Real-Time Control of Solar PV System by Adaptive Extremum Seeking Technique

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***Abstract*— Solar energy is considered a long-term cost-effective alternative source of energy. It can be found in many households, most especially as the cost of environmentally unfriendly fossil fuels continues to rise. Unfortunately, the inability of photovoltaic (PV) panels to generate sufficient power at all times due to inadequate irradiance tracking and changes in temperature have become a significant setback to its utilization. An attempt to improve on this limitation has led to the development of the Maximum Power Point Tracking (MPPT) mechanism which seeks to balance the impedances in order to facilitate maximum power transfer between the cells and the load at different irradiative conditions. This study embarked on the analyses of the existing MPPT models and modified the Extremum Seeking Control (ESC) MPPT algorithm to achieve maximum power generation from the panels. With data obtained from the Nigerian Meteorological Department, the work analysed the performances of existing ESC and the artificial intelligence-based methods using Fuzzy Logic and Artificial Neural Networks (ANN) when connected to loads with lots of cycle limits. The results showed that the existing ESC had a power output of 200kW, the Fuzzy logic model had 249.4kW, and the ANN model delivered 269.6kW while the modified ESC MPPT provided a better power output of 290kW on the same PV and load ratings. It is therefore highly recommended for further studies and implementation.**

Keywords*— Extremum Seeking Control, Maximum Power Point Tracking, Photovoltaic Cells, PV impedance matching, PV power transfer algorithm.

I. INTRODUCTION

Renewable energy emanates from natural resources that can be replenished, such as rain, wind, tides, sunlight, biomass and geothermal heat. They are inexhaustible unlike the dwindling conventional crude oil and other fossil fuels. The use of solar energy to generate power is said to have started when a British astronomer John Herschel [1] used solar collector to cook in his expedition in Africa. With good design and production of solar photovoltaic cells, incident radiations are converted to electrical energy which is the most usable form of energy. Previous studies show that only about 30% to 40% of energy incident on the photovoltaic cells are converted to electric energy [2, 3]. Hence, a maximum power point tracking (MPPT) algorithm became necessary to maximize the efficiency of the conversion of energy incidence on the solar panel. Extremum seeking control (ESC) is a control technique for real time optimization of dynamic systems; it is a simple objective type of controller and is not usually deployed for multivariate objective functions. ESC controller usually seeks to enhance up to extreme an objective function (usually plants output) by adjusting the manipulated variables (plant inputs). Hence, ESC provides an ideal solution for various applications that needs its objective function to be maximized or minimized. ESC is proven to provide stable and accurate responses in control system applications [4]. Researchers and authors have reported on the utilization of conventional MPPT algorithm and their achieved improvements such as in [5] where MPPT algorithm contributed an increase of 8-10% in conversion of incidence energy to electrical energy. As the Clean Development Mechanisms (CDMs) [6] are being adopted by organizations all across the globe due not only to the rapidly decreasing reserves of fossil fuels which has seriously increased the cost, but mainly to environmental pollution associated with their combustion, against which renewable energy sources are known to be much cleaner and produce energy without the harmful effects of pollution [7]. More so, a lot of applications today require solar energy sources mostly in the rural areas of Nigeria, such as powering rural broadband solutions [8] and as backup power supply to public facilities [9-11] and since there is enough sunlight in Nigeria, this work is considered necessary. This study therefore seeks to improve on the extremum seeking controller's ability to track and leverage on solar energy harvesting variables to maximize the power output and ensure maximum amount of electricity conversion from solar energy that are incidence on the photovoltaic cell.

II. RESEARCH BACKGROUND

From the Maximum Power Transfer Theorem, the power output of a circuit is maximised when the Thevenin's impedance of the source circuit matches with the load impedance. Hence our problem of tracking the Maximum Power Point (MPP) reduces to an impedance matching problem [12]. Some techniques have been used to track the maximum power points in PVs; such as the incremental conductance method, the fractional open circuit voltage method, the perturb and observe or hill climbing method, the fractional short circuit current method as well as the Artificial Intelligence (AI) driven neural networks and fuzzy logic methods [13, 14], the choice which depends on factors such as the cost and ease of implementation as well as the time complexity the algorithm takes to track the MPP. Fig. 1 shows the chart for the classification of commonly used MPPT techniques in the PV system.

The incremental conductance method deploys two voltage and current sensors to sense the output voltage and current of the PV array and analytically represented by equation (1).

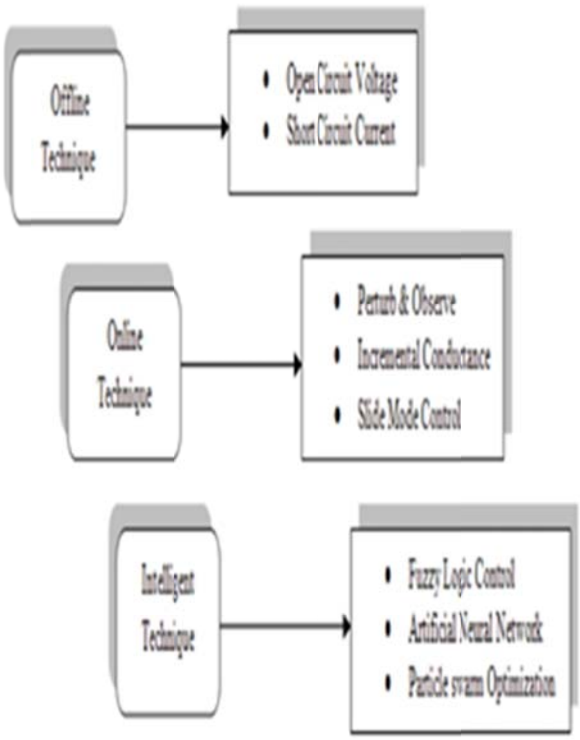

Fig. 1: Maximum power point tracking methods

At MPP the slope of the PV curve is said to be 0 [1][15].

$$\left(\frac{dP}{dV}\right)_{MPP} = \frac{d(VI)}{dV} \quad (1)$$

Where P is the power, V is the voltage and I is the current. The left hand side of equation 1 represent the instantaneous conductance of the solar panel, which when equals the conductance of the solar then MPP is reached, increasing on the left of the MPP and decreasing on the Right side of the MPP as shown in the basic equations of the method in Table 1 [1]. Dual sensing (voltage and current) makes this method very reliable.

Table 1: Basic incremental conductance models [1]

MODEL	MPP OUTCOME
$\frac{dP}{dV} = 0$	at MPP
$\frac{dP}{dV} > 0$	left of MPP
$\frac{dP}{dV} < 0$	right of MPP
$\frac{dP}{dV} = \left(\frac{d(VI)}{d(V)}\right) = I + V * \frac{dI}{dV}$	

The fractional open circuit voltage (FOCV) uses the difference in electrical potentials between two terminals of a device when disconnected from the circuit and in the absence of external load and current flow and is supported by the near linear relationship between V_{MPP} and V_{OC} of the PV array, under varying irradiance and temperature levels [1] as shown in equation 2.

$$V_{MPP} = kV_{OC} \quad (2)$$

Where k is a constant of proportionality, V_{MPP} is the maximum power point voltage and V_{OC} is the open circuit voltage. Since k is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} for the specific PV array at different irradiance and temperature levels. This method incurs some disadvantages, including temporary loss of power [15] which is why it is considered an offline method.

Perturb & Observe (P&O) is said to be the cheapest and simplest method as it uses only one sensor known as the voltage sensor to sense the PV array voltage. The time complexity of P&O algorithm is small although the perturbing does not stop at the MPP rather on getting closed continues on the both directions so the setup of an appropriate error limit or use of wait function is required, but this will also increase the time complexity of the algorithm. However this algorithm depends on perturbation and therefore cannot account for rapid changes of irradiation level and may result to calculating wrong MPP [17].

The fractional open circuit current (FOCC) is also an offline method where the PV is isolated at interval of time to measure the irradiance. They are very simple to deploy and easily converge to a MPP with good accuracy. To prevent the regular outages during measurements, additional sensors are usually deployed for measurement which then increases the complexity of the system [14]. Similar to the FOCV, fractional ISC results from the fact that, under varying atmospheric conditions, maximum power point current (IMPP) is approximately linearly related to the short circuit current (ISC) of the PV array [18] as stated in equation 3.

$$I_{MPP} = k_1 I_{SC} \quad (3)$$

The Fuzzy logic method takes decisions and control using fuzzy logic. The main components in fuzzy logic based MPPT controller are fuzzification, rule-base, inference and defuzzification as shown in Fig. 2.

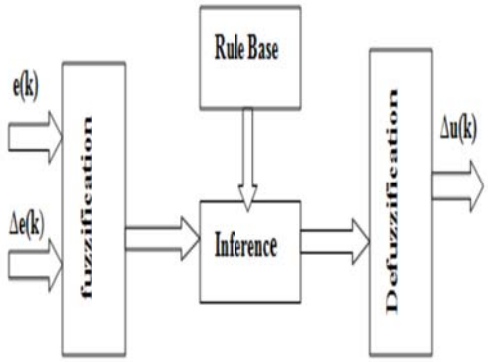

Fig. 2: Block Diagram of Fuzzy Logic [14]

The fuzzification block handles the conversion of the crisp inputs to fuzzy inputs. The rules are formed in the rule base and are applied in the inference block. The defuzzification reconverts the fuzzy output to the crisp output. The fuzzy inference is carried out by using Mamdani's method [19], and the defuzzification uses the centre of gravity to compute the output of this Fuzzy logic controller (FLC) with a change in the duty cycle.

Neural networks are fast and precise in decision making and can be deployed for the tracking and specification of the reference voltage of maximum power point under different atmospheric conditions. It draws inferences from the input variables like VOC and ISC, atmospheric data like irradiance and temperature, or any combination of these parameters. Using several reference signals such as the duty cycle signal, the power converter is driven to operate at the MPP [14, 17]. This work concentrates on the use of extremum seeking control (ESC) method that an ideal solution for many applications that require a certain objective to be maximized or minimized, such as maximization of output power or production or minimization of energy consumed or emissions produced by a system [7].

III. Methodology

A. Research Procedure

Sun irradiance data and atmospheric temperature of Uyo, Akwa Ibom State was obtained from the state's Meteorological Department in Uyo. The models for the photovoltaic cells were implemented in MatLab/Simulink and the power output, voltage output and current output obtained. ESC MPPT algorithm was implemented in the PVC model in SIMULINK with the outcome obtained and compared with the solar PVC system without ESC. Finally, the power output efficiency of the ESC utilized was compared with other MPPT algorithms to obtain the best MPPT algorithm control to be utilized in ensuring maximum power output. The flow diagram for the summary of the research procedure was shown in Fig. 3.

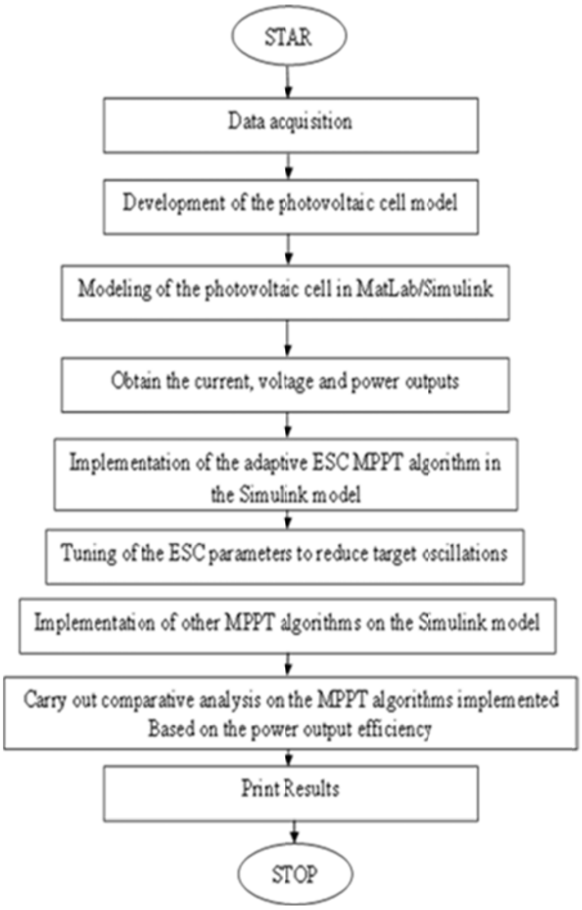

Fig. 3: Research Procedure Flow Chart

B. Photovoltaic cell modeling Units

The data used in the modeling of the PV cells were gotten from the meteorological unit and from solar panel specifications and is as presented in Table 2. It was assumed that series loss and leakages to ground were absent, current source were assumed constant at a fixed value of radiation and temperature and shunt resistance was used to represent shunt leakage current. The series resistance represented the voltage drop at the output, the PV power conversion efficiency was considered sensitive to changes in series resistance and insensitive to changes in the shunt resistance and the cell current to the external load is equal to the load current and cell voltage equals to the load voltage. Fig. 4 shows the circuit model of the PV cell.

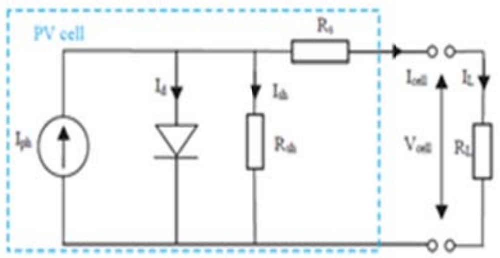

Fig. 4: Circuit Model of PV Cell

Table 2: Data Utilized for PV Modeling

DATA SPECIFICATION	VALUES
Irradiance at normal incidence	1000Wm^{2}
Cell temperature	25^{o}C
Solar Spectrum	1.52
Reference current	3.5A
Reference voltage	17.1V
Short circuit current temperature coefficient	3x10^{-3}mA/^{o}C
Open circuit current temperature coefficient	-73x10^{-3}mW/^{o}C
Series resistance	0.47ohm
Short circuit current	3.8A
Internal resistance	1ohm
Internal capacitance	1x10^{-2}F
Maximum power Voltage	17.3V
Maximum power current	7.23A
Maximum power rating	300kW
Maximum system voltage	600V

The Kirchhoff's current law for non-ideal PV cell was given as equation (4);

$$I_{cell} = I_{ph} - I_d - I_{sh} \quad (4)$$

Where I_{cell} is the current of the PV cell, I_{ph} is the current source, I_{sh} is the shunt current and I_d is the dissipated current.

Then the overall cell current I_{cell} is given in (5);

$$I_{cell} = I_r + \left[\alpha\left(\frac{G}{G_r0}\right)(T_c - T_{cr}) + \left(\frac{G}{G_r} - 1\right)I_{sc}\right] \quad (5)$$

Where T_c represents the module temperature, T_{cr} represents the reference temperature of the module, G_r represents the reference solar irradiance, G is the actual solar irradiance, I_{sc} is the short circuit current, α is the temperature coefficient at short circuit current and I_r is the reference current.

The change in current ΔI is given as;

$$\Delta I = I_{cell} - I_r = \left[\alpha\left(\frac{G}{G_r0}\right)(T_c - T_{cr}) + \left(\frac{G}{G_r} - 1\right)I_{sc}\right] \quad (6)$$

The cell voltage V_{cell} is given as;

$$V_{cell} = -\beta(T_c - T_{cr}) - R_s\Delta I + V_r \quad (7)$$

Where β represents the temperature coefficient of an open circuit voltage, R_s is the series resistance V_r is the reference voltage. Hence, the change in voltage is given as;

$$\Delta V = V_{cell} - V_r = -\beta(T_c - T_{cr}) - R_s\Delta I \quad (8)$$

The output voltage V_m and the output current I_m were given as;

$$V_m = N_{sc}V_{cell} \quad (9)$$

$$I_m = N_{pc}I_{cell} \quad (10)$$

Where N_{sc} is the number of panel connected in series and N_{pc} are the number of panels connected in parallel.

The power output P_m was given as;

$$P_m = V_m I_m \quad (11)$$

The voltage drop V_d in between the silicon layers of the PV cell was shown in equation 12.

$$V_g = \frac{V_m}{1+e^{\gamma(I_L - I_m)}} \quad (12)$$

Where V_m is the voltage output, I_m is the current output; I_L is the load current and γ is a constant parameter. The PV cell was implemented in Simulink

C. Extremum Seeking Control (ESC)

ESC MPPT was used to iteratively adjust the manipulated variable of the PV system to obtain the output at its optimum value. The ESC MPPT algorithm utilizes the injection of a minute dither signal $\sin(\omega_p t)$ with relatively high frequency for optimum input estimation. The dither signal causes the output to oscillate which is passed through a high pass filter and the output modulated by dither function to produce a gradient approximation. The existing ESC control system model is shown in equation 13.

$$y = f\left(\left(v + a\sin(\omega_p t)\right)\right) \quad (13)$$

Where a is the amplitude, ω_p is the frequency of the dither signal, y is the output of the high pass filter, ω_h is the cutoff frequency of the high pass filter, and k is the gradient updating gain.

The developed ESC MPPT is shown in equation 14.

$$y = f(u) = f(v + a\sin(w_p t)) \quad (14)$$

Where a is the amplitude of the dither signal, w_p is the frequency of the dither signal, w_h is the cut off frequency of the high pass filters, w_l, is the cutoff frequency of the low pass filter. K is the gradient update gain. This model was applied to the PV system to obtain the optimum power output. The outcome was compared to the PV system tuned with fuzzy logic and neural network systems. Fig. 5 shows the simulation of the existing ESC while Fig. 6 shows the modified design simulation.

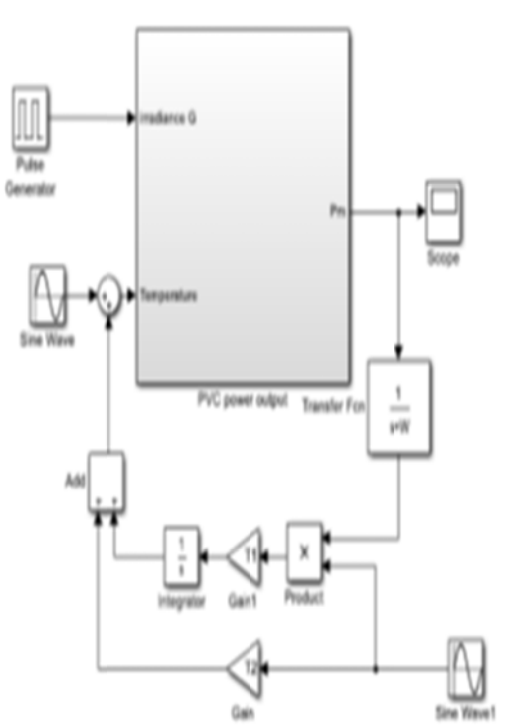

Fig. 5: Existing ESC MPPT Model

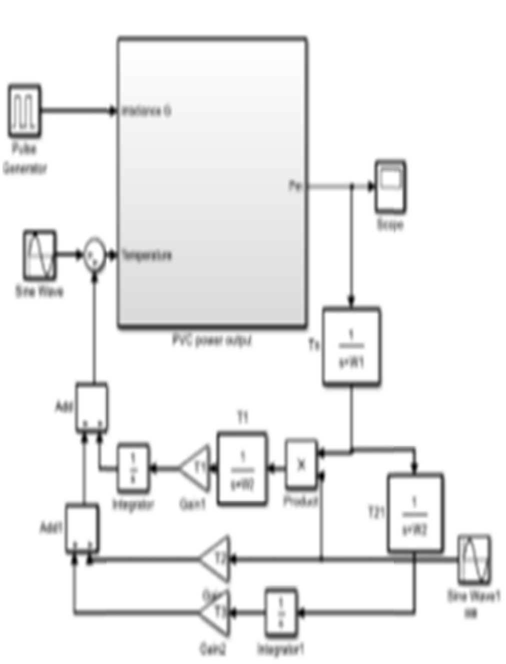

Fig. 6: Modified ESC MPPT Model

IV. RESULTS

From meteorological data, the temperature against the sunshine hours is shown in Fig. 7 with the highest temperature of 34^oC attained at sunshine hour of 2:00 p.m. and the sun irradiance was at its peak at 1:00 p.m. time (peak sunshine hour) as shown in Fig. 8.

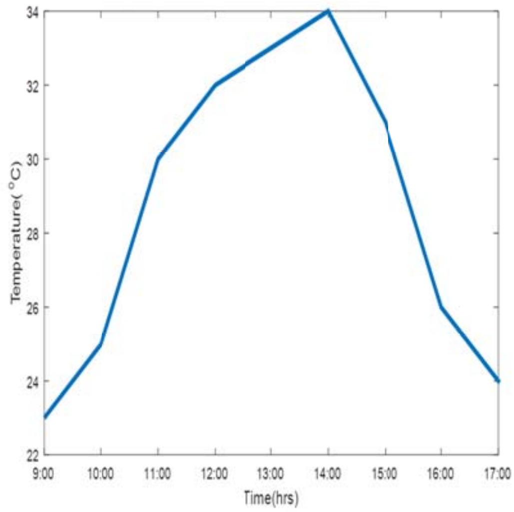

Fig. 7: Temperature against Time

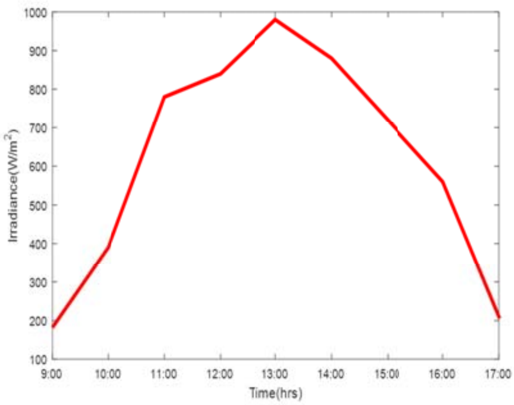

Fig. 8: Sun Irradiance against Time of the Day

A. *PV System Output with and without Load and without MPPT*

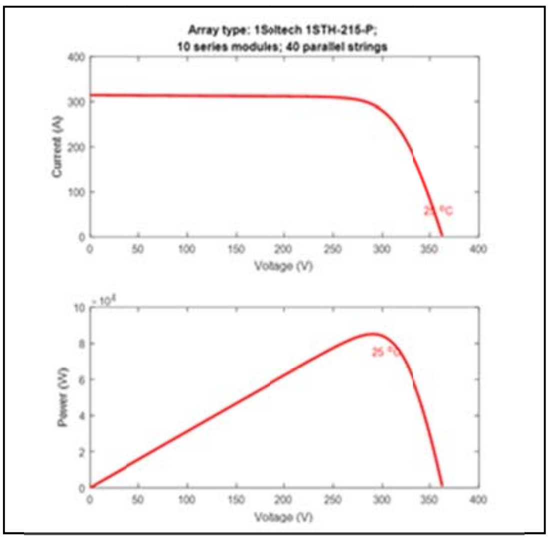

Fig. 9: Current and Power Output of PV Cell without Load and MPPT

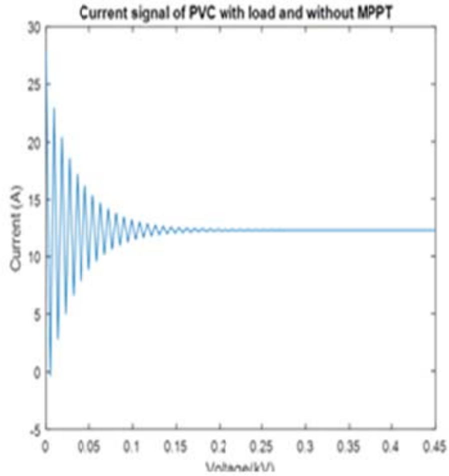

Fig. 10: PVC Current with Load and without MPPT.

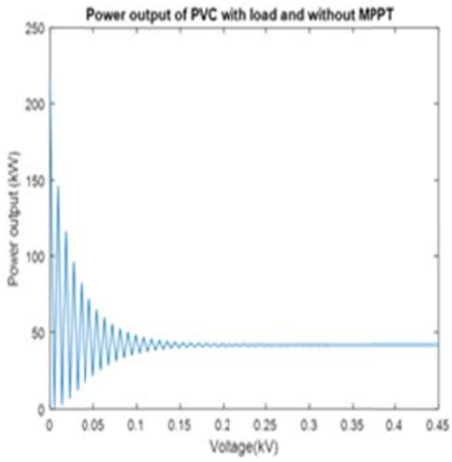

Fig. 11: PVC Power Output with Load and without MPPT.

The PV output without load and without MPPT is shown in Fig. 9. The cycle limit presence in the cell could constitute issues with the PVC system as shown in Fig. 10 and 11 with cycle sinusoidal as a result of disturbances at startup voltages were seen, this normalizes as voltage increases. Hence, voltage enhancement normalizes and reduces the limit cycle. Aside from improving the power generated, ESC aids in reduction of limit cycles.

B. *PV Outputs with and without Load when Deployed with Existing MPPT*

The current signal and power output of the PVC connected to a load with the existing extremum seeking control (ESC) MPPT is shown in Fig. 12 and Fig. 13 respectively. The maximum current obtained was 30 A and the power of 200 kW.

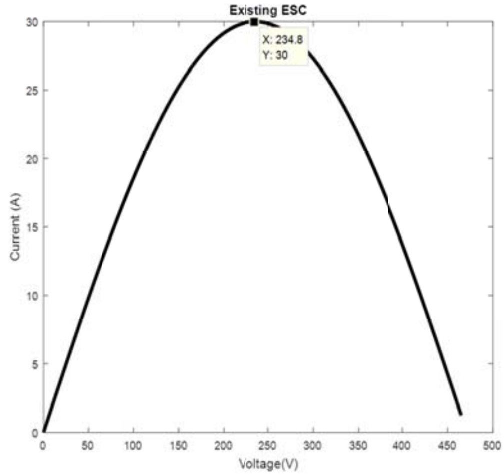

Fig. 12: PVC Current with ESC-MPPT when Connected to a Load

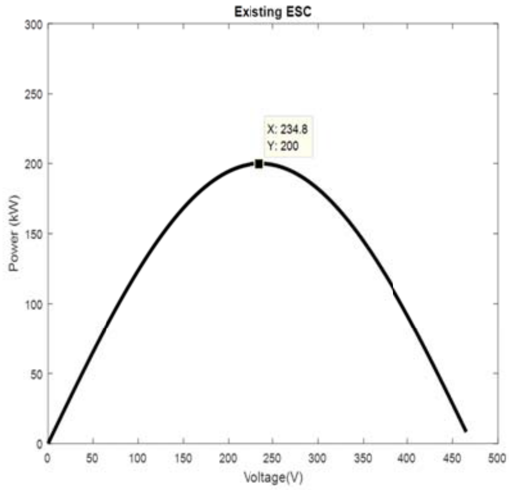

Fig. 13: PVC Power Output with ESC-MPPT when Connected to a Load

C. *Load connected PVC Outputs with artificial intelligent MPPT*

Using AI enabled MPPT techniques gave an improved outcome as shown in Fig. 14 and 15 with Fuzzy logic tracked MPPT and Artificial Neural Network (ANN) MPPT shown in Fig. 16 and 17.

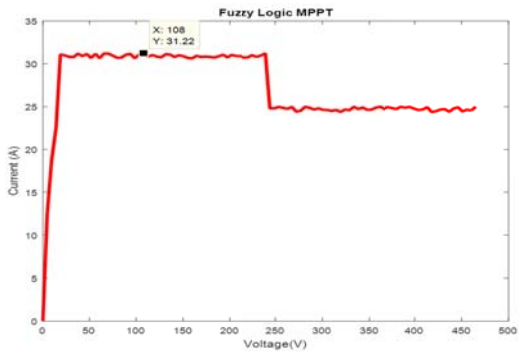

Fig. 14: Fuzzy Logic MPPT Current signal of Load Connected PVC

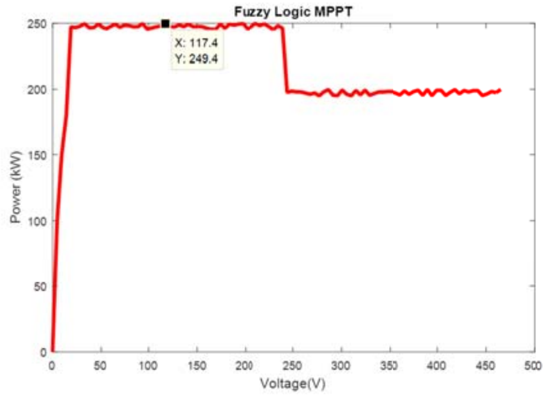

Fig. 15: Power Output with Fuzzy Logic MPPT of Load Connected PVC

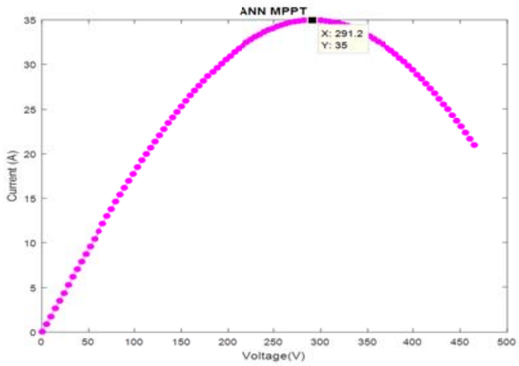

Fig. 16: ANN MPPT Current of Load Connected PVC

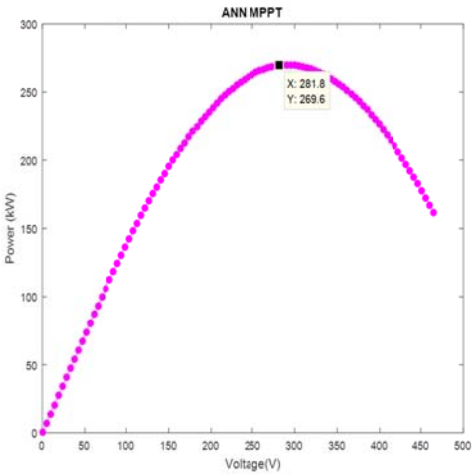

Fig. 17: Power Output with ANN MPPT of Load Connected PVC

D. Load Connected PVC Outputs with Modified ESC MPPT

The current signal and power output of the PVC connected to a load with the existing extremum seeking control (ESC) The existing ESC was modified to achieve better outputs as shown in Fig. 18 and Fig. 19. An output current of 40 A was possible with the power output improved to 290 kW.

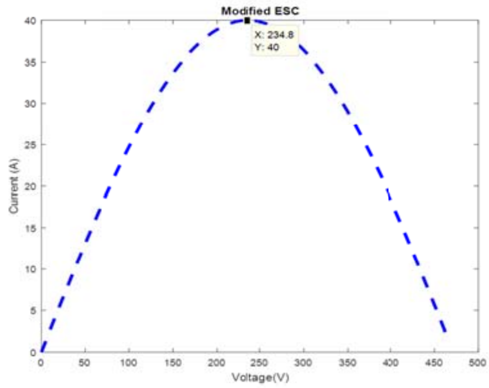

Fig. 18: Modified ESC MPPT of Load Connected PVC Current.

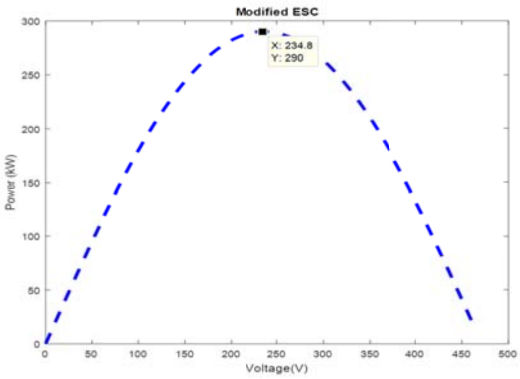

Fig. 19: Modified ESC MPPT of Load Connected PVC Power Output.

E. Load Connected PVC Outputs with Modified ESC MPPT

The maximum current signal and maximum power output obtained with the various MPPT are shown in Table 3.

Table 3: Values of Maximum Current and Power Outputs of Various MPPT Algorithms

MPPT algorithm	Maximum current (A)	Maximum power (kW)
Existing ESC	30.00	200.0
Fuzzy Logic	31.22	249.4
ANN	35.00	269.6
Modified ESC	40.00	290.0

Table 3 shows that the modified ESC MPPT algorithm had the most efficient current and power tracking efficiency having the highest power outcome of 290 kW. The comparative plot of current signal of the PVC with load with various MPPT is shown in Fig. 20.

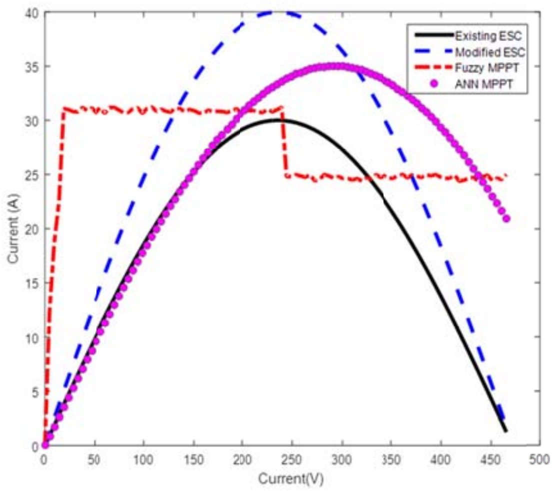

Fig. 20: Comparative Analysis of the Current Signal of various MPPT

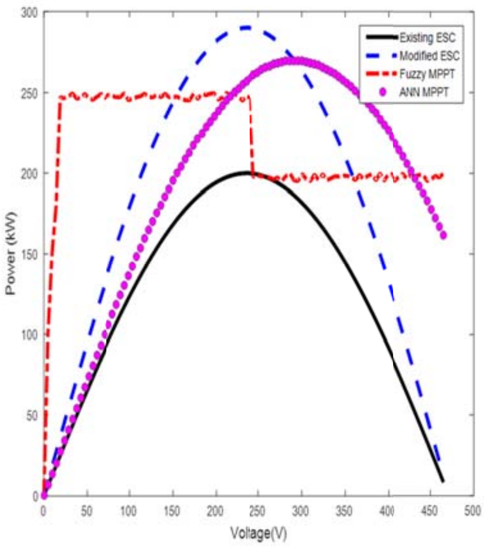

Fig. 21: Comparative Analysis of the PVC Optimal Power Output with Various MPPT

The outcome in Fig. 20 shows that the modified ESC MPPT algorithm had a better optimal current signal tracking when compared with other intelligent and conventional MPPT models. The power signal of the PVC at various MPPT is as shown in Fig. 21, as similar results are seen for the power output.

V. CONCLUSION

The primary aim of this study was to modify the existing extremum seeking control MPPT algorithm to ensure a high efficient power and current tracking in a load connected PVC. This was achieved with the maximum power and current values obtained compared to the intelligent MPPT which were; fuzzy inference system (fuzzy logic) and artificial neural network (ANN). The model of the PVC was done in Simulink and the generation of the MPPT algorithms were carried out in MATLAB environment and implemented in SIMULINKS. From the results presented, there appears to be a high cycling limit when loads were connected to the PVC. However, with the introduction of MPPT, the cycle limits were cleared and maximum current and power tracked were obtained. From the comparative analysis, it was seen that the artificial intelligent MPPT had a better power and current tracking when compared to the existing ESC MPPT. Hence, the ESC MPPT was modified and applied to the system. The modified ESC MPPT had a better outcome with a power output of 334200W followed by the ANN with the maximum power of 313300W, Fuzzy logic with maximum power of 308700 W and existing ESC with maximum power output of 302200 W.

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