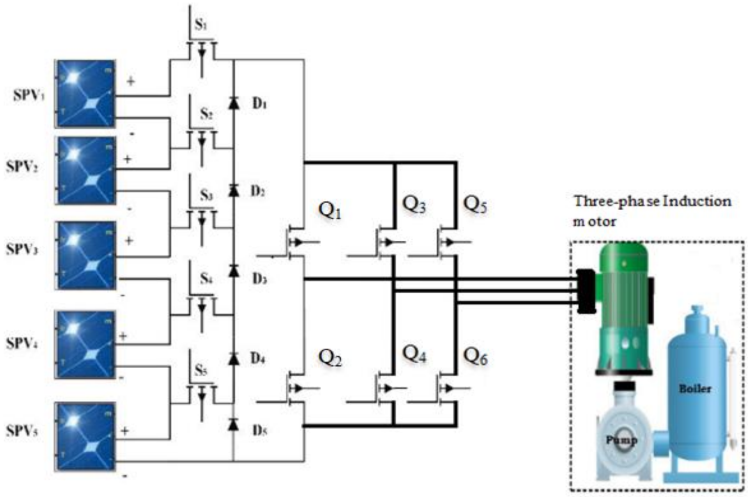


Figure2: Proposed Multilevel Inverter

C. Design of a Capacitor

The design of a capacitor needed for the system is demonstrated in the following stages derived from equations (3)-(4).

$$C_1 = \frac{I_{(out)} \times D}{f_s \times \Delta V_{out}} \tag{3}$$

$$\Delta V_L = (2\% - 4\%) \times V_{out(max)} \times \frac{I_{out}}{I_{in}} \tag{4}$$

The PV module's maximum voltage under STC is $V_{out(max)}$).[1]

D. Design of Multilevel Inverter

There are five solar PV modules (labelled SPV1, SPV2, SPV3, SPV4, and SPV5) in sequence at the input end of the voltage separator, as displayed in (figure 2). Following this, the information voltage is parted and sent through a way comprised of semiconductor gadgets (both controlled and uncontrolled in nature) signified by the letters S1, S2, S3, S4, S5, D1, D2, D3, D4, and D5. Following this route, you'll arrive at an H-bridge (Q1, Q2, Q3, Q4, Q5, and Q6). The symmetrical modular multilevel construction dramatically expands the range of possible output voltages, as seen by Eqs. (5) and (6).[1][3]

$$N_{level} = 2S + 1 \tag{5}$$

$$N_{level} = s + 4 \tag{6}$$

III. Control Topology for MMI

Figure 3 depicts the solar photovoltaic (PV)-fed Induction Motor (IM) drive for marine water siphoning using a Modular Multilevel Inverter (MMI). The intended function of the suggested setup is to regulate the MMI with the help of Fuzzy Logic (FL) and an Adaptive Neuro-Fuzzy Inference System (ANFIS). Precise switching sequences for the inverter are orchestrated by Pulse Width Modulation (PWM) techniques, enabled by intelligent control methods, to manage the multilevel inverter's operation and regulate the speed of the three-phase induction motor.[2][3]

The control approach used here is the voltage-to-frequency (v/f) control scheme, in which voltage and frequency are varied in an Alternate Phase Opposition Disposition (APOD) pattern, which falls under the umbrella of multi-carrier pulse-width modulation (PWM) techniques. [4][6] The necessary PWM signals are generated by superposing one sinusoidal reference waveform on top of five separate three-sided transporter waveforms (each stage moved by 180 degrees). Dynamic heartbeats for the inverter switches are derived from the modulating signals by comparing them to the carrier signal, a process used by both the FL and ANFIS controllers.

The exhibition appraisal of the three-stage enlistment engine is directed under different circumstances, including steady and variable burdens, open-circle, and shut circle operations, employing FL and ANFIS controllers. The subsequent sections provide an in-depth exploration of the design and implementation of these controllers, highlighting their role in enhancing the performance of the three-phase induction motor in conjunction with the MMI.

A. Fuzzy Logic Controller based Speed controller

Since can be seen in Figure 4, a fuzzy logic controller is a powerful tool for enhancing electrical equipment, since it provides rapid evaluation of speed controllers while also incorporating human reasoning and rule-based processes. The voltage/recurrence approach, the transition control technique, and the vector control strategy are the most well-known method for directing enlistment engines. The shut circle v/f control framework is in many cases considered the best quality level for speed control because of its usability and pinpoint exactness. [7][4]

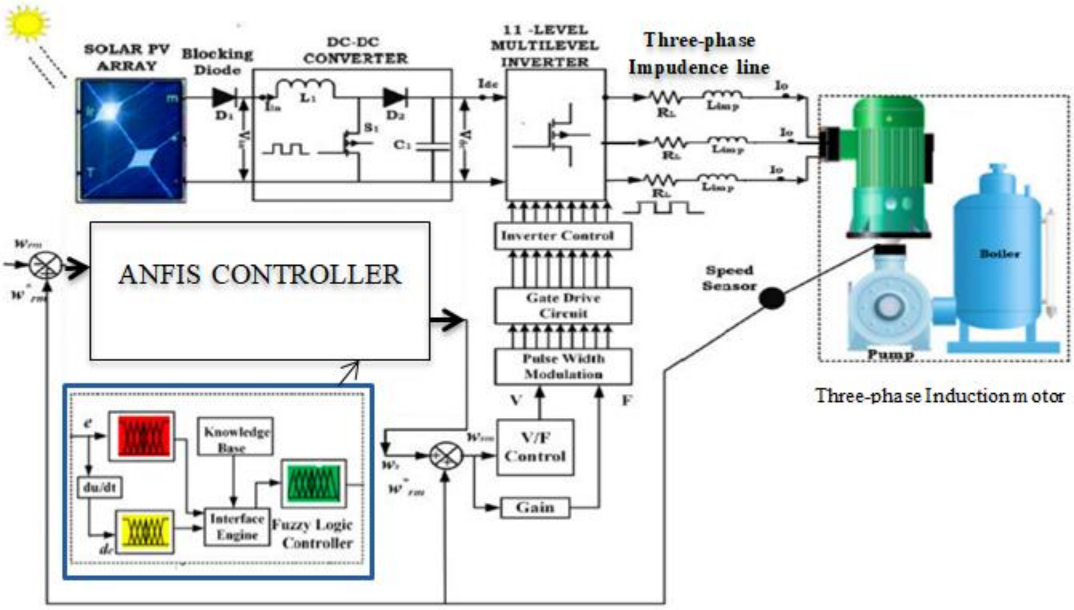


Figure 3: Schematic diagram of a Controllable Tropology

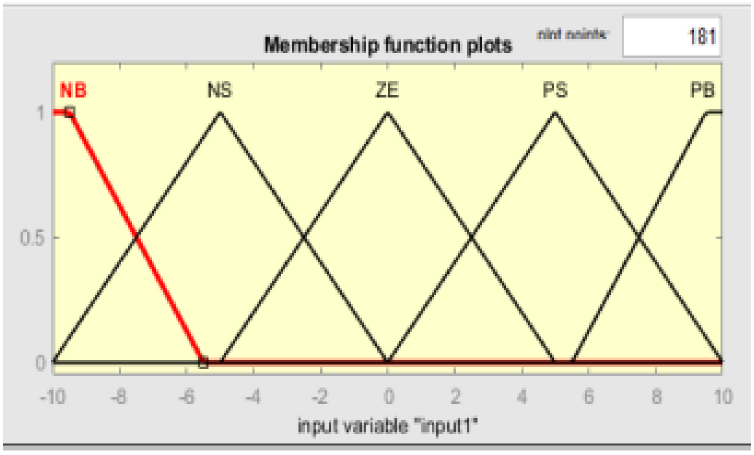


Figure 4: Allocation of range for subsets

Several limitations apply to open and closed control operations using a fuzzy logic controller, including the stator current being higher than the evaluated current, the slip speed being unsound, and the rotor speed being possibly changed and lower than coordinated speed.. These FL regulator issues are generally present under operating settings that change often. ANFIS overcomes this FL controller limitation in single phase induction motor.

Table 1: Fuzzy rules

e/ce	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	ZE	NS	NB	NB	NB
NS	ZE	NS	NB	NS	NB
ZE	PB	PS	ZE	NS	NB
PS	PB	PS	PS	ZE	NS
PB	PB	PB	PB	PS	ZE

Fuzzy operator takes multiple relationship values from input factors, delivering a solitary truth esteem. Input 1 represents error, while input 2 indicates changing error as shown if (figure 4). Linguistic variables consist of eight fuzzy subsets, using five: NB, NS, PS, PB, and ZE as tabulated in table (1). The FLC structure is guided by the inverter's pulse generator, the FLC structure employs input fuzzification within ranges of (-1, 0, 1), divided into positive (0–1) and negative (-1 to 0) quarters. Six membership functions shape output. Two controllers handle water pumping: v/f for the inverter and v/f for motor speed. [2][4] FLC control has limitations, addressed by ANFIS due to improved slip speed management under fluctuations.

B. ANFIS CONTROLLER

ANFIS, short for "Adaptive Network-Based Fuzzy Inference System," is a system that approximates functions using a data-centric method similar to neural networks. It organizes numerical samples from a training dataset into ANFIS networks, finding applications in tasks such as classification, rule-based control, pattern recognition, and more. It uses the Takagi-Sugeno-Kang fuzzy model to infer rules from input-output data (figure 6). Let's assume for the sake of argument that a fuzzy surmising framework requires only two information sources and a solitary result. Following the Takagi-Sugeno methodology, the collection of rules is built with fuzzy if-then statements: For any given values of x and y, we determine z using the function f(x, y). Table (2) provides details of the antecedent fuzzy sets A and B, while the subsequent fuzzy set z is defined by the function f(x, y). As illustrated in figures (7, 8, and 9), although F(x, y) is often represented as a polynomial, it can take the form of various approximation functions.

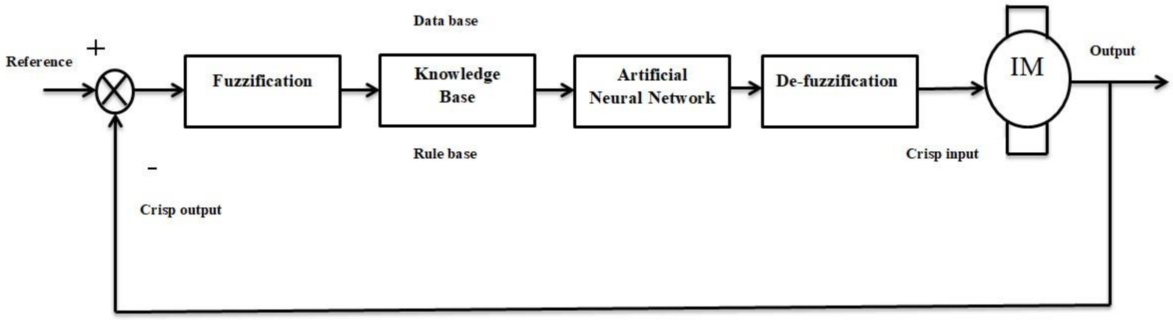


Figure 5: ANFIS Block diagram

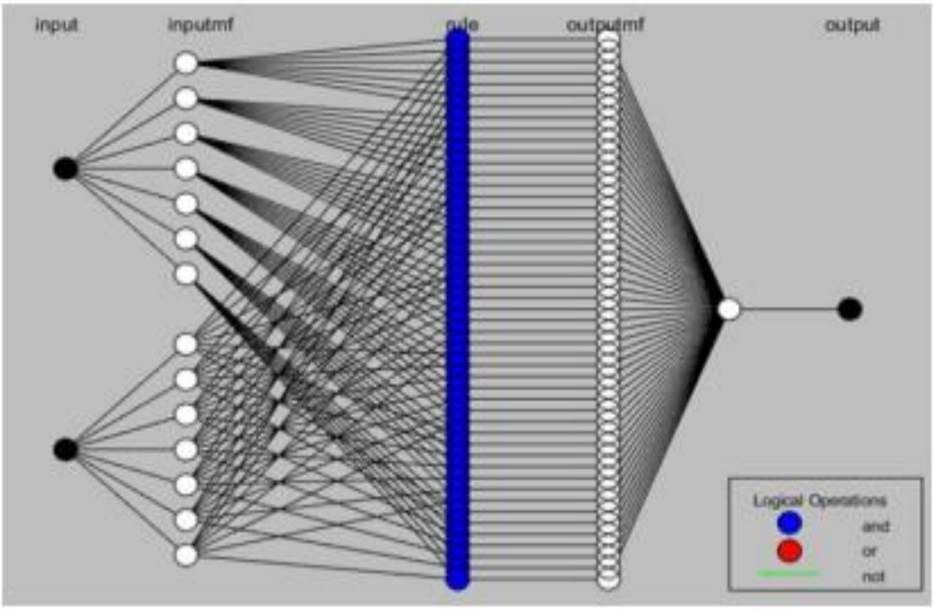
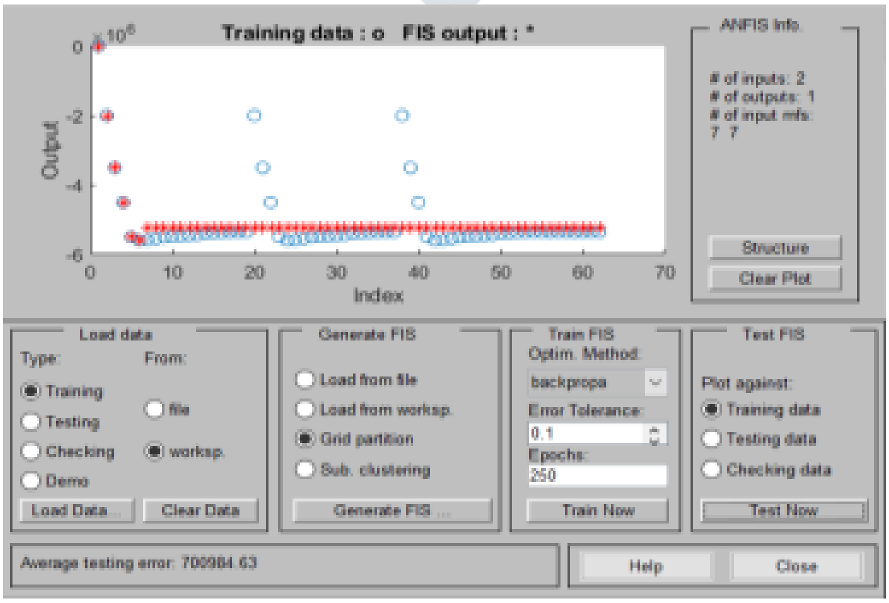


Figure 6: Structure of ANFIS

Rule 1: If x is A1 and y is B1, then f1 = p1x + q1y + r1.

Rule 2: If x is A2 and y is B2, then f2 = p2x + q2y + r2.

Type-3 Takagi-Surgeon fuzzy inference system adopted. Each rule's output is input variables linear combination with a constant ANFIS equivalent structure as shown in (figure 5). A combination of its controlled power distribution and diminished torque pulsations, three-phase induction motors operate more efficiently and smoothly than their single-phase counterparts.



# of inputs: 2
# of outputs: 1
# of input mfs:
7 7

Load data — Type: ● Training ○ Testing ○ Checking ○ Demo; From: ○ file ● worksp.

Generate FIS: ○ Load from file ○ Load from worksp. ● Grid partition ○ Sub. clustering

Train FIS — Optim. Method: backpropa; Error Tolerance: 0.1; Epochs: 250

Test FIS — Plot against: ● Training data ○ Testing data ○ Checking data

Average testing error: 700984.63

Figure 7: Output for FIS

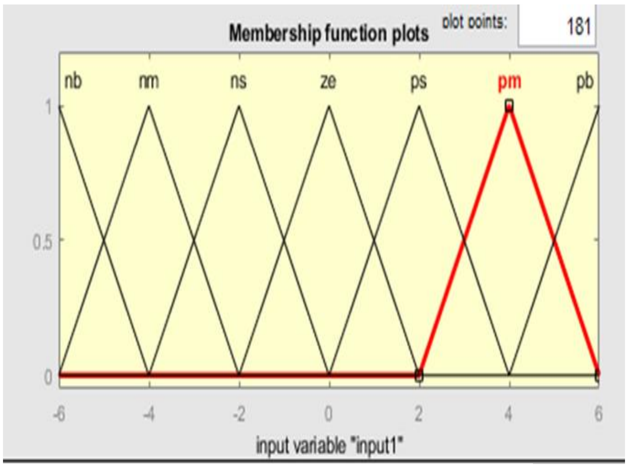


Figure 8: Input variable1 for FLC in ANFIS

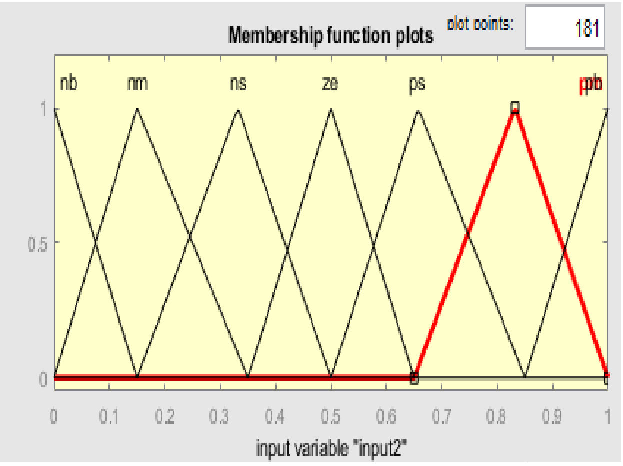


Figure 9: Input variable2 for FLC in ANFIS

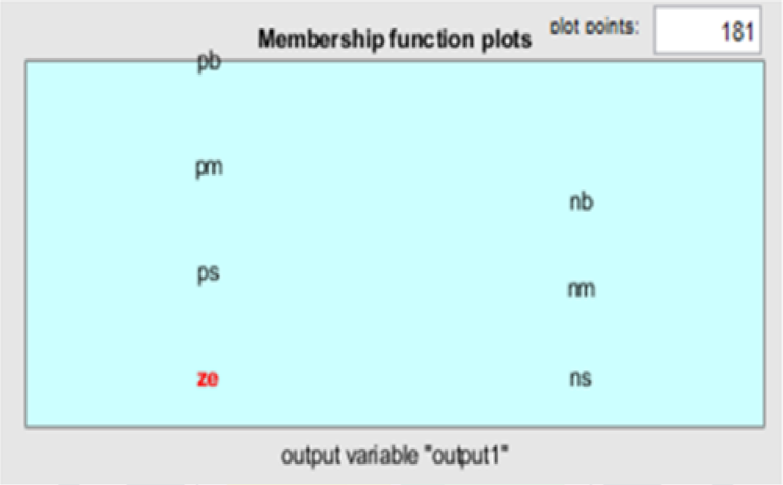


Figure 10: Output for FLC in ANFIS

By refining control techniques and addressing problems like unequal power distribution in complex systems (figure 10), ANFIS (Adaptive Network-Based Fuzzy Inference System) can further boost their performance.

Table2: Fuzzy rues for ANFIS

E/CE	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Paper showcases FLC and ANFIS controllers for water pumping improves performance in single-phase induction motor and ANFIS also improves in three-phase induction motor for water pumping. Inverter controlled via voltage and frequency; motor speed with v/f method.

IV. Results and Discussion

By utilizing MATLAB/Simulink (2018), a simulation model compares FLC and ANFIS controller performance, including harmonic reduction and open/closed-loop analyses in single-phase induction motor and ANFIS also in three-phase induction motor.

A. Speed Performance Tracking and Harmonics Analysis of Inverter

The objective of the single-stage enlistment engine that drives the pump is to reach speeds between zero and one thousand revolutions per minute. Fuzzy Logic Control (FLC) was compared to an Adaptive Neuro-Fuzzy Inference System (ANFIS) in a study of speed control, ANFIS outperforms FLC by exhibiting lower overshoot, undershoot, and speed errors, particularly at 1000 rpm. In figure 11, we see the motor stabilise at 1000 rpm after 0 seconds of operation in the FLC simulation; in figure 12, we see the same motor stabilise after 0.35 seconds of operation with the ANFIS controller, suggesting that the latter allows for faster speed achievement. Additionally, power quality analysis shows that FLC results in a Total Harmonic Distortion (THD) of 8.57% (figure 13), whereas ANFIS achieves a lower THD of 7.27% (figure 14). ANFIS not only enhances speed tracking but also reduces THD in the 11-level inverter output voltage integrated with the marine pump system (figure 15). Furthermore, ANFIS demonstrates improved speed control across various motor speeds (1000, 1500, and 1800 rpm) with faster stabilization at 0.34 seconds (fig 16, 17, and 18) and a THD value of 7.27% fig 19. Additionally, three-phase induction motors exhibit greater torque capabilities fig 20 compared to single-phase counterparts, including higher starting torque.

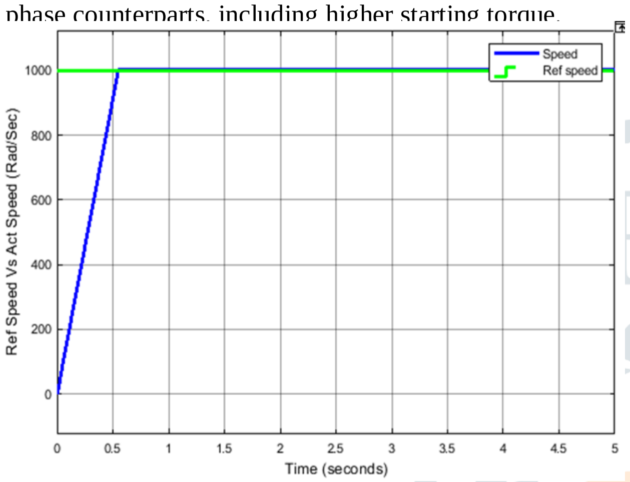


Figure 11: Speed response of the FL controller at 1000rpm in a Single-phase induction motor

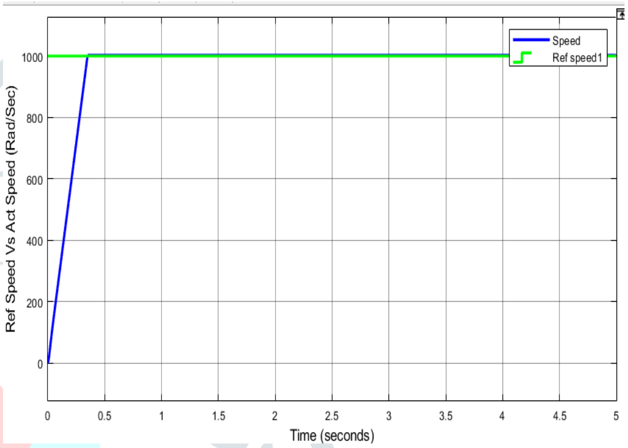


Figure 12 shows the ANFIS controller's speed response for a 1000 rpm single-phase induction motor.

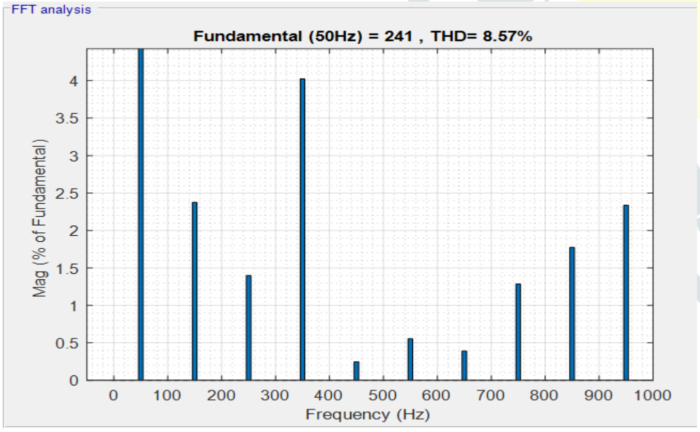


Figure 13 shows the THD values for a single-phase induction motor used in an FLC.

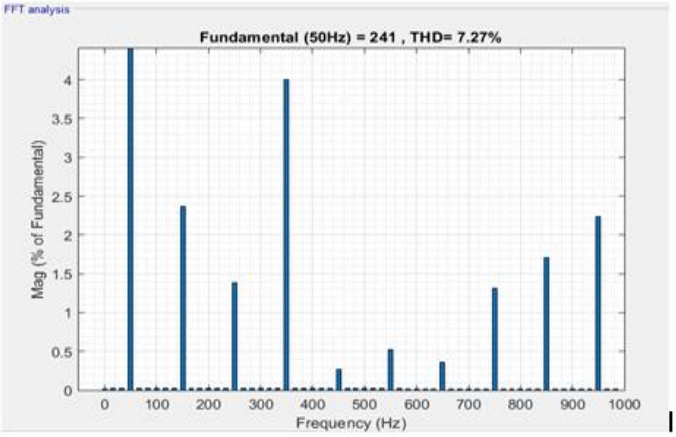


Figure 14: Three-phase induction motor THD results for ANFIS.

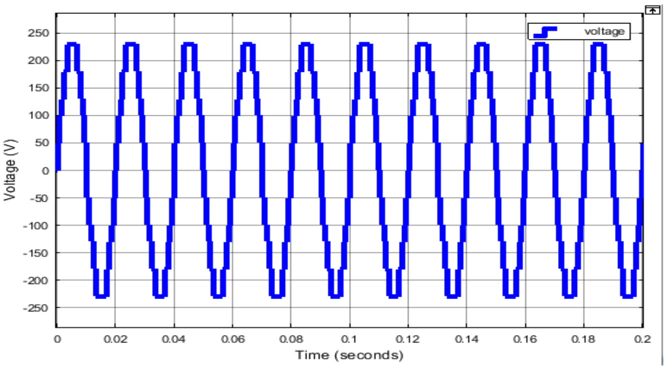


Figure 15: An 11-level inverter's output voltage waveform for a single-phase induction motor

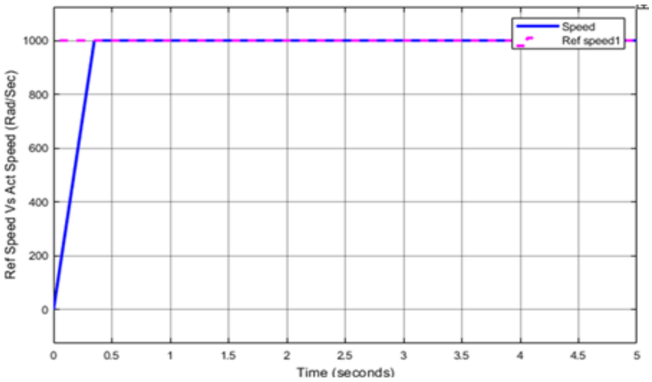
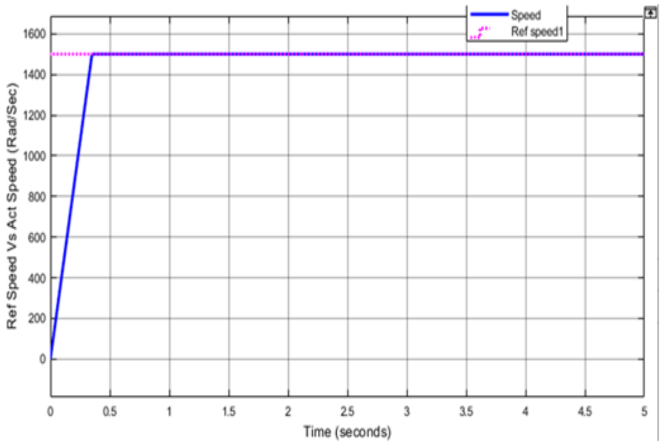


Figure 16 shows the three-phase induction motor's ANFIS controller's speed response at 1000 rpm.



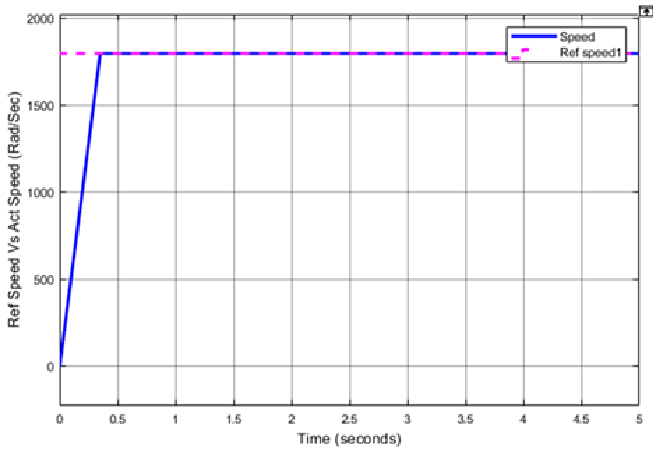
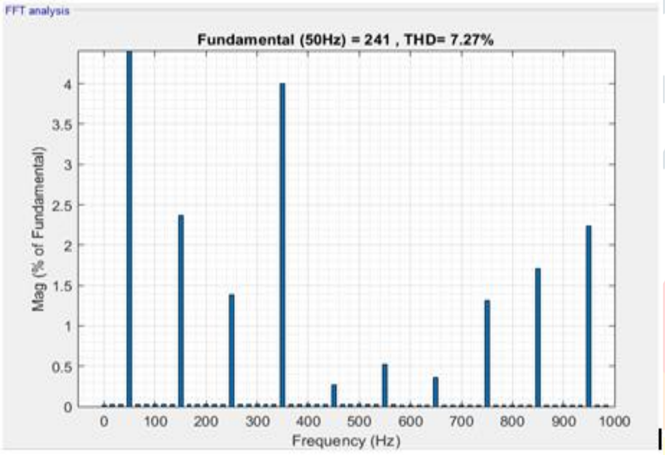


Figure 17 shows the ANFIS controller's speed response for a three-phase induction motor operating at 1500 revolutions per minute.



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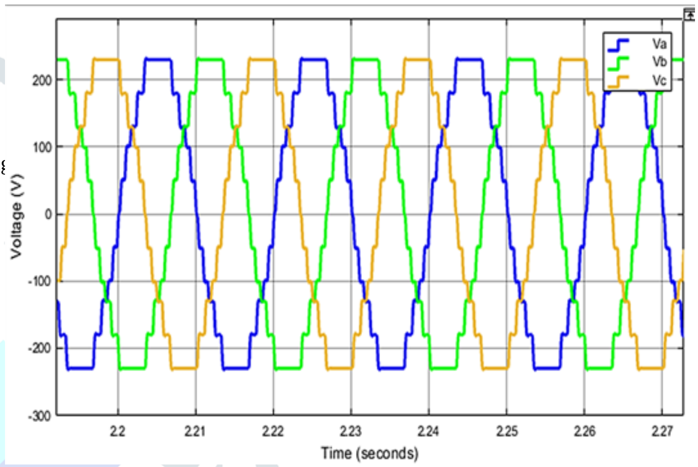

Figure 20 shows the voltage waveform at the motor's terminals as a function of speed for a three-phase induction motor driven by an inverter with 11 levels.

Fig. 19 for THD figures for an ANFIS powered by a three-phase

V. Conclusion

In conclusion, the integration of ANFIS-based control with a solar PV-fed modular multilevel inverter has demonstrated significant advancements in both single-phase and three-phase motor-driven marine water pumping applications compared to Fuzzy Logic Control (FLC). Through a comprehensive study encompassing both motor types, this project has underscored the versatility and efficacy of ANFIS in optimizing variable-speed marine water pumping systems.

The project revealed that when employing a single-phase induction motor, ANFIS control achieved notably superior results compared to FLC, with a reduction in Total Harmonic Distortion (THD) values. This reduction in THD indicates improved power quality and reduced electrical losses in the system, highlighting the potential for enhanced efficiency and reliability in single-phase applications.

Similarly, in the case of three-phase induction motors, ANFIS control exhibited substantial improvements over FLC, showcasing quicker speed attainment and stabilization. This translates to enhanced performance and responsiveness of the water pumping system. The THD values in the three-phase system were also favorably lower with ANFIS control, further emphasizing its ability to enhance power quality and reduce harmonic distortions.

Overall, this research project has not only validated the effectiveness of ANFIS-based control in marine water pumping applications but has also demonstrated its adaptability to different motor configurations. ANFIS control holds great promise in the pursuit of sustainable and energy-efficient water pumping solutions for marine environments, with the added benefit of improved power quality and reduced THD.

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