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Optimization of a Fuzzy-Based MPPT Controller for a PV Water Pumping System Through a PSO-Based Approach

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ABSTRACT

Water is essential for many agricultural and human needs. The use of fossil fuels in water pumping systems has an effect on the environment. A new energy paradigm is being adopted as part of the sustainable development goals, and carbon-free technologies are being widely used to generate renewable energy. This paper presents a fuzzy-based maximum power point tracking (MPPT) approach for a photovoltaic (PV) water pumping system that employs particle swarm optimization (PSO). Additionally, the fuzzy logic control (FLC) scheme for power converters was used in SIMULINK/MATLAB to design and simulate the MPPT of the PV system. The FLC inputs and output scaling gains were adjusted using the PSO algorithm. In addition, a comparative evaluation of the performance of different MPPT controllers was carried out. It made use of fuzzy logic, a PSO-based fuzzy controller, and the perturb and observe technique. According to the simulation results, the simulated photovoltaic water pumping application has high efficiency levels of a normal fuzzy logic, a PSO-based fuzzy controller, and the perturb and observe technique are 95.65%, 96.5%, 84.99%, respectively. The results further indicate that the overall efficiency of the PV water pumping system can be significantly increased by using the recommended PSO-based fuzzy controller technique.

1. INTRODUCTION

Water is essential for many agricultural and human needs, such as for drinking, cooking, cleaning, bathing, maintaining health, ensuring the vitality of food production, and restoring the environment. In many rural locations, water sources are too far from present grid lines, spanning many miles of land space. In remote areas, constructing new transformers and transmission lines is too expensive. Various diesel engines are as of presently utilized to power standalone water pumping frameworks, but they have various disadvantages, including high operating costs, restricted supply, frequent site visits for maintenance and refueling, and environmental pollution [1, 2]. Providing drinking water with environmentally friendly technology is essential. Because fossil fuels emit pollutants into the atmosphere, their use affects the environment and this is a major contributing factor to climate change [3, 4].

As part of the sustainable development strategy, a new energy paradigm is emerging with an emphasis on carbon-free technologies for energy generation, transmission, and consumption [3]. Developments in digital signal processors and power-switching devices, which are parts of power converters, are driving this shift in perspective. The development of renewable energy sources, including geothermal, wind, bioenergy, and photovoltaic solar energy, is the current focus of recent technologies. Among these technologies, photovoltaic (PV) solar energy is growing at the fastest rate because it is a clean, abundant, and silent energy source that can be adjusted to the required output for specific applications. Research and use of photovoltaic water pumping technology for off-grid purposes have been ongoing for over four decades, most notably for drinking [5, 6]. However, research and development of these systems have accelerated due to the remarkable drop in PV module costs brought about by the PV market's recent, rapid global expansion, enabling more flexible systems and more modern applications [7].

There are different approaches, counting as the incremental conductance approach, P&O approach, open-circuit voltage and short-circuit current procedures, and intelligent strategies like fuzzy control, can be utilized to maximize the output energy from PV modules. The MPP can be found utilizing the standard strategy for certain temperature and solar radiation conditions, but the comes about display oscillatory reaction over the maximum power point underneath standard working conditions [8-11]. This work aimed to create a fuzzy MPPT control system based on PSO that would optimize energy production to meet the required demand. This would improve PVWPS's energy conversion efficiency and enable it to pump groundwater to satisfy residential household demands. To design and choose the best PV pumping system, details about the site's sun irradiation, water pumping requirements in gallons per day, and total system dynamic head are crucial. So, this research study concentrated on finding a fix for the water issues that plagues 5200 residential homes in Gamo Zone, Ethiopia.

The remaining sections of this paper are organized as follows: Section 1 is introduction part which depicts background of PVWPS. Section 2 presents the modeling and design of the PV water pumping system (PVWPS) and the modeling of the whole components and description of their operations. This section introduces the PVWPS MPPT controller design. This section provides a detailed discussion of three MPPT techniques, namely: particle swarm optimization, fuzzy logic control, and the perturb and observe method. The results of the proposed system's MATLAB/Simulink implementation are presented and discussed in Section 3. In Section 4, MATLAB/Simulink simulation results for the three proposed MPPT techniques are analyzed and conclusions are drawn, along with recommendations for additional research.

2. MODELLING OF THE PV WATER PUMPING SYSTEM

The pump controller, electric pump (which comprises of a motor and pump), and solar array are the three primary components of the proposed solar water pumping framework. The pumping framework must coordinate the different components as examined in Sections 2.1-2.6 in arrange to achieve the modeling of the PVWPS.

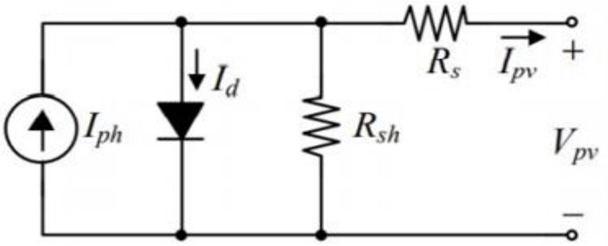

Figure 1. Equivalent circuit of a photovoltaic module

2.1 PV array

One of the most widely used circuit demonstrations to model and analyze solar behavior is the one as depicted in Figure 1, with one diode and two resistors [12]. The PV current and voltage are obtained using Eqs. (1) and (2).

$$I_{pv} = I_{ph} - I_s\left(exp\,(\frac{V_{pv} + I_{pv}R_s}{\alpha V_t}) - 1\right) - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (1)$$

where,

$$V_t = \frac{kT}{q} \quad (2)$$

2.2 DC-DC boost converter

Figure 2 depicts the model of a boost converter, which raises a continuous source's voltage. The boost converter is in charge of controlling and increasing the PV system's DC output voltage [13]. The output voltage is calculated using Eq. (3).

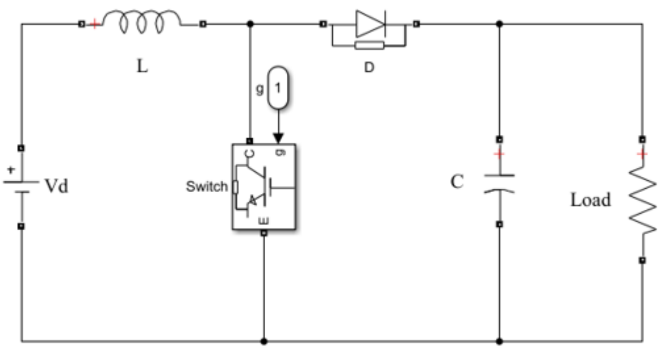

Figure 2. Step-up (boost) converter

$$D = 1 - \frac{V_d}{V_{out}} \quad (3)$$

where, D is the duty cycle, V_d is the input voltage and V_{out} is the output voltage.

2.3 DC-Link design

The second part of the solar converter, the DC/AC converter, depends on a DC/DC converter to supply the right least DC input voltage; a DC link capacitor connects the two parts, and evens out the DC link voltage [14, 15]. Using Eq. (4), the DC link capacitor is calculated.

$$\frac{1}{2}C_{dc}\left[{V_{dc}}^2 - {V_{dc,ref}}^2\right] = 3\alpha VIt \quad (4)$$

where, I is the IMD phase current, t is the time it takes for the voltage to drop to the lowest allowed DC link voltage, $V_{dc,ref}$ is the lowest allowed DC link voltage, and α is the over-burdening factor.

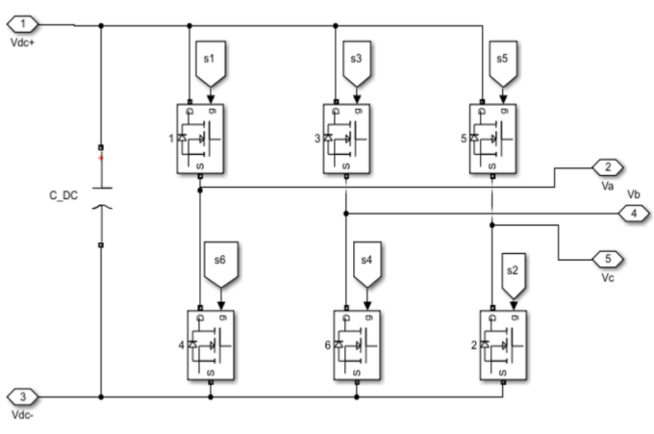

Figure 3. Three-phase VSI schema

2.4 DC-AC converter (Inverter)

Figure 3 depicts the three-phase Voltage source inverter configuration. Similar to the single-phase voltage source inverter, the voltages Vdc, 0V, and -Vdc on the resulting AC output line are discrete values because the three-phase inverter alternates between states to produce a specific voltage waveform. If the upper and lower switches, that is, switches (1 and 6), (3 and 4), or (5 and 2), were turned ON simultaneously, commutation failure across the dc-link voltage source would result [16].

2.5 LCL filters

As illustrated in Figure 4, a few important factors to consider when designing an LCL filter are the maximum power variations in the filter capacitance, the inverter-to-load inductor ratios, and the inverter output ripple current [17]. It is expected that with in inverter design L_{inv} the output ripple current (ΔI_L) could reach a maximum of 10% of the inverter's rated output current (L_{inv}). This can be calculated using Eqs. (5) and (6).

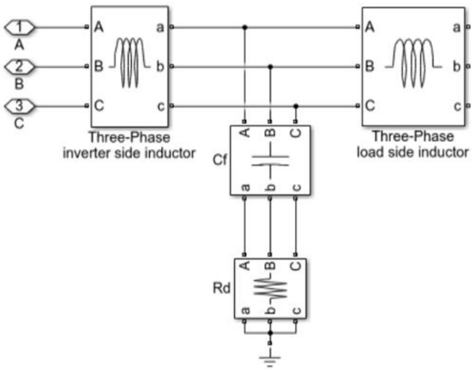

Figure 4. LCL filter

$$L_{inv} = \frac{V_{dc}}{6f_{sw}\Delta I_{max}} \tag{5}$$

$$\Delta I_{max} = \frac{V_{dc}}{6f_{sw}L_{inv}} \tag{6}$$

The reactive power demand of the LCL filter capacitor is less than 5% of the total of the *P*, as given by Eq. (7) [18, 19].

$$C_{fmax} = 5\% \frac{P}{2\pi f_g V^2{}_g} \tag{7}$$

2.6 MPPT control strategy

By altering the duty cycle in response to the operating point's divergence from the MPP, MPPT aims to bring the operating point closer to the MPP.

2.6.1 Perturb and observe method

PV array terminal current or voltage on a regular basis and comparing it to the matching power output; if the PV array power increases (ΔPPV > 0) as a result of the terminal voltage perturbation, it should be maintained in that path; if not, it should be moved in the opposite direction. Until the maximum power is reached, or ΔPPV = 0, the perturbation cycle is repeated [20].

2.6.2 Fuzzy logic controller MPPT techniques

The use of fuzzy control makes it possible to create nonlinear controllers based on input from an expert using heuristic methods. Fuzzification involves processing input signals and assigning them fuzzy values. A set of rules provides a linguistic description of the variables that must be managed, leveraging the process expert's knowledge. The fuzzy information from the inference mechanism is then defuzzied to provide non-fuzzy information that may be utilized for process management. The inference process examines the data while taking into consideration the rules and their membership functions [21]. Fuzzy control systems have been used as a significant modeling tool in a variety of practical and commercial applications because they can manage nonlinearities and uncertainties, inaccurate inputs that don't need accurate mathematical modeling [22]. The primary drawback of fuzzy logic methods is the difficulty in determining the ideal number of tuning parameters. The fuzzy controller's input and output data are provided by Eqs. (8)-(10). Eqs. (8)-(10) and their corresponding membership functions for (a) error, (b) change of error, and (c) output are shown in Figure 5.

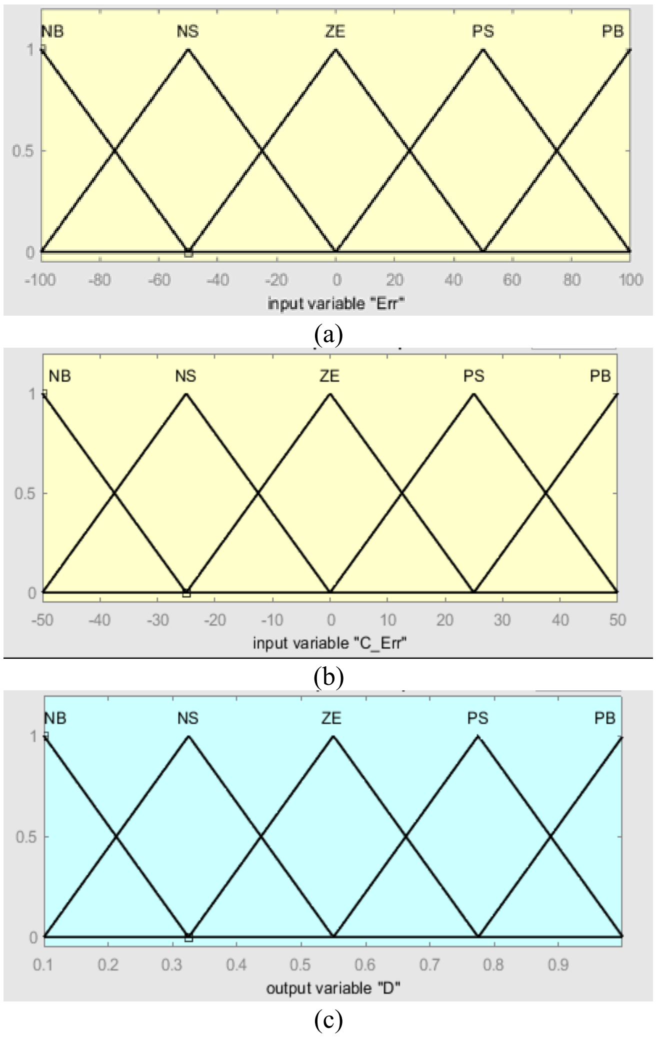

Figure 5. Membership functions for (a) Error, (b) Change of error, and (c) Output

$$E(x) = \frac{P(x) - P(x-1)}{V(k) - V(k-1)} \tag{8}$$

$$CE(x) = E(x) - E(x-1) \tag{9}$$

$$D(x) = D(x-1) - dD \quad (10)$$

An IF-THEN set of statements containing all the data for the controlled parameters is used to configure the fuzzy control rules. Five sets of data are assigned to the output: positive big (PB), positive small (PS), zero (ZO), negative big (NB), and negative small (NS). The triangular functions represent the two inputs' membership functions (ΔP_{pv} and ΔV_{pv}). The inputs are input 1 (-100, 100), input 2 (-50, 50), and output (0.1, 0.9).

2.7 Particle swarm optimization for tuning of FLC

The particle swarm optimization (PSO) approach employs a population of particles to intuitively determine optimum ranges inside complex search areas [23]. Engelbrecht and Cleghorn [23] proposed the approach of using social behavior as a metaphor. The primary advantages of PSO are that its paradigm is computationally affordable in terms of speed and memory needs, and it may be implemented as straightforward computer codes. Because PSO can begin from any arrangement and get the most excellent arrangements that converge to the ideal arrangement in a shorter time than other conventional search tools, it has experienced some success recently, especially with regard to optimization and search-related issues [24, 25]. PSO is used to ascertain whether the quantity of rules is sufficient and to determine the appropriate relationships between the rules, as shown in Figure 6. Its position and velocity are updated using Eqs. (11) and (12).

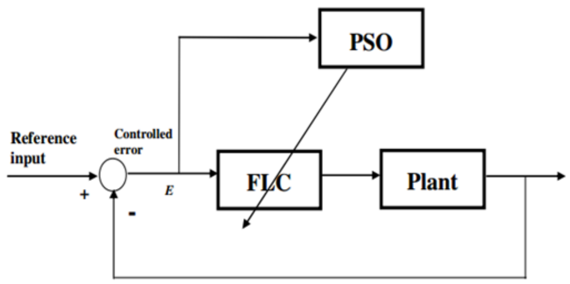

Figure 6. Proposed PSO-based fuzzy tuning method

$$v = w * v + C_1\text{*rand }(0, 1)\text{*}(P_{best} - x) + C_2\text{*rand }(0, 1)\text{*}(g_{best} - x) \quad (11)$$

$$x = x + v \quad (12)$$

The PSO's goal is to reduce the FLC's control error. The Integral of the Squared Error (ISE) is the definition of the PSO objective or cost function given by Eq. (13).

$$ISE = \int_0^t [e(t)]^2 \quad (13)$$

where,

$$e(t) = \frac{\Delta P_{pv}}{\Delta V_{pv}} \quad (14)$$

Eq. (15) establishes the tracking efficiency, or the ratio of the PV array's as the efficiency requirement, real power to its theoretical power at the same instant of time of an MPPT controller [26, 27].

$$\eta_{MPPT}(\%) = \left(\int_0^t P_{MPPT}(t)dt \Big/ \int_0^t P_{ref}(t)dt \right) * 100 \quad (15)$$

where, P_{ref} is the maximum power produced under the same temperature and radiation conditions without MPPT. The measured power generated by the MPPT PV panel is P_{MPPT}. Simulink was used to determine the efficiency results for the three suggested controllers using Eq. (15).

3. RESULTS AND DISCUSSION

The simulation's PV array has a power of 32.29 kW, which is made up of 12 strings and 11 modules of 245 W each generating the needed power under typical circumstances of irradiation (G=1000 kW/m^2) and temperature (T=25°C). To turn on the PV control, 122 modules are used, and 32.29 kW of power is produced for the intended usage. To assess the effectiveness and practicality of three proposed MPPT approaches, a photovoltaic water pumping system with an AC water pump load of 22 kW is simulated using MATLAB/Simulink. Because of its simplicity and versatility, the P&O approach is commonly used for maximum power point tracking (MPPT). However, because of an inherent trade-off between step size and perturbation frequency, tracking accuracy and speed are compromised. Furthermore, there is a value fluctuation issue with MPP. The P&O method uses a stochastic system; it cannot find the proper duty cycle value that reaches the MPP unless to find the precise value at that one moment in time, the PV framework alters the duty cycle value. As a result, this step must take some time, squandering valuable time.

With 25 fuzzy rules and 50 consequent constants, the PSO algorithm's problem space is 50 dimensions large. The objective of the procedure is to optimize the parameters to k_best, the best value, so that the trajectory deviation error gets close to zero. The task is described as a minimization problem, where the integral of squared error (ISE) at each iteration serves as the basis for the fitness function. Fuzzy-based approaches are very flexible and adaptive when handling MPPT problems in solar systems with a lot of unknown parameters. Figure 7 illustrates the designed model in the MATLAB/Simulink environment.

Figure 8 depicts different irradiance for analysis of various MPPT techniques. A constant temperature of 25°C is used to obtain the following results under variable irradiance.

The simulation results of the PV array and boost converter output voltage, current, and power, along with the three-phase induction motor's speed and torque, are displayed in Figures 9-15. Manganese, blue, and green are the colors that stand for P&O, fuzzy logic, and the fuzzy controller based on PSO, respectively.

For particle swarm optimization, the following are the simulation parameters:

Quantity of variables: 3

Quantity of iterations: 5

Quantity of particles in the swarm: 50

The starting range of the first variable: [1, 50]

The starting range of the second variable: [1, 20]

The starting range of the third variable: [0.1, 1]

The acceleration factors: Social rate C_1=1.5, Cognitive rate C_2=1.8; Over time, the inertia weight ω decreases linearly from 0.95 to 0.2.

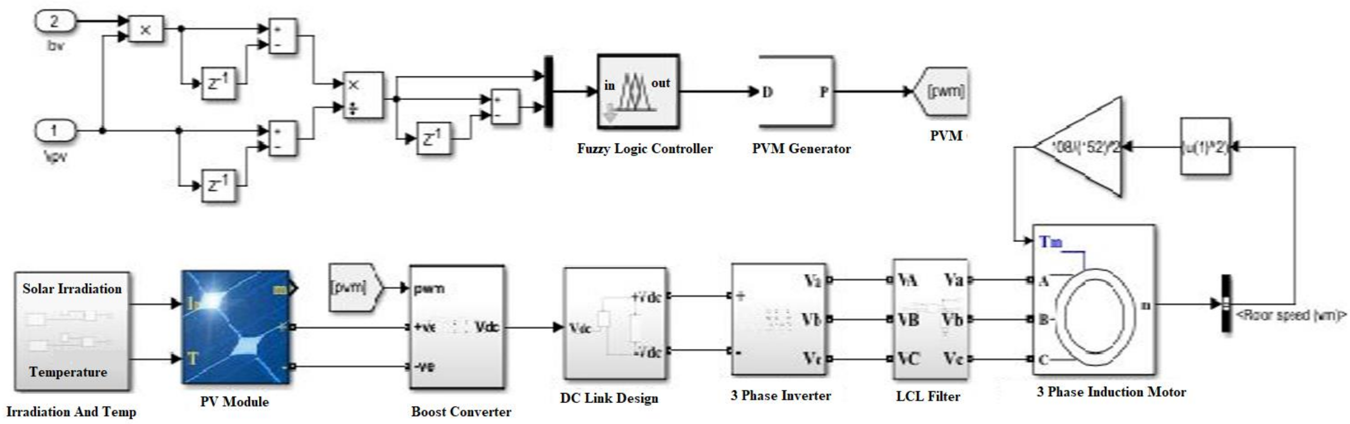

Figure 7. Designed model in MATLAB/Simulink

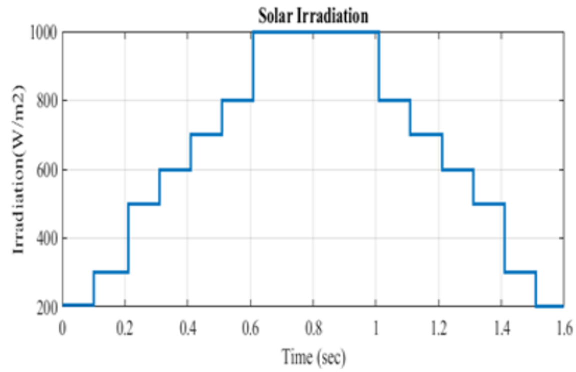

Figure 8. Daily trend of solar irradiation

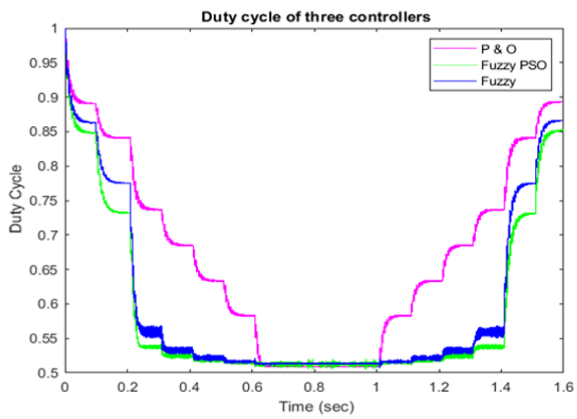

Figure 9. Duty cycle

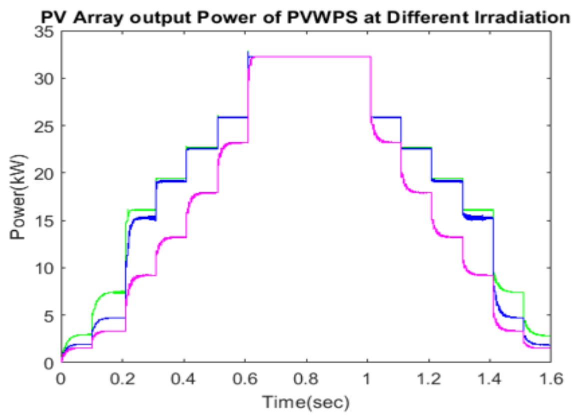

Figure 10. Daily trend of module output power

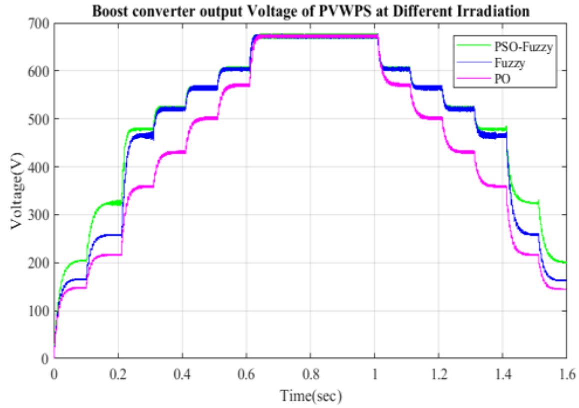

Figure 11. Daily trend of boost converter output voltage

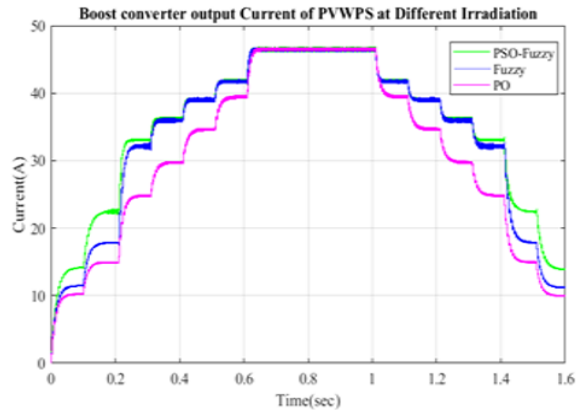

Figure 12. Daily trend of boost converter output current

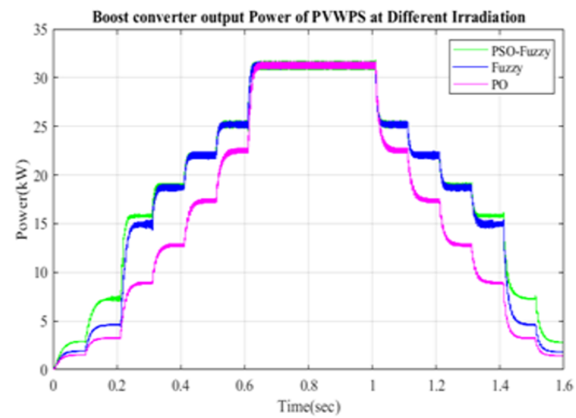

Figure 13. Daily trend of boost converter output power

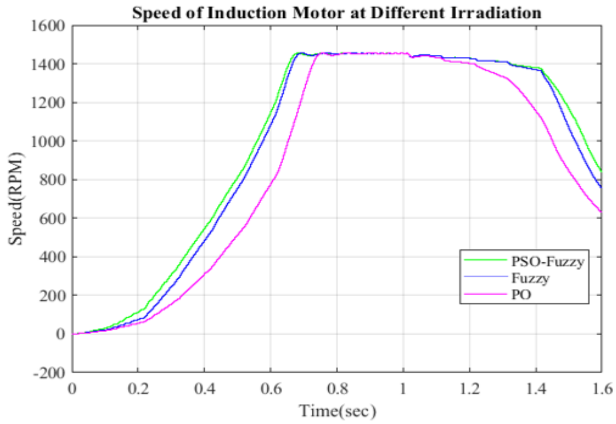

Figure 14. Rotor speed of induction motor

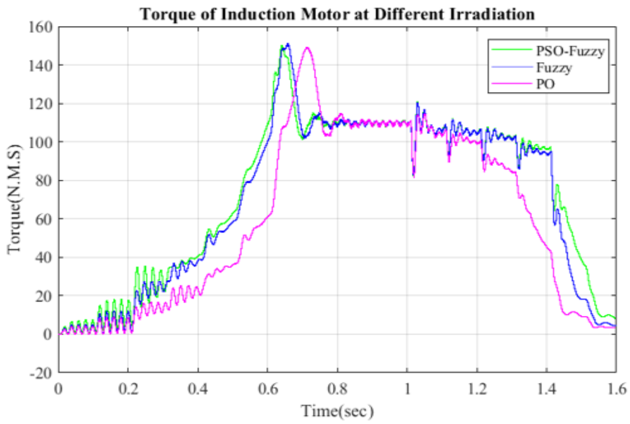

Figure 15. Electromagnetic torque of induction motor

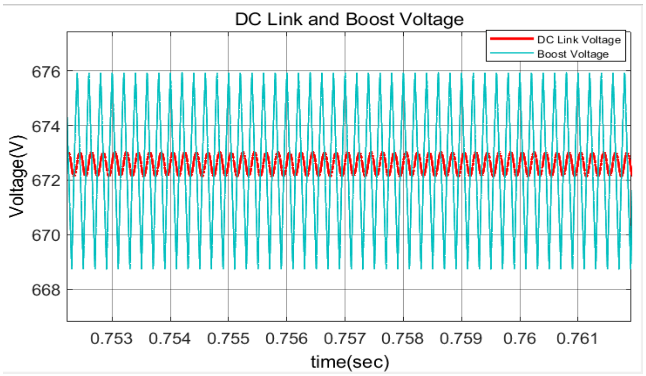

Figure 16. DC link and Boost converter voltage comparison

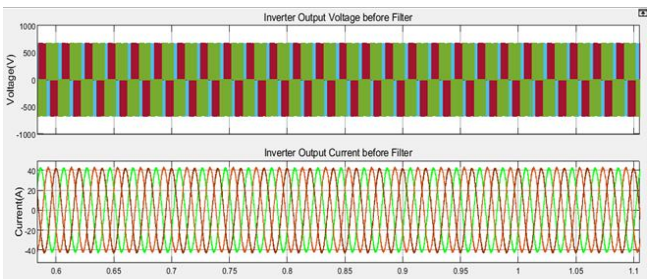

Figure 17. Output waveform of inverter voltage and current

Figure 16 presents the DC link and boost converter voltage comparison

Figure 17 shows the output waveform of inverter voltage and current, while Figure 18 presents the variations in the waveform of the induction motor's stator voltage and current output.

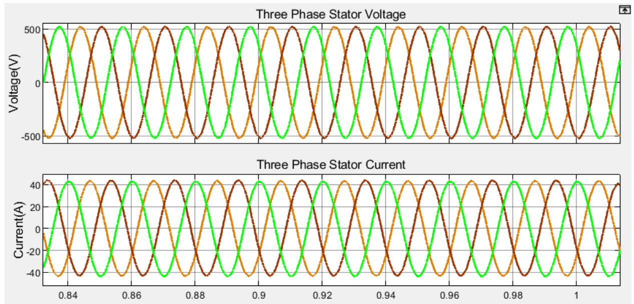

Figure 18. Waveform of the induction motor's stator voltage and current output

4. CONCLUSION

In this paper, particle swarm optimization (PSO) is utilized to optimize a fuzzy-based MPPT for a photovoltaic (PV) water pumping framework. A fuzzy logic control (FLC) power converter conspire was used in SIMULINK/MATLAB to design and simulate the MPPT of the PV framework. MPPT controllers come in three varieties: the conventional "perturb and observe" controller, as well as intelligent "Fuzzy" and "PSO-based Fuzzy controller were used." The PSO-based Fuzzy MPPT algorithm has good MPPT efficiency and a high convergence speed compared to P&O and fuzzy. According to the simulation results, the simulated photovoltaic water pumping application has high efficiency levels of a normal fuzzy logic, a PSO-based fuzzy controller, and the perturb and observe technique are 95.65%, 96.5%, 84.99%, respectively. To support the findings that the suggested MPPT method can raise the PV water pumping system's overall efficiency to a considerable degree, another option would be to employ a hybrid PSO-based genetic algorithm in the future to accelerate convergence and enhance the global optimum finding capability. To achieve this, we aim to use the cost-effective Arduino platform for integrating the PSO-based fuzzy controller. It should be noted that implementing fuzzy control on microcontrollers is both convenient for users and comes with several benefits.

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