PI-like fuzzy based synchronous SEPIC converter control for PV-fed small scale irrigation DC pump

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Abstract: For off-grid, standalone solar-fed water pumping has become a very viable option for small householder farmers. Appropriate configuration and control to suit this specific application are required. Buck, boost, and buck-boost converters are used to ensure impedance adaption between the solar PV generation and the load. However, these converters have switching harmonic problems. This problem is solved by the use of a single-ended primary inductor converter. Thus, a single-ended primary inductor converter is designed to overcome these drawbacks. Therefore, the objective of this paper is to design a single-ended primary inductive converter with a PI-like fuzzy controller. In this paper, synchronous SEPIC converter with PI-like fuzzy controller for PV-fed pumping system is modeled and designed. The system performance at different input conditions is evaluated. PI and PI-like fuzzy controllers have been compared using MATLAB/SIMULINK. PI-type fuzzy controller is less sensitive to input parameters variation than PI due to auto-tuning capability. Less than 2% output variation is recorded between 200 and 1000 W/m² irradiance. This show that output voltage is less sensitive to the input solar radiation with this SEPIC converter control. The steady-state result obtained in speed and flow rate were 141.4 rpm and 1.56 l/s, respectively, and the voltage error was 1.4 V. Thus, PI-like fuzzy controller was used to reduce the steady-state error. The results obtained with

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PUBLIC INTEREST STATEMENT
There has been growing interest in standalone solar-fed water pumping for small householder farmers due to easy to use, less cost. Fuzzy logic-based PI-like fuzzy Synchronous SEPIC converter control system is one of the intelligent methods of speed and flow rate control system that aims at constant speed and flow rate. Effectiveness of fuzzy logic controller depends on the set of linguistic variables and values. These should be considered to obtain optimal results in terms of maintaining speed and flow rate. PI-like fuzzy approach is used due to its ability to maintain speed and flow rate with minimum voltage error and is less sensitive to input parameters. In Ethiopia, most of the populations use petroleum-powered pumps with high running cost and low performance. Thus, solar-fed water pumping has become very viable option for small householder farmers with PI-like fuzzy synchronous SEPIC converter control system to improve pumping system performance.
PI-like fuzzy controller in speed and flow rate were 143.6 rpm and 1.624 l/s at 6 m head, respectively. The voltage error is 0.2 V which is less than the PI converter error (1.4 V).

**Subjects:** Power & Energy; Design; Electrical & Electronic Engineering

**Keywords:** PI-like fuzzy; Synchronous SEPIC; PV feed small scale irrigation

1. Introduction

Eco-friendly irrigation powered by photovoltaic systems can make a difference for millions of farmers in Africa. Ninety percent of the farmers in Africa currently depend on rainfall to cultivate their crops. Time intensive and inefficient manual irrigation systems, expensive and polluting petroleum-powered pumps, and cleaner and relatively cheap to run solar pump systems are among the possible options for farmers to adapt to changing patterns due to climate change (Belay et al., 2017; Sharp, 2016). For domestic and irrigation applications in developing countries, photovoltaic-based water pumping systems are used to draw water from the source. It is a cost-effective method than wind turbine for remote area applications (Allouhi et al., 2019).

For off-grid or limited access to central electric grid areas and high diesel cost, which affects the requirement of water, standalone photovoltaic water pumping systems have become a very competitive solution for small-scale irrigation applications (Shebani & Iqbal, 2017; Mohammed Wazed et al., 2018). Hence, photovoltaic has a less environmental impact and low running cost.

In Ethiopia, solar PV-fed water supply and irrigation systems are gaining interest than other forms of renewable energy resources due to the available resource and significant reduction in investment cost. Therefore, an efficient and cost-effective design of photovoltaic-powered pumps for small householders farmers is required.

In the study by Senpagapandi et al. (2017), performance analysis of a DC photovoltaic water pumping system with direct connection and DC-DC converter has been performed. The study results showed that the DC-DC converter coupled system has better performance than a direct connection for their ability to be matched to the output of the solar panel.

In the study by Shebani and Iqbal (2017), dynamic modeling of a solar PV water pumping system with permanent magnet DC motor (PMDC) was presented in MATLAB/SIMULINK environment. Fractional open-circuit voltage (FOVC) based maximum power point tracking (MPPT) was done with and without a storage device. The result obtained shown that system efficiency improvement was achieved when the PMDC motor runs at a specific speed rather than at a PV peak.

In the study of Sado and Hassan (2018), generalized method of PV-powered water pump using PMDC was developed. The result obtained from the simulation shown that the PMDC pumping system was economical, efficient, and has better discharge than the AC pumping system. For PV pumping applications, the PMDC motor was preferred among other types because it can provide high starting torque.

Various types of DC/DC converters, such as buck, boost, and buck-boost converters, are used to ensure impedance adaption between the solar PV generation and the load. A single-ended primary inductor converter (SEPIC) is another DC/DC converter designed to overcome the drawback of the above converters. It is positively regulated, has wide operation ranges and has better efficiency (Khather & Ibrahim, 2020; Vaigundamoorthi et al., 2020). Moreover, synchronous SEPIC converters are DC-DC converter that can maintain a constant output voltage under varying input conditions such as voltage reduction as hard shade is applied and load condition. Solar radiation and ambient
temperature are factors that affect the efficiency of PV-powered pumping systems. The DC power required to fuel the DC water pump generated by the PV module is linearly dependent on the radiation (Tiwari & Kalamkar, 2018).

In the studies by Salilah et al. (2020) and Motahhir et al. (2018), effects of solar radiation and ambient temperature on the performance of a PV pumping system have been demonstrated. The results of this paper have shown that the increase in temperature yields a significant decrease in pump flow rate. The simulation result obtained from the same work indicated that the increase in solar radiation yields a better pump flow rate at a constant temperature. This shows that the variation in ambient temperature and radiation results in a variation in the flow rate.

The fuzzy logic controller has now become feasible for power converters like SEPIC due to the recent advancement of microcontrollers. Complexity, nonlinearity, and/or impreciseness make SEPIC converters difficult to model. SEPIC converters have a time-varying structure and consist of parasitic elements. A fuzzy controller is best suited for such kinds of problems. Despite its advantages, there is no defined procedure or trial and error in designing and underdetermined performance until the design is finished, which are the problems with the fuzzy controller. This control technique relies on the human capacity to understand the system’s behavior which determines how effective linguistic rules of the Fuzzy Controllers are and is based on qualitative control rules (Perry et al., 2007).

There are different PI converter controller-related studies in which PI converter controller has been used for constants speed and flow. In this study, PI-like fuzzy converter controller system has been used for constant speed and flow rate. The existing literature review explored that many researchers used different methods to maintain constant speed and flow rate. This study contributes to the existing literature by proposing PI-like fuzzy synchronous SEPIC converter control system that maintains a constant flow rate and speed with less sensitive to input parameters variation and minimum steady state error.

In this study, a synchronous SEPIC converter is designed and simulated using MATLAB/SIMULINK environment for solar-powered pumps of small-scale farmers. The speed and flow rate performance at different input conditions with a PI-like Fuzzy controller is evaluated. The synchronous converters are now becoming favorable than other types due to their reduced voltage ripple, current ripple, better efficiency, and elimination of the use of MPPT techniques (Meligy et al., 2020; Murdianto et al., 2019; Hussein et al., 2020). Therefore, it is necessary to design the SEPIC converter to work at its maximum yield of the pump at variable input conditions.

1.1. Materials and methods
This study aims to model and design of the PI-like fuzzy controller to improve the flow rate and speed with minimum voltage error. The method adopted in this paper to study the model and design PI-like fuzzy controller is a survey of relevant literature, modeling of arrays, SEPIC converter, DC motor and centrifugal pump, design of SEPIC converter for the specific pump motor, design of the PI-like fuzzy controller for constant output voltage of the converter, simulation of conventional PI and PI-like fuzzy controller for the overall systems using MATLAB/SIMULINK. The results of the controller are discussed and conclusions are drawn from Figure 1.

2. Photovoltaic array model and design
A photovoltaic array is made up of combined series/parallel modules, which are composed of usually series PV cells. A photovoltaic cell is a PN junction semiconductor that absorbs light and converts it into electrical energy in the form of DC with a photovoltaic effect (Premkumar et al., 2020; Zou et al., 2020).
The operating of a solar cell can be represented by the equivalent circuit model which consists of a current source diode, parallel resistor expressing leakage current, and series resistor describing an internal resistance (Figure 2).

The photovoltaic panel is composed of cells placed in parallel Np or series Ns. It is modeled by a current source connected with a parallel diode with shunt and series resistors.

The output current, $I$ is given by (Mahmoud & Xiao, 2018)

$$I = I_{ph} - I_D - I_{sh}1$$

Where: $I_{ph}$—photo current

$I_D$—diode current
Module shunt saturation current, $I_{sh}$, is given by (Gul et al., 2019)

$$I_{sh} = \frac{V + N_p + \beta}{R_{sh}}$$

To find saturation dark current, $I_D$, it is important to define module reverse saturation current as (Meyer, 2017)

$$I_{rs} = \frac{I_{sc}}{\exp \left( \frac{qV_{oc}}{nkT} \right) - 1}$$

Where: $q$—electron charge = $1.6 \times 10^{-19}$ C

$V_{oc}$—open circuit voltage

$n$—Ideality factor of the diode

$k$—Boltzmann’s constant = $1.3805 \times 10^{-23}$ J/K

Then saturation dark current, $I_D$ is given by (Meyer, 2017)

$$I_D = I_{rs} \left[ \frac{T}{T_r} \right]^3 \exp \left[ \frac{qE_g}{nkT} \right] \left[ \frac{1}{T} - \frac{1}{T_r} \right]$$

Where: $T_r$—nominal temperature = 298.5 K

$E_g$—band gap energy of semiconduction = 1.1 eV

Finally, the output current $I$ is detailed as (Gul et al., 2019)

$$I = N_p \cdot I_{ph} - N_p I_{D} \left[ \exp \left( \frac{V + R}{N_p V_T} \right) - 1 \right] - I_{sh}$$

But thermal voltage $V_t$ is
Typically, $R_{sh}$ is very large and $R_s$ is very small. It is common to neglect these resistances to simplify the model. The simplified voltage, current characteristics of photovoltaic cell is given by

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{qV}{nRT} \right) - 1 \right]$$

The typical output power characteristics of a PV array under various degrees of irradiation and temperature are illustrated in Figure 3. It is demonstrated that a particular optimal voltage for each radiation and temperature corresponds to the maximization of power output. Therefore, the output power from the array can be drawn by adjusting the output voltage or current.

For photovoltaic panel and array configuration, it is important to determine the solar panel rating. For this design, a 370WDC pump that can deliver up to 6500 l/h at 6 m head is selected. Assume the operating hours of the pump is 4 h/day. The Wh per day will be 1480 Wh/day.

### Table 1. Parameters of the COPEX M250 module 25°C and 1000 W/m²

| Parameter                        | M250 module |
|----------------------------------|-------------|
| Nominal max power ($P_{max}$)    | 250 W       |
| MPP voltage ($V_{MPP}$)          | 30.7 V      |
| MPP current ($I_{MPP}$)          | 8.14 A      |
| Short circuit current ($I_{sc}$) | 8.96 A      |
| Open circuit voltage ($V_{oc}$)  | 37.4 V      |
| Temperature coefficient ($I_{sc}$) | $-0.06^\circ C$ |
| Temperature coefficient ($V_{oc}$) | $-0.35^\circ C$ |
| Number of cells in series       | 60 = 6 * 10 (series) |
| Series resistance ($R_s$)        | 0.08 Ω      |
| Parallel resistance ($R_{sh}$)   | 194.55 Ω    |
| Diode ideality factor           | 1.3         |
Considering the clearance and 7 hours peak sun hour in Ethiopia, commercially available 250 W solar panel is selected (Table 1).

2.1. Synchronous SEPIC converter design and operation
A SEPIC converter consisting of a switch $S$, a diode, two inductors $L_1$ and $L_2$, two capacitors $C_1$ and $C_2$, and motor load are presented in Figure 4.

To create continuous conduction mode and remove the inverse voltage, the diode (D) swiped by the switch $Q_2$ (Figure 5). The term synchronization comes from synchronizing the pulse of the MOSFET/IGBT switch. The two switches $Q_1$ and $Q_2$ are controlled by two complementary PWM signals (Nagarajan et al., 2017).

In continuous conduction of SEPIC converter, there are two modes of operations that $Q_1$ is ON, $Q_2$ is OFF and $Q_1$ is OFF, $Q_2$ is ON.

Operation mode 1: When $Q_1$ is ON and $Q_2$ is OFF, the current flows through $L_1$ and therefore $L_1$ and $L_2$ are charging whereas $C_1$ is discharged.

Operation mode 2: When $Q_1$ is OFF and $Q_2$ is ON, the inductors $L_1$ and $L_2$ discharges and the capacitor $C_1$ discharges.

2.1.1. Design process of Synchronous SEPIC converter
For continuous conduction mode (CCM) of a SEPIC converter duty cycle (Iii & Issn, 2016; Leema Rose & Sankaragomathi, 2016) is given by

$$ D = \frac{V_o}{V_{os} + V_{PV}} \quad D - dutycyle9 $$

The output voltage $V_{os}$, of the Synchronous SEPIC converter considering the input voltage $V_{PV}$ from the solar PV output is given by
The input current from the SEPIC converter, $I_{in}$, is calculated as

$$V_{os}I_{os} = V_{PV} - I_{in}$$  \hspace{1cm} 11$$

Where: $I_{os}$—output current

$I_{in}$—Input current

One of the initial steps in designing any PWM switching controller is to decide how much inductor ripple current, $\Delta I_L$, to permit. The switching frequency, $f_{sw}$, is selected to keep ripple current low and to reduce inductor size. A general rule is to use $20–40\%$ of the input current, the ripple current is given by $\Delta I_L = 30\%I_{in}$ (Ili & Issn, 2016; Leema Rose & Sankaragomathi, 2016).

Permitting the peak-to-peak ripple current to be roughly $30\%$ of the maximum input current at the minimum input voltage determines the inductance. The ripple current flowing at equal values of the inductors $L_1$ and $L_2$ are given by (Ili & Issn, 2016)

$$L_1 = L_2 = \frac{V_{PVmin} * D_{max}}{2 + \Delta I_L * f_{sw}}$$  \hspace{1cm} 12$$

The output current of the SEPIC converter is given by

$$I_{out} = \frac{V_{PV} * I_{in}}{V_{os}}$$  \hspace{1cm} 13$$

Synchronous SEPIC AC coupling capacitor is selected using

$$C_1(\text{min}) = \frac{I_{out} * D}{\Delta V_{C1} * f_s}$$  \hspace{1cm} 14$$

And the capacitor $C_2$ is calculated by

$$C_2 = \frac{I_{out} * D}{\Delta V_{\text{ripple}} * f_{sw}}$$  \hspace{1cm} 15$$

Where

$$\Delta V_{\text{ripple}} = 2\% * V_{os}$$  \hspace{1cm} 16$$

The selection of SEPIC capacitor, $C_1$ depends on the PMS currents which is given by

$$I_{corms} = I_{out} \sqrt{\frac{V_{os}}{V_{PVmin}}}$$  \hspace{1cm} 17$$

The SEPIC capacitor must be rated for a large PMS current. The voltage rating of the SEPIC capacitor must be greater than max input voltages. The peak-to-peak ripple voltage on $C_s$

$$\Delta V_{Cs} = \frac{I_{out} * D_{max}}{C_s * f_{sw}}$$  \hspace{1cm} 18$$
2.2. Permanent magnet (PMDC) motor model
In this motor, the permanent magnet is used as field winding so the motor does not require external excitation. The equivalent circuit of a PMDC motor (Shebani & Iqbal, 2017; Humaidi & Ibraheem, 2019; Senthil Kumar et al., 2018) (Figure 6)

The supply voltage ($V_s$) (Senthil Kumar et al., 2018) can be written as

\[ V_s = I_a R_a + L_a \frac{dI_a}{dt} + k_m \omega_m \]  \tag{19}

Where: $V_s$ is DC source voltage (V)

$I_a$—the armature current (A)

$R_a$—armature resistance (Ω)

$L_a$—armature inductance (H)

$k_m$—torque constant (vΩ/s/rad)

$\omega_m$—motor speed (rpm)

Electrical torque $T_e$ (Nm) is given by

\[ T_e = k_m I_a \]  \tag{20}

The motor speed as a function of the electrical torque and load torque $T_l$ (Nm) is given by

\[ J \frac{d\omega_m}{dt} = T_e - T_l - B_m \omega_m \]  \tag{21}

Where: $J$—inertia constant (kg·m²)

$B_m$—Constant (N·m·s)

Rearranging all the above equations, the dynamic model of a PMDC motor can be described as

\[ \frac{dI_a}{dt} = \frac{1}{L_a} (V_s - I_a R_a - k_m \omega_m) \]  \tag{22}
\[ \frac{d\omega_m}{dt} = \frac{1}{J} (Te - Tl - Bm \cdot \omega_m) \]

The parameters for the PMDC are presented in Table 2.

### 2.3. Water pump model

A centrifugal pump load is expressed by using the following equation which indicates the load torque (Shebani & Iqbal, 2017; Senthil Kumar et al., 2018; Al-obaidi, 2020; Al-Obaidi, 2020)

\[ T = 4.8 \times 10^{-6} \cdot \omega^2 + 0.00019 \cdot \omega + 0.09224 \]

The flow rate according to Senpagapandi et al. (2017) and Al-Obaidi (2020) can be given by

\[ Q = \frac{\eta \cdot P}{\rho \cdot g \cdot H} \]

Where: 
- \(P\)—input power required (W)
- \(\rho\)—fluid density (kg/m³)
- \(H\)—total head
- \(g\)—gravitational acceleration (9.8 m/s²)
- \(Q\)—flow rate (m³/s)
- \(\eta\)—efficiency of the pump

### 2.4. PI-like fuzzy controller SEPIC model

Fuzzy logic control is one of the emerging intelligent methods that has been developed and used for controller design in order to replace the conventional controllers. It also provides the accuracy of a dynamic model of the system to be controlled. It is based on linguistic variables and rules rather than numerical values and complex equations. FLC is used where an exact mathematical formulation of the problem is difficult due to non-linear time-varying nature of response, large unpredictable disturbance, etc. (Yousefi et al., 2018).

The voltage error (\(e_{\omega}\)) and the change in voltage error (\(\Delta e_{\omega}\)) from the SEPIC to the PMDC motor are the inputs of PI-like fuzzy logic controller (El Khateb et al., 2014). The output of the PI-like fuzzy controller is the duty cycle (D) of the PWM signal, which regulates the output voltage of the

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**Table 2. Parameters of PMDC**

| Parameter                          | Value        |
|------------------------------------|--------------|
| Armature voltage \((V_s)\)         | 105 V        |
| Armature current \((I_a)\)         | 5.2 A        |
| Armature resistance \((R_a)\)      | 20 Ω         |
| Armature inductance \((L_a)\)      | 1.06 mH      |
| Moment of inertia \((J)\)          | 1.06 \times 10^{-6} kg \cdot m² |
| Viscous friction coefficient \((Bm)\) | 3.79 \times 10^{-3} M \cdot m \cdot s/rad |
| Constant \(k_m\)                   | 0.52         |
synchronous SEPIC converter. The Synchronous pulse from FLC output is also fed to the synchronous converter.

The first input is the error in voltage ($e_o$)

$$e_o(k) = \omega_{ref} - \omega_o(k)$$

The second input is the change in error ($\Delta e_o$)

$$\Delta e_o(k) = e_o(k) - e_o(k - 1)$$

The output variable is the duty cycle (D)

Where: $\omega_{ref}$—reference Voltage

$\omega_o(k)$—measured voltage in the $k^{th}$ sample

$D(k)$—duty cycle sent to the PWM

$\Delta e_o$—Change in voltage error

$e_o$—Voltage error

The block diagram of control model is shown in Figure 7.

For simplicity triangular membership function are used (Azam et al., 2020). A five-term fuzzy set (BN—Big Negative, SN—Small Negative, ZO—Zero, SP—Small Positive, BP—Big Positive) are defined and selected for each input.

The fuzzy output $u(k)$ changes the pulse duties which determine the motor speed and the flow rate of the pump by controlling the output voltage of the synchronous SEPIC converter. Therefore, stable speed and flow rate will be maintained in the case of variable solar inputs, such as irradiation and temperature.

The structure of the proposed PI-like fuzzy knowledge-based controller consists of normalization, fuzzification, membership function definition, rule base, defuzzification, and denormalization. All the functions are defined on a normalized interval $[-1, 1]$ (Azam et al., 2020; Oudda & Hazzab, 2016a; Oudda & Hazzab, 2016b).

PI-like FLC consists of the following rules of the term (El Khateb et al., 2014)
If $\omega_e$ is <This> and $\Delta \omega_e$ is <This> then $\Delta v$ is The fuzzy rule base to control the duty cycle is composed of 25 rules (Table 3).

### 3. Simulation result

The simulation results of this study are based on the following parameters (Table 4). Those designed and determined parameters are used to test the performance of PI and PI-fuzzy controller models in MATLAB/SIMULINK environment.

MATLAB/SIMULINK is used to model of PI controller for Synchronous SEPIC converter. The model (Figure 8) represents a model of the PI controller. The DC source with inductors, capacitors and MOSFETs are used to represent the source and PI controller, respectively.

**Table 3. Fuzzy rules**

| Voltage error $\omega_e$ | Change in voltage error $\omega \Delta e$ |
|--------------------------|------------------------------------------|
|                          | BN  | SN  | Zo  | SP  | BP  |
| BN                       | BP  | BP  | BP  | SP  | ZO  |
| SN                       | BP  | BP  | SP  | ZO  | BN  |
| Zo                       | BP  | SN  | SP  | ZO  | BP  |
| SP                       | SN  | ZO  | SP  | BP  | BP  |
| BP                       | ZO  | SP  | BP  | BP  | BP  |

**Table 4. Simulation parameters**

| No. | Parameters          | Values  | Remarks                  |
|-----|---------------------|---------|--------------------------|
| 1   | Input voltage       | 30.7 V  | Design input parameters  |
| 2   | Output voltage      | 103 V   |                          |
| 3   | Output current      | 5.2 A   |                          |
| 4   | Switching frequency | 20 kHz  |                          |
| 5   | Inductor, $L_1$     | 10.8 µH | Determined variables    |
| 6   | Inductor, $L_2$     | 10.8µH  |                          |
| 7   | Coupling Capacitor, $C_1$ | 205 µF |                          |
| 8   | Output Capacitor, $C_2$ | 100µF |                          |
| 9   | Duty cycle, $D$     | 0.77    |                          |

*Figure 8. MATLAB/SIMULINK model of PI controller for Synchronous SEPIC converter.*
The output voltage of the SEPIC converter by using the PI feedback controller is 103.2 V (Figure 9). The PI controller has 1.4 V steady-state error with a ripple. The ripple can be adjusted by using the appropriate value of inductors and capacitors.
The steady-state simulation result obtained in speed is 141.4 rpm (Figure 10). Due to 1.4 V error in voltage output of the SEpic converter, it is difficult to find the P and I values from the precise tuning of the PI controller. Therefore, in this paper, PI-like fuzzy controller is preferred to reduce the steady-state error.

The simulation result obtained for the flow rate is 1.56 l/s (Figure 11). Due to a large error in voltage output of the SEpic converter, the flow rate is less than that of PI-like fuzzy controller. Thus, in this paper, PI-like fuzzy controller is preferred to increase the flow rate.

MATLAB/SIMULINK is used to model PI-like converter to reduce the steady-state error (Figure 12). The model represents solar PV input, fuzzy controller, converter, and model of motor and pump as subsystem (Figure 13). The motor and pump models are used as an input at “A” for the overall system model. Rules are formulated and loaded to control the system accordingly.

For PI-fuzzy controller, the flow rate from the simulation is 1.624 l/s (Figure 14). Due to less error in voltage output of the SEpic converter, the flow rate is increased in the case of PI-like fuzzy controller. This shows that PI-like fuzzy controller solves the drawbacks of the PI controller.
It has been tested with two different irradiances such as 200 and 800 W/m² at a fixed ambient temperature of 26.5°C. The result obtained demonstrated that the expected flow rate of 1.624 l/s at 6 m head and 143.6 rpm (Figure 15) has been achieved in both cases. The voltage error is 0.2 V.

### 3.1. Sensitivity analysis of SEPIC

Sensitivity analysis is the study of how a certain system responds to a variation of its inputs. It is an analysis method for systematically changing variables in a model to determine the effects of such changes to its output. Sensitivity analysis is used to evaluate a system output on small changes in the input. Solar radiation is the most important parameter in the sensitivity analysis of the SEPIC output. In this study, a sensitivity analysis is done for SEPIC converter control. As the solar radiation is

| Solar radiation as SEPIC converter input | 200 W/m² | 400 W/m² | 600 W/m² | 800 W/m² | 1000 W/m² |
|-----------------------------------------|---------:|---------:|---------:|---------:|---------:|
| SEPIC converter output (V)              | 103.2   | 103.9   | 103.9   | 104.2   | 104.7   |

Figure 14. The PI-like fuzzy simulation result of flow rate.

Figure 15. The PI-like fuzzy simulation result of the speed.

Table 5. Solar input for SEPIC converter
increased, there is a small change in SEPIC converter output (Table 5). The SEPIC converter output is less sensitive to solar radiation inputs which less than 2%.

Sensitivity of the system output $y$ to variations in the system input $x$ is defined as,

$$\text{Sensitivity} = \frac{dy}{dx}$$

$$\frac{dy}{dx} = \frac{\Delta \text{output}}{\text{max input}} = \frac{(104.7 - 103.2)}{104.7} = 0.014$$

$$\frac{dx}{dx} = \frac{\Delta \text{input}}{\text{max input}} = \frac{(1000 - 200)}{1000} = 0.8$$

Sensitivity SEPIC = $\frac{dy}{dx} \times 100 = \frac{0.014}{0.8} \times 100 = 1.75$

4. Conclusion
Synchronous SEPIC converter is designed and simulated for small-scale farmers. The speed and flow rate performance at different input conditions of PI-like Fuzzy controller is evaluated. Error in voltage, change in duty cycle were the major factors for PI-Fuzzy controller logic rule formulation. PI-fuzzy controller improves the speed of the system from 141.6 to 143.6 rpm. It also improves the flow rate from 1.575 to 1.624 l/s. In addition, PI-fuzzy controller reduces the error in voltage.

It is concluded that PI-like fuzzy controller steady-state error is much less that the PI controller. A fuzzy PI controller is presented, which can provide improved performance such as well-damped output voltage for synchronous SEPIC converters. PI-type fuzzy controller is less sensitive to input parameter variation due to auto-tuning capability.

Thus, with different input parameters constant flow rate and speed are achieved with minimum steady-state error. It is, therefore, important for the long life of the pump. It is also relatively easy to implement on the hardware platform. These features also make it suitable for high-voltage and high-power applications. The PI-like FLC is, however, known to give poor performance in starting response due to the internal integrating operation.

4.1. Limitations
The major concern of this study is the model and design of PI-like fuzzy synchronous SEPIC converter control without considering the effects of starting response of the PI-like FLC. Improving the starting response of the PI-like FLC is suggested.

| Abbreviations       | Description                                      |
|---------------------|--------------------------------------------------|
| DC:                 | Direct current                                   |
| AC:                 | Alternative current                              |
| W:                  | Watt                                             |
| Wh:                 | Watt hour                                        |
| PV:                 | Photovoltaic                                     |
| SEPIC:              | Single ended primary inductor converter          |
| FOVC:               | Fractional open circuit voltage                  |
| PMDC:               | Permanent magnet DC                              |
| MPPT:               | Maximum power point tracking                     |
| PI:                 | Proportional integral                            |
| V:                  | Volt                                             |

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**Availability of data and materials**

All data generated or analyzed during this study are included in this published article.

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