USE OF MPPT TECHNIQUES TO REDUCE THE ENERGY PAY-BACK TIME IN PV SYSTEMS

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Abstract--- Photovoltaic (PV) energy is a free-energy that is used as an alternative to fossil fuel energy. However, PV system without maximum power point tracking (MPPT) produces a low, unstable power and with a long energy pay-back time. This paper presents an innovative artificial neuro-fuzzy inference system (ANFIS) MPPT technique that could extract maximum power from a complete PV system and with a lessened EPBT. To confirm the effectiveness of the ANFIS algorithm, its result was compared with the results of PV system using Perturb&Observe (P&O) technique, non-MPPT technique, combination of artificial neural network and support vector machine as ANN-SVM technique and using Pretoria city weather data as case studies. Results show that ANFIS-MPPT yielded the best result and with the lowest EPBT.

Keywords— Artificial Intelligence (AI); ANFIS; ANN; DC to DC converter; Energy pay-back time; Machine learning; MPPT; Support vector machine; Perturb&Observe; Photovoltaic systems.

I. INTRODUCTION

Photovoltaic (PV) solar energy is the fastest growing type of renewable energy that obtains its energy from the sun. PV energy serves as a substitute to fossil energy that is used in most countries to power grid network [1]. Most homes in the developing countries such as South Africa and Nigeria still depend fully or partly on electricity from the grid [2]. However, tariff charged using electricity from the grid has increased over the years [3, 4]. On the other side, apart from the cost of implementation, PV energy is considered economical, freely available, inexhaustible, less polluted, noise-free, low running cost, and with drop in cost of PV panels over the years as newer technology that are cheaper are used for the production of photovoltaic panels [5, 6, 7].

Also, Africa is a continent that experience more sunlight thus allowing more energy to be extracted from the PV system which can lead to a reduced energy pay-back time (EPBT) of the panel [8, 9]. EPBT is the length of time (in years) needed for a complete PV system to recompense for the use of energy for its production [5]. Mathematically, Equation 1 is used to estimate the EPBT of a PV panel while equation 2 estimates the profit earned using photovoltaic energy. $C_{in(R)}$ is the total cost of production in rands, $EPBT_{(yrs.)}$ is the energy pay-back time in years, $P_{01(kw/yr)}$ is the annual power obtainable from a PV system, t is the time of operation in hours, $tariff_{(R/kWh)}$ is the tariff charged on electricity per kwh in rands in South Africa, $PV_{profit(R)}$ is the profit made using solar energy, $L_{(yrs.)}$ is the life span of a PV panel which is like 25-50 years, $P_{02(kw)}$ is the annual power obtainable from a PV after considering losses caused by other factors such as degradation of panel over the years [5].

$$C_{i(R)} = EPBT_{(yrs)} * P_{01(kw/yr)} * t_{(hr)} * tariff_{(R/kwh)} \quad (1)$$

$$PV_{profit(R)} = (L_{(yrs)} - EPBT_{(yrs)}) * P_{02(kW/yr)} * t_{(hrs)} * tariff_{(R/kWh)} \quad (2)$$

Apart from location zone that determines the amount of sunlight that a PV panel gets, other factors also contribute to the energy pay-back time of a photovoltaic panel [10]. This includes the material or technology used in the photovoltaic system, the solar cell efficiency, and losses incurred in PV systems [11, 12]. In terms of material used, this includes the maximum power point tracking (MPPT) technique and solar cell technology used in the PV design. MPPT techniques are algorithms used in PV system to extract maximum power from the PV panel [5, 13]. MPPT techniques are classified into three types (online, offline, and hybrid MPPT techniques) [14, 15].

Solar cell has three classes of technology (first, second, and third-generation PV cells) [16]. First-generation cells are made from silicon wafer e.g. monocrystalline cells and with an efficiency of 15-20%. First-generation cells still dominates the market till date due to their good performance and high stability [17]. Second-generation cells are made from thin, inorganic film materials such as Gallium Arsenide (GaAs) and with an efficiency of 10-15% [18]. Third-generation cells are developed from organic materials such as polymers, dendrimers, and dyes. Advantages of the 3rd generation cell is the reduced material, high efficiency, and the low cost of constituent elements compared to the 1st and 2nd generation cells. The reduced material makes the cost of panel to be cheaper which results in a lower EPBT. However, 3rd generation cells have some drawbacks: fast degradation rate due to photo oxidation, large optical band gap, interfacial instability delamination, etc. [18].

The solar cell efficiency is the ratio of rated power of the panel at standard test condition (STC) to the surface area of the panel in m^2 [19]. The losses in PV system include losses due to degradation, cell mismatch, partial shading, and cabling [20]. Degradation loss are caused from aging of cell while cell mismatch and partial shading are caused by trees, dust particles on PV panel surface, shadows of moving clouds, and buildings [20].

Recent work is done in getting improved materials (cell technology and MPPT techniques) and with higher efficiency that can be used to lower the energy-payback time of photovoltaic system [21].

The contribution of this paper is to compare the results of Perturb&Observe (P&O), artificial neuro-fuzzy inference system (ANFIS) technique, combination of artificial neural network (ANN) and support vector machine (SVM) as ANN-SVM technique, and complete PV system that lacks working MPPT. This work was done to determine the most suitable MPPT technique that could be recommended for energy pay-back time reduction in photovoltaic systems.

The synopsis of this paper is prepared as follows, section 2 will present a summary of the used MPPT techniques. In section 3, a report of the experiments setup and method is provided. Section 4 will present the results, and section 5 will include the conclusions.

II. MPPT TECHNIQUES

The MPPT techniques used in this study are briefly discussed below:

A. Perturb&Observe Technique

Perturb&Observe (P&O) is a power electronic technique categorized under online MPPT methods [5]. P&O is considered in this work because of its cheapness, easy implementation, and good performance with microcontrollers [22]. P&O is similar to hill climbing (HC) technique as both techniques use perturbation process to track the MPP [23]. However, P&O uses voltage perturbation whereas HC uses duty cycle for perturbation process. To track MPPT, P&O uses two sensors, voltage sensor and current sensor to measure PV voltage (V_{pv}) and the PV current (I_{pv}), then measure the power, and the instantaneous change in power and voltage. For power increment, voltage perturbation is done in the positive direction till maximum power point (MPP) is tracked. For power decrement, voltage perturbation is done in the negative direction. Limitations of P&O includes drift in power near MPP and the poor response to a sudden change in irradiance [24].

B. ANFIS Technique

ANFIS is a machine learning or artificial intelligence technique categorized as offline MPPT methods. ANFIS is a combination of artificial neural network (ANN) and fuzzy logic control (FLC) [5]. ANFIS works competently with non-linear I-V and P-V characteristics of photovoltaic cells. ANFIS is used to improve the dynamic performance of PV systems [25]. ANFIS training data can be obtained from real-time system or through simulation by developing a dynamic PV panel that consists of several cells. For improvement, proportional-integral-control (PID) technique is used for fine tuning and optimization in complete PV system that uses ANFIS technique [26, 27].

C. ANN-SVM Technique

ANN-SVM is another machine learning technique that is classified as offline methods. The algorithm combines the state of the art of support vector machine technique and artificial neural network [5]. The SVM is used for optimization, prediction and generation of new training data from few samples. The ANN trains the model by using the newly generated and optimized samples [28].

III. SIMULATION MODEL

To investigate the feasibility of this study, an experiment was conducted using a complete photovoltaic system that comprises of soltech 1STH-215-P PV panel, modified cuk DC-DC converter, MPPT controller, and a 20 Ω resistive load. The experiment was done using Pretoria, South Africa as a case study. The Pretoria city weather data was generated using PVsyst software while the training data used in ANFIS and ANN-SVM were generated from Psim software. Table 1 illustrates the specification of the PV panel and the MCUK DC-DC converter. The PV efficiency, DC-DC converter loss, and the extracted PV power for a year were obtained using equations (3-6). $P_{pv(mppt)}$ is the 1STH-215-P rated power at STC (standard test condition), $P_{pv(max)}$ is the PV extracted power, P_{out} is the output power at the 20 Ω resistive load, and N is the number of months in a year.

$$\text{PV Efficiency at MPPT} = \frac{\int_0^t P_{pv(max)t}.dt}{\int_0^t PV_{pv(mppt)t}.dt} \tag{3}$$

$$\text{MCUK load efficiency at MPPT} = \frac{\int_0^t P_{out(mppt)t}.dt}{\int_0^t PV_{pv(mppt)t}.dt} \tag{4}$$

$$\text{MCUK Losses} = \text{input power} - \text{output power} \tag{5}$$

$$\text{MCUK power} = \sum_{n=1}^{N=12} (\text{output power} \times \text{days in a month} \times 24\text{hrs}) \tag{6}$$

Table 1: PV and MCUK DC-DC converter specifications

SOLAR PANEL SPECIFICATIONS		**MCUK SPECIFICATIONS**	
PV Model	1STH-215-P	L_1	4 mH
Standard Test Condition	1000W/m^2, 25°C	L_2	4 mH
Maximum Voltage (V_{mo})	29.0V	C_1	100 µF
Maximum current (I_{mp})	7.35A	C_2	100 µF
Maximum Power (P_{mp})	213.15W	R_0	20 Ω
N_s - number of cell in series	60	C_0	270 µF
I_{sc} - short circuit current	7.84A		
V_{oc} – open circuit voltage	36.30V		
Temp. coefficient of I_{sc}	-0.36099% / °C		
Temp. coefficient of V_{oc}	0.102% / °C		
A-Diode ideality factor	0.98117		
R_s– series resistance	0.39383 Ω		
R_{sh}– shunt resistance	313.3991 Ω		
Cell type	Polycrystalline		
Life span of 1STH-215-P	40 years		

Table 2 shows the weather for Pretoria city that was used as a case study.

Table 2: Annual data for Pretoria city in year 2017

Season	**Month**	**Average insolation**	**Temp**

		(W/m^2)	**(°C)**
Summer	Jan.	281	22.7
	Feb.	259	22.5
Autumn	Mar.	233	21.4
	Apr.	195	18.5
	May	177	14.6
Winter	Jun.	164	12.1
	Jul.	176	11.6
	Aug.	212	15.6
Spring	Sep.	252	19.1
	Oct.	269	21.8
	Nov.	282	21.7
Summer	Dec.	297	22.8

However, to calculate the energy pay-back time, some assusmptions were made: that the tariff charged on 1 kWh energy for future years was based on the current rate (R1.89/kWh), weather data for future years was the same as year 2017 weather data, and losses caused from the degradation of photovoltaic cells, partial shading and mismatch were ignored.

For the MPPT techniques implemetation. Figure 1 is the algorithm of the ANFIS technique. Figure 2 shows the block diagram of the complete photovoltaic system designed using ANFIS MPPT technique. The ANFIS inputs were irradiance (G), temperature (T), and outputs predicted response (reference current, I_{ref}). The reference current was compared with the PV current (I_{pv}) as error signal ($I_{ref} - I_{pv}$). The error signal was passed through a PI controller for fine tuning and outputs duty cycle signal (D). The duty cycle signal was then passed through a pulse width modulator (PWM) as pulse signal which was used to activate the Mosfet gate of the DC-DC converter.

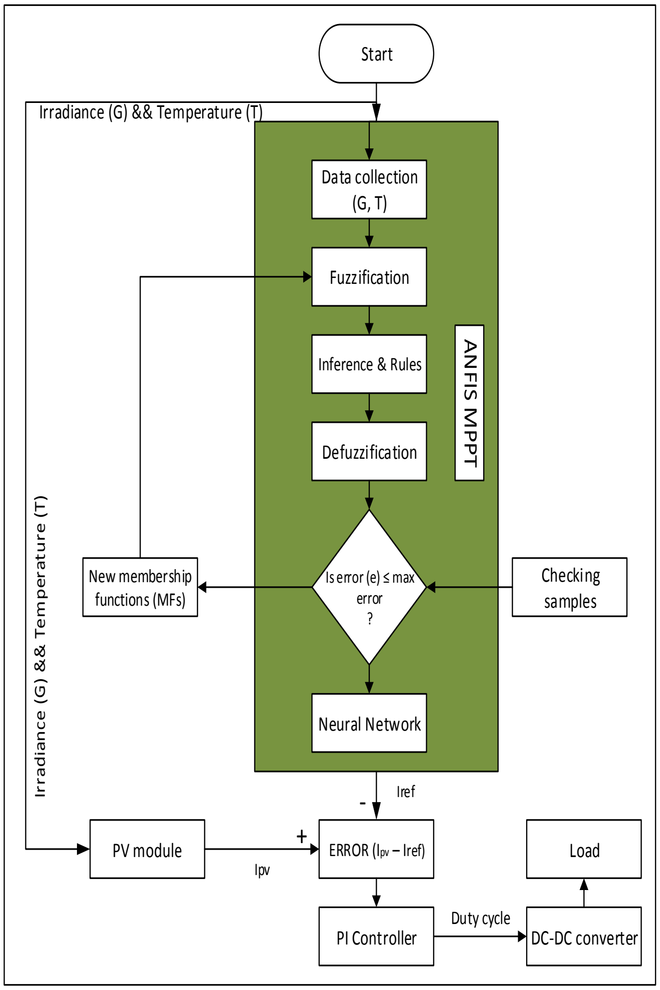

Fig. 1 : ANFIS-MPPT algorithm

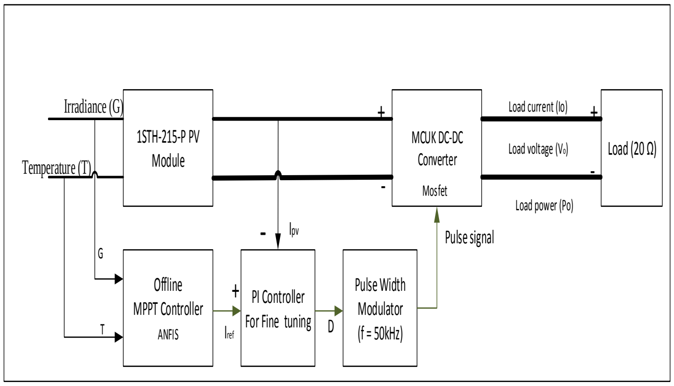

Fig. 2: Complete PV system designed using ANFIS-MPPT technique

Table 3 displays the average testing error of the ANFIS MPPT technique trained using 129 samples in the proportion 70% training, 15% testing, and 15% validation.

Table 3: ANFIS testing error

ANFIS	**Samples**	**Average testing error**
Training	91	0.0017483
Testing	19	0.044183
Validation or checking	19	0.010415

For the ANN-SVM MPPT technique, Figure 3 presents the block diagram of the complete PV system designed using ANN-SVM technique. The work was done in twofolds (optimization and training). First part was the optimization using support vector machine technique. The SVM learnt using 15% of the PSIM data, optimized that data using coarse Gaussian kernel. The kernel was used to generate the fitness function (yfit) that was further used to generate the remaining 85% data that has been optimized. The newly optimized data was then used to train the ANN controller. The SVM that is commonly used for pattern recognition and face detection problems was used as a feasibility for the optimization of PV system and to extract maximum power from the photovoltaic panel. The algorithm of the ANN-SVM MPPT technique is displayed in Figure 4 below.

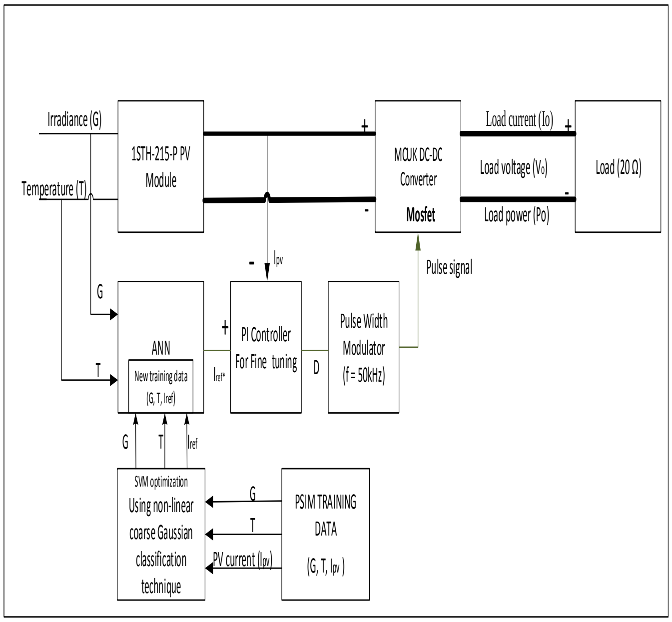

Fig. 3: Complete PV system designed using ANN-SVM technique

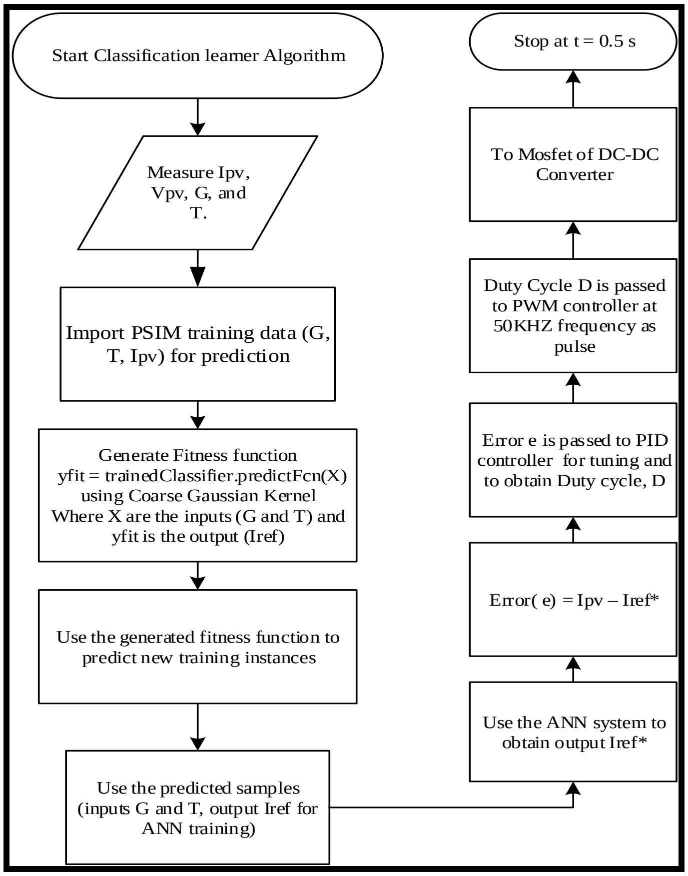

Fig. 4: ANN-SVM algorithm

For the Perturb&Observe (P&O) MPPT technique, Figure 5 displays the block diagram of the complete PV system designed using conventional P&O technique. The P&O inputs were PV current (I_{pv}) and PV voltage (V_{pv}) which were sensed using current sensor and voltage sensor respectively. The P&O controller had both power (P_{pv}) and instateneous change in voltage (dP_{pv}) measured. The measured values were used to control the perturbation process and evaluate if perturbed voltage should be increased or decreased in order to track the MPP of the PV system.

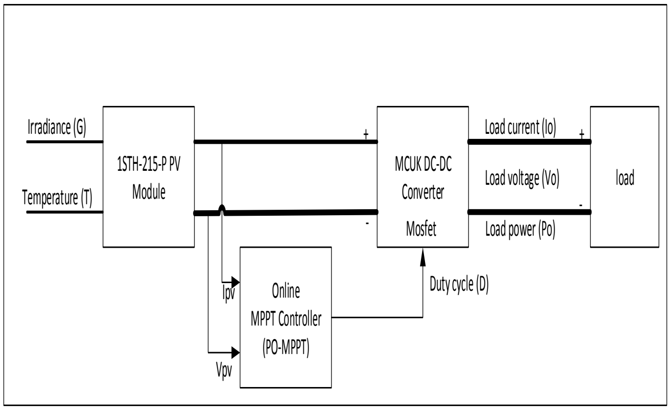

Fig. 5: Complete PV system designed using P&O technique

For the complete PV system that lacks working MPPT technique (NO-MPPT). Figure 6 presents the block diagram of the non-MPPT photovoltaic system.

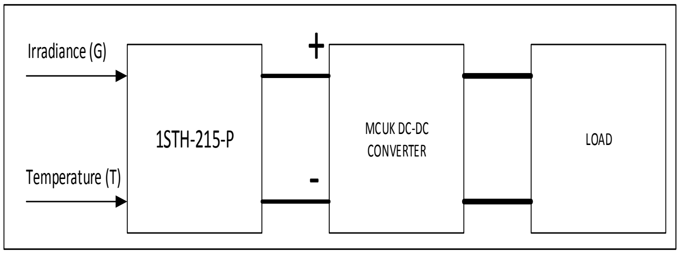

Fig. 6: Photovoltaic system that lacks MPPT algorithm

IV. EXPERIMENTAL RESULTS

Table 4 and Figure 7 display the results of the extracted power and energy at the PV end using ANFIS, ANN-SVM, P&O MPPT techniques, and non-MPPT technique. Table 5 and Figure 8 present the results of the extracted power and energy at the resistive load end, and the energy pay-back time using the above-mentioned MPPT techniques. Results show that ANFIS-MPPT technique had the best result with an energy pay-back time of 5.45 years, followed by P&O (6.28 yrs.), and ANN-SVM (6.54 yrs.). The outcome of the experiment displayed the importance of MPPT technique in a complete PV system as the energy compensation period could take 22.22 yrs. If used without a working MPPT technique.

Results also show that R149.36 profit was earned using 1STH-215-P panel without MPPT throughout its expected life span (40 yrs.) whereas R4828.06 profit was earned with ANFIS-MPPT technique. The annual output-power of the complete PV system using ANFIS-MPPT technique was the highest (16.79 kW) while the non-MPPT technique had the lowest annual output-power at the 20Ω resistive load end (4.115 kW). Results display that the PV performances were reduced during winter period (June to August) in Pretoria city, South Africa. Lastly, the DC-DC converter losses incurred with ANFIS was the lowest as 4.68% of the energy generated by the PV system was dissipated by converter. The NON-MPPT technique experienced the highest DC-DC converter loss (14.45%).

Table 4: extracted power and energy at the PV end

Season	Month 2017	Average monthly PV input power NO-MPP (W/day)	Average Monthly PV input Power P&O (W/day)	Average Monthly PV input power ANFIS (W/day)	Average Monthly PV input Power ANN-SVM (W/day)
Summer	Jan.	26.00 W	60.50 W	60.16 W	53.03 W
	Feb.	16.02 W	53.17 W	54.36 W	36.85 W
Autumn	Mar.	12.60 W	43.78 W	49.14 W	25.07 W
	Apr.	9.66 W	33.86 W	43.37 W	26.34 W
	May	7.60 W	26.46 W	37.72 W	36.98 W
Winter	Jun.	6.28 W	21.68 W	31.69 W	31.65 W
	Jul.	7.23 W	24.28 W	35.30 W	35.29 W
	Aug.	9.51 W	32.47 W	44.19 W	44.26 W
Spring	Sep.	13.40 W	45.68 W	51.81 W	50.81 W
	Oct.	14.86 W	50.89 W	53.75 W	43.79 W
	Nov.	16.41 W	55.48 W	56.35 W	48.04 W
Summer	Dec.	18.13 W	59.65 W	59.77 W	53.37 W
PV annual power		4.81 kW	15.48 kW	17.61 kW	14.82kW
PV annual energy		115.5kWh	371.6kWh	422.7kWh	355.7kWh

Table 5: extracted power and energy at the PV end

Season	Month 2017	Average monthly PV input power NO-MPP (W/day)	Average Monthly PV input Power P&O (W/day)	Average Monthly PV input power ANFIS (W/day)	Average Monthly PV input Power ANN-SVM (W/day)
Summer	Jan.	17.74 W	57.76 W	57.33 W	50.15 W
	Feb.	14.53 W	51.06 W	52.66 W	35.54 W
Autumn	Mar.	11.66 W	42.21 W	47.44 W	23.52 W
	Apr.	8.89 W	32.63 W	41.82 W	24.52 W
	May	6.83 W	25.13 W	36.58 W	35.30 W
Winter	Jun.	5.50 W	20.22 W	30.52 W	30.59 W
	Jul.	6.02 W	21.94 W	32.98 W	32.95 W
	Aug.	8.12 W	29.52 W	41.41 W	41.45 W
Spring	Sep.	11.59 W	41.69 W	48.63 W	48.26 W
	Oct.	13.24 W	47.53 W	51.28 W	41.90 W
	Nov.	14.68 W	51.97 W	53.56 W	44.34 W
Summer	Dec.	16.20 W	56.09 W	56.43 W	49.61 W
Output power/yr.		4.115 kW	14.56 kW	16.79kW	13.98kW
PV power/yr.		4.81 kW	15.48 kW	17.61kW	15.74kW
MCUK losses		0.695kW	0.920 kW	0.824 kW	1.760kW
Losses percentage		**14.45%**	**5.94%**	**4.68%**	**11.18%**
Output energy /yr.		98.76 kWh	98.76 kWh	403kWh	336kWh
Tariff per kWh		R1.89	R1.89	R1.89	R1.89
Solar savings		R186.66	R660.54	R761.59	R703.99
Cost of PV panel		R4147.32	R4147.32	R4147.32	R4147.32
EPBT (yrs.)		22.22 yrs.	6.28 yrs.	5.45 yrs.	6.54 yrs.
Life span - EPBT		17.78 yrs.	33.72 yrs.	34.55 yrs.	33.46yrs.
PV energy profit		R149.36	R3546.72	R4828.06	R3601.76

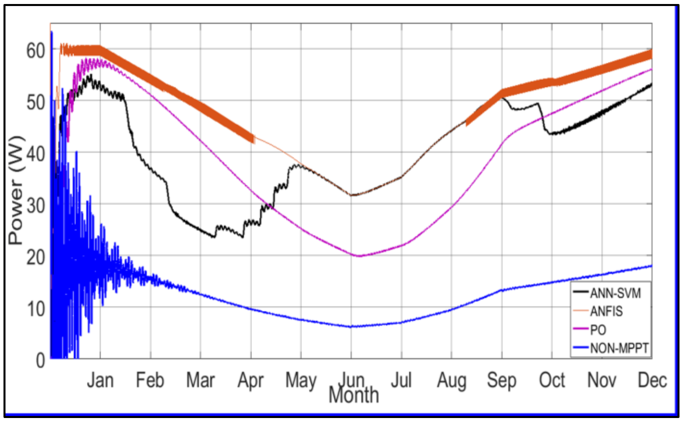

Fig. 7: Extracted power at the photovoltaic end

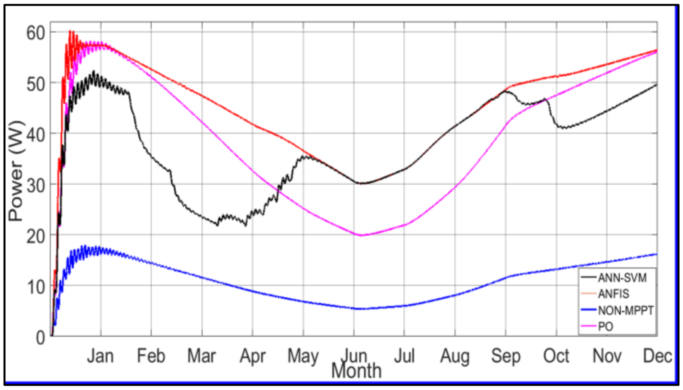

Fig. 8: Extracted power at the resistive load end

V. CONCLUSIONS

This paper presents the comparison of different MPPT techniques in order to improve the efficiency of a complete photovoltaic systems and to lower the energy pay-back time of a PV panel. Obtained results suggest that ANFIS MPPT technique should be recommended as the energy pay-back time using ANFIS was the lowest (5.45 yrs.), followed by Perturb&Observe MPPT technique (6.28 yrs.). Also, ANN-SVM tracked the MPPT fast and attained a sensible power from the panel and a reasonable EPBT (6.54 yrs.). The EPBT of a complete PV system without a working MPPT algorithm was the longest (22.22 yrs.).

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