Curve Fitting Polynomial Technique Compared to ANFIS Technique for Maximum Power Point Tracking

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Abstract--- **In this paper, an approach of designing a fast tracking MPPT is introduced using a predicted sixth order polynomial curve fitting MPPT technique. The results are compared with the lower order polynomials curve fitting MPPT and also compared with the Artificial Neuro-Fuzzy Inference System (ANFIS) results. The polynomials were generated from an offline solar data. This work was done to validate the effect of using a higher order polynomials under various weather conditions using modified CUK DC-DC converter. Findings suggest that using the 6th order polynomial curve fitting and the ANFIS techniques could track the highest maximum power point than the lower order curve techniques.**

Keywords— ANFIS, Artificial Intelligence (AI), curve fitting polynomials, DC to DC converter, MPPT, PV system, stand-alone system.

I. INTRODUCTION

Photovoltaic (PV) solar system performance improves when connected to a proper Maximum Power Point Tracking (MPPT) charge controller [1]. MPPT controller enhances the power supplied by a PV model to ensure that the PV operates at the optimum voltage (V_{mp}) and at the optimum current (I_{mp}) to give a maximum power (P_{mp}) [1]. PV panel depends on the environmental conditions (insolation and the temperature) for determining the I-V and the P-V curve characteristics. Fig. 1 shows the equivalent circuit diagram of a single diode PV cell and equations 1-9 show the parameters of a PV cell [1, 2].

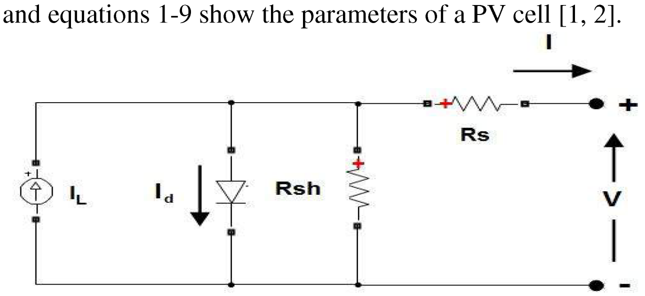

Fig. 1: Equivalent circuit diagram of a PV Solar cell

$$V_t = \frac{KT_c}{q} \quad . \qquad (1)$$

$$a = \frac{N_s AKT_c}{q} = N_S AV_t \, . \qquad (2)$$

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad . \qquad (3)$$

$$I_d = I_0[\exp(\frac{V + IR_s}{a}) - 1] \quad . \qquad (4)$$

$$I_{sh} = \frac{V + IR_s}{R_p} \quad . \qquad (5)$$

$$I_{pv} = I_{ph} - I_0[\exp(\frac{V + IR_s}{a}) - 1] - \frac{V + IR_s}{R_p} \quad . \qquad (6)$$

$$I_{ph} = \frac{G}{G_{ref}}[I_{ph(ref)} + K_i(T_c - T_{ref})] \quad . \qquad (7)$$

$$I_0 = I_{0(ref)}[\frac{T_c}{T_{ref}}]^3 \exp[(\frac{qE_g}{AK})(\frac{1}{T_{ref}} - \frac{1}{T_c})] \quad . \qquad (8)$$

$$V_{pv} = -I_{pv}R_s + k\log[\frac{I_{ph} - I_{pv} + I_0}{I_0}] \quad . \qquad (9)$$

Where, k = Boltzmann's constant = 1.38e-23, V_t = terminal voltage, q = charge of an electron = 1.6e-19, T_{ref} = reference temperature = 298K, T_c = actual cell temperature in Kelvin, A = ideality factor, a = modified ideality factor, I_{ph} = photo current (amps/A), N_s = number of cells connected in series, N_p = number of cells connected in parallel,, I_d = diode current (A), I_{sh} = current leak in parallel resistor, R_p (A), I_{pv} = PV current (A), I_o = reverse saturation current or leakage current (A), R_s = series resistance (Ω), R_{sh} = shunt resistance (Ω), V_{pv} = PV voltage (V), G_{ref} = reference insolation at STC = 1000W/m^2, K_i = coefficient of short circuit temperature [3-5].

Equation (10) is used to evaluate the efficiency of a PV Module when operating at its MPP. While equation (11) is for calculating the PV rating. The rated power of used panel is 215W = 0.215kW at STC and surface area (1626 mm x 964 mm = 1.5675 m^2) which gives an efficiency rating of 13.72% [4- 8].

$$\text{Efficiency at MPPT} = \frac{\int_0^t P_{pv(max)t.dt}}{\int_0^t PV_{pv(mppt)t.dt}} \quad . \qquad (10)$$

Where t is the simulation time, $P_{pv(max)}$ is the Power from the PV Panel at MPP, and Ppv(mppt) is the manufacture's MPPT power at STC.

$$\text{Efficiency rating} = \frac{\text{Rated power of the PV panel at STC in KW}}{\text{Surface Area of the panel in m}^2} \qquad (11)$$

Recently, work related to curve fitting polynomial technique used the 3rd order and the 4th order curve fitting technique to track MPP was conducted [3, 4]. However, few work is done using curve fitting technique that is higher than the 4th order polynomial prediction technique.

The contributions of this paper are to investigate the accuracy of the 3rd, 4th, 5th, and the 6th order polynomial curve fitting technique and compare the results with the Artificial Neuro-Fuzzy Inference System (ANFIS) results. All work in this paper was simulated using Matlab and Psim professional software.

The structure of this paper is organized as follows, section 2 presents an overview of the used MPPT techniques. Section 3 gives an account of the experiment setup and approach used. Section 4 will present the results, and section 5 will include the conclusions.

II. MPPT TECHNIQUES

MPPT techniques can be classified either online, offline, or hybrid methods. Online methods are methods that do not depend on previous knowledge of a PV system characteristic while the offline methods depend on prior knowledge of the PV characteristics. Offline techniques are based on mathematical relationships derived from empirical data. Example of an offline method is the MPPT based on artificial intelligence such as Fuzzy Logic, curve fitting, ANFIS, etc. [9].

Maximum Power Point of a Photovoltaic (PV) system usually lies at the point where the input impedance (Z_i) of the panel is equal to the load impedance (Z_{out}) [6, 7]. MPPT lies at the point where $\frac{dP}{dV} = 0$, dP is the instantaneous change in Power and dV is the instantaneous change in Voltage. Using the curve fitting tool approach, we can approximate the mathematical equation that relates Power (P) and Voltage (V) by fitting a curve in the P-V curve of the working module. For MPPT, the relationship can be of the form given in (11a), where V is the voltage, P is the Power, n is the order of polynomials, and a, b, c, …, d, e are the coefficients that relates P and V. Differentiation of P with respect to V can be carried out and estimated to be equal to zero using eqn. (11b)

$$P = aV^n + bV^{n-1} + cV^{n-2} + \dots + dV + e \qquad (11a)$$

$$\frac{dP}{dV} = anV^{n-1} + b(n-1)V^{n-2} + c(n-2)V^{n-3} + \dots + d = 0 \qquad (11b)$$

As an example, where n=3 and for MPPT to occur $\frac{dP}{dV} = 0$.

$$P = aV^3 + bV^2 + cV + d \qquad (12a)$$

$$\frac{dP}{dV} = 3aV^2 + 2bV + c = 0 \qquad (12b)$$

Solving this, $V = V_{mpp} = \frac{-b \pm \sqrt{b^2 - 3ac}}{3a}$, where V_{mpp} is the voltage at maximum power point and a, b, and c are the coefficients using the 3rd order polynomial. [2-4], [8-10]. ANFIS is an algorithm that is designed using trained sample data. ANFIS is a hybrid combination of two offline algorithms (Neural Network for training and Fuzzy logic for inference) using Sugeno inference system [11-13]

III. SIMULATION MODEL

The PV panel used for the experiments is (1Soltech 1STH-215-P) PV model at Standard Test Condition (G=1000W/m^2, T= 25°C) . This first experiment was done using five different weather conditions and the second experiment was done using Johannesburg average climatic weather [14-15]. The payback cost of the panel was estimated using ANFIS and the 6th order curve fitting MPPT techniques for a 1Soltech STH-215-P Photovoltaic panel model from Jan–Dec 2016. The enviromental conditions used are STC (1000W/m^2, 25°C) PTC (1000W/m^2, 20°C) NOCT (800W/m^2, 47.4°C) (800W/m^2, 20°C) and at (600W/m^2, 20°C) The first experiment was carried out for t = 0.5s and a discrete sampled period T_S = 1.00e-6 sec Table I shows the specification of the PV panel used and the specification of the modified CUK DC-DC converter. The irradiance was kept constant at G=1000W/m^2 and the temperature is varied from 15°C to 45°C at a step of 5°C. Seven temperature measurements were taken as shown in tables 2-5. The coefficients of the predicted 6th, 5th, 4th, and 3rd order curve fitting polynomial were determined. From each table, the corresponding coefficients (a, b, c, d) can be related mathematically to T_{cell} using the Polyfit (x,y,n) command. Where x is the cell temperature (T_{cell}), y is the desired coefficient to be computed in terms of cell temperature (Tcell) and irradiance, and n is the order of polynomial.

TABLE I: PV AND MODIFIED CUK SPECIFICATIONS

SOLAR PANEL SPECIFICATION		MCUK SPECIFICATION	
PV Model at STC	1Soltech STH-215-P	L_1	4 mH
Standard Test Condition	1000W/m^2, 25°C	L_2	4 mH
Maximum Voltage (V_{mp})	29.0 V	C_1	100 µF
Maximum current (I_{mp})	7.35 A	C_2	100 µF
Maximum Power (P_{mp})	213.15 W		
N_s - number of cell in series	60	R_0	20 Ω
I_{sc} - short circuit current	7.84 A		
V_{oc} – open circuit voltage	36.30 V		
Temp. coefficient of I_{sc}	-0.36099% /°C	C_0	270 µF
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		

Figures (3 – 6) represent the graphs of the P-V prediction of the Soltech 1STH-215-P using 3rd order, 4th, 5th, and 6th order curve prediction fitting polynomial function respectively. This is a case where n=3 n=4, n=5, and n=6 respectively. However, solving using the 3rd order may not be accurate as the 3rd order polynomial is not fitting well enough with the real P-V curve. Thus, the V_{mpp} error value is relatively high. The same applies when using the 4th order polynomial as it can be seen from Fig. 4. Hence, it can be assumed that as the order of polynomial is increasing, the predicted polynomial curve fits in better with the real P-V curve of the used model. The predicted P-V curve strongly depends on the cell temperature (T_{cell}). The T_{cell} can be obtained using (12c), and is further used to estimate the coefficients (a, b, c, d, …) of the P-V curve that relates the Power and Voltage equation as shown in (12d).

$$T_{cell} = T_{ambient} + \frac{(NOCT - 20)G}{800} \qquad (12c)$$

$$P = a(T_{cell})V^n + b(T_{cell})V^{n-1} + c(T_{cell})V^{n-2} + \dots \qquad (12d)$$

Where T_{cell} is the cell temperature of the PV module in Celsius, NOCT is the nominal operation condition temperature of the PV =47.4°C for 1Soltech 1STH-215-P, $T_{ambient}$ is the ambient temperature of the environment, and G is the irradiance in W/m^2.

For the ANFIS technique implementation, 129 training data was collected using PSIM Professional software. Where 70% of the data is for training, 15% for testing, and the remaining 15% data is for checking. The optimization used for training the FIS is the Hybrid Method. The training data has two inputs (Irradiance and Temperature) and an output (maximum current or **Impp**). The input data were obtained randomly under a range of $50W/m^2$ to $1000W/m^2$ irradiance, and a temperature range from 15°C to 75°C as this falls within the operating temperature of the Soltech 1STH-215-P from the lookup data sheet (-40°C to 85°C), and the output maximum current the PV can supply at that weather condition is recorded. The predicted output I_{mpp} is compared with the I_{mpp} from the datasheet and the measured error is passed into discrete PI controller for tuning and to obtain duty cycle (D) then further transmitted into DC-DC Pulse Width Modulation as a pulse for the Mosfet of the Modified CUK.

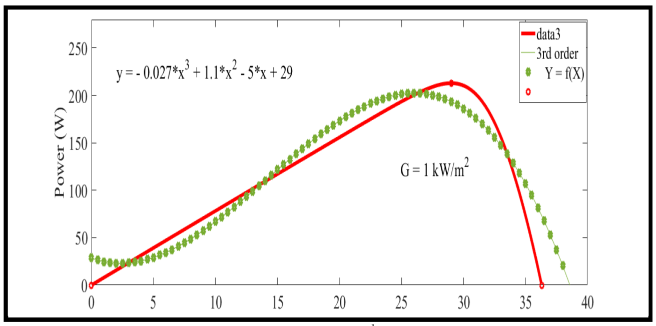

Fig. 3: P-V prediction using the 3rd order polynomial function

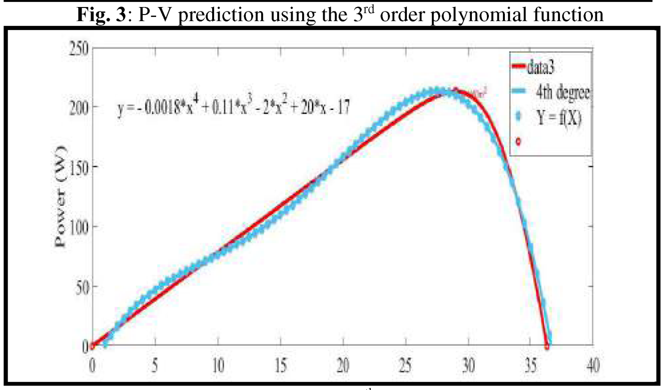

Fig. 4: P-V prediction using the 4th order polynomial function

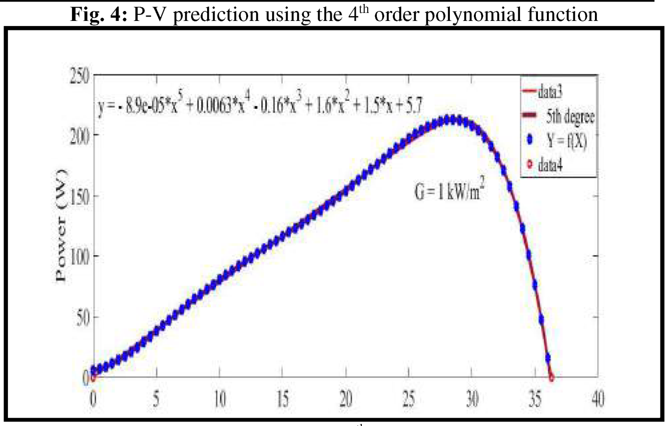

Fig.5: P-V prediction using the 5th order polynomial function

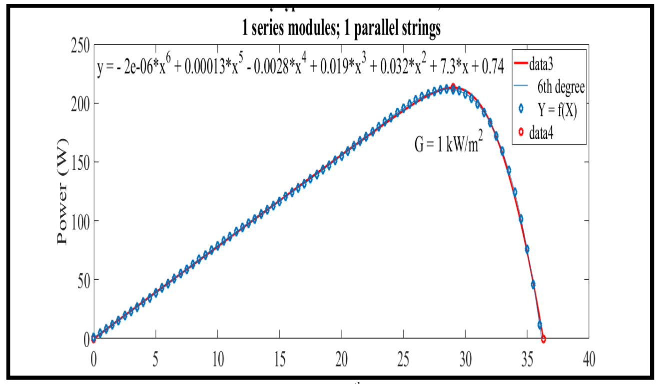

Fig. 6: P-V prediction using the 6th order polynomial function

TABLE II: 6th ORDER POLYNOMIAL CURVE FITTING PREDICTION

T_{amb} (°C)	a	b	c	d	e	f	g
15	-2.5E-6	0.00019	-0.0054	0.067	-0.36	8.4	-0.13
20	-2.3E-6	0.00016	-0.0042	0.045	-0.18	7.9	0.3
25	-2.0E-6	0.00013	-0.0028	0.019	0.032	7.3	0.74
30	-1.8E-6	0.0001	-0.0015	-0.0022	0.19	6.8	1.00
35	-1.5E-6	6.7E-5	-2.9E-4	-0.023	0.34	6.5	1.30
40	-1.2E-6	3.3E-5	9.6E-4	-0.042	0.47	6.2	1.50
45	-7.5E-7	-1.5E-5	0.0027	-0.068	0.64	5.8	1.70

TABLE III: 5th ORDER POLYNOMIAL CURVE FITTING PREDICTION

T_{amb} (°C)	a	b	c	D	e	f
15	-8.6E-5	.0064	-0.17	1.8	.081	7.4
20	-8.8E-5	.0064	-0.16	1.7	.79	6.5
25	-8.9E-5	.0063	-0.16	1.6	1.5	5.7
30	-9E-5	.0061	-0.15	1.5	2.3	4.8
35	-9.1E-5	.0060	-0.14	1.4	2.8	4.4
40	-9.1E-5	.0058	-0.13	1.2	3.6	3.6
45	-9.1E-5	.0055	-0.12	1.1	4.4	2.8

TABLE IV: 4th ORDER POLYNOMIAL CURVE FITTING PREDICTION

T_{amb} (°C)	a	b	c	d	e
15	-8.6E-5	.0064	-0.17	1.8	.081
20	-8.8E-5	.0064	-0.16	1.7	.79
25	-8.9E-5	.0063	-0.16	1.6	1.5
30	-9E-5	.0061	-0.15	1.5	2.3
35	-9.1E-5	.0060	-0.14	1.4	2.8
40	-9.1E-5	.0058	-0.13	1.2	3.6
45	-9.1E-5	.0055	-0.12	1.1	4.4

TABLE V: 3rd ORDER POLYNOMIAL CURVE FITTING PREDICTION

T_{amb} (°C)	a	b	c	d
15	-0.025	1.1	-5.1	30
20	-0.026	1.1	-5.0	29
25	-0.027	1.1	-5.0	29
30	-0.028	1.2	-4.7	27
35	-0.029	1.2	-4.5	27
40	-0.030	1.2	-4.1	25
45	-0.031	1.2	-3.9	24

For the second experiment, Fig. 7 and Fig. 8 show the Johannesburg average monthly insolation and temperature.

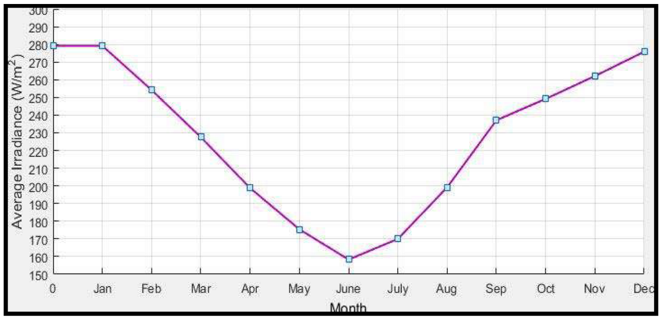

Fig. 7: Average Johannesburg Monthly insolation from Jan. to Dec. 2016

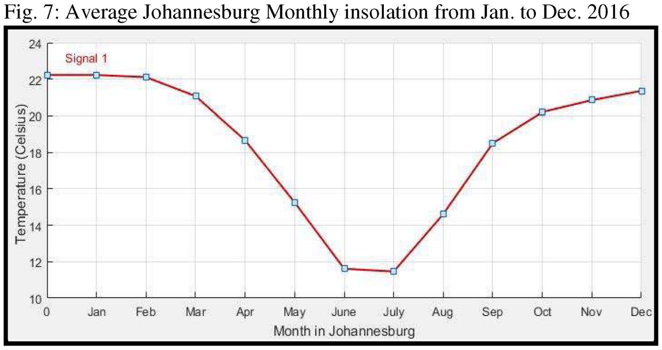

Fig. 8: Average Johannesburg Monthly Temperature from Jan. to Dec. 2016

IV. EXPERIMENTAL RESULTS

After using the above measures for the two experiments, simulations were completed and the experimental results were recorded. For the first experiment, Figures (9 – 18) are the power input and power output graphs comparison of the 6th order, 5th, 4th, 3rd order, and ANFIS MPPT results using the five varied weather conditions, and Table VI is the MPPT experimental results. From Table VI result, at (G=600W/m^2, T= 30°C), and at STC ((G=1000W/m^2, T= 25°C)**,** the 6th order efficiency was the highest while for other conditions, ANFIS is leading, where from the (power input) figures, the 3rd order and the fifth order curve fitting power were unstable.

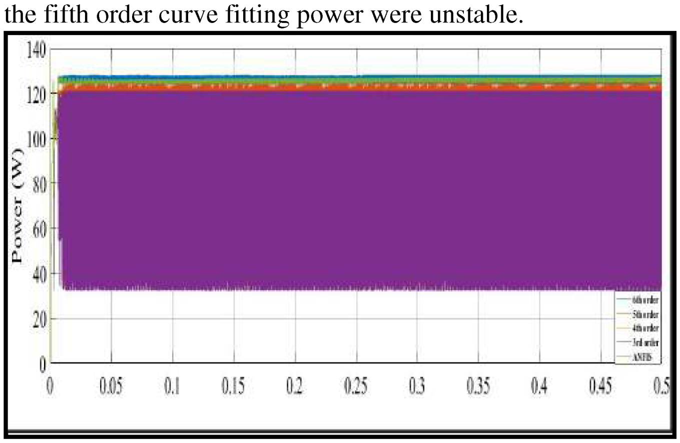

Fig. 9: Graph of 1STH-215-P Power input at (G=600W/m^2, T= 30°C)

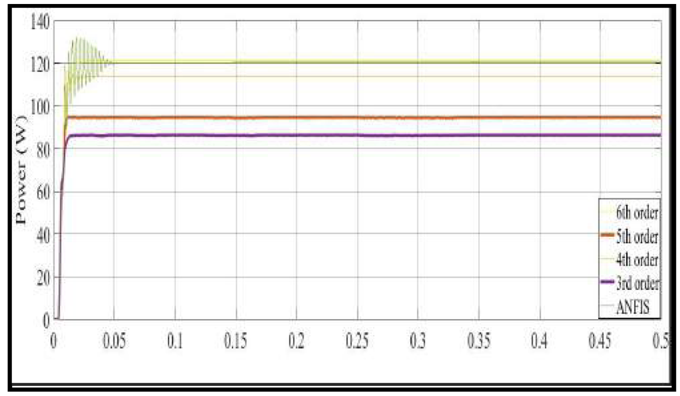

Fig. 10: Graph of 1STH-215-P Power output at (G=600W/m^2, T= 30 °C)

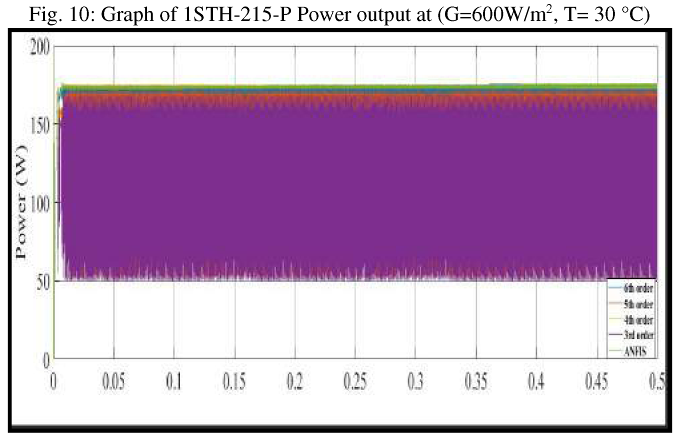

Fig. 11: Graph of 1STH-215-P Power input at (G=800W/m^2, T= 20 °C)

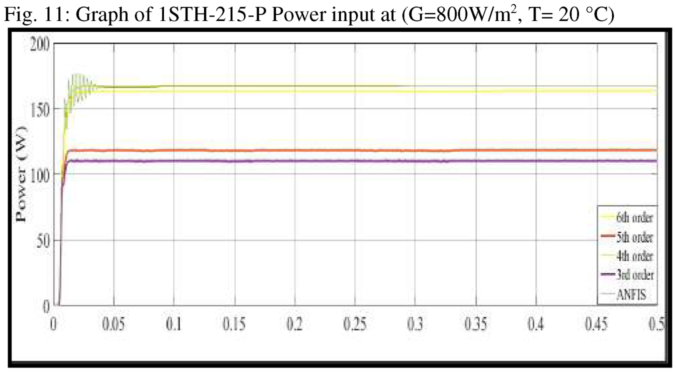

Fig. 12: Graph of 1STH-215-P Power output at (G=800W/m^2, T= 20 °C)

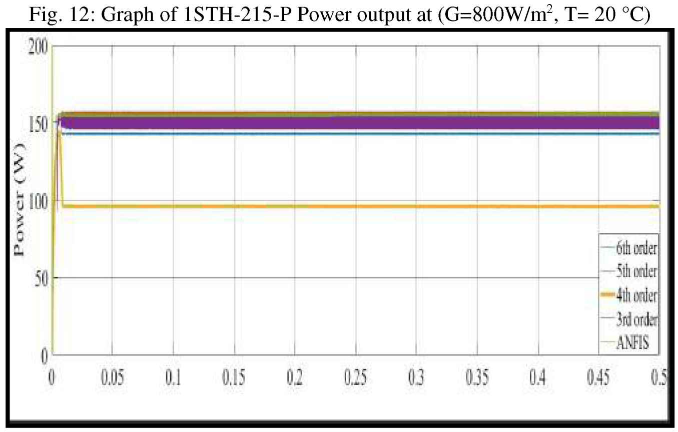

Fig. 13: Graph of 1STH-215-P Power input at (G=800W/m^2, T=47.4 °C)

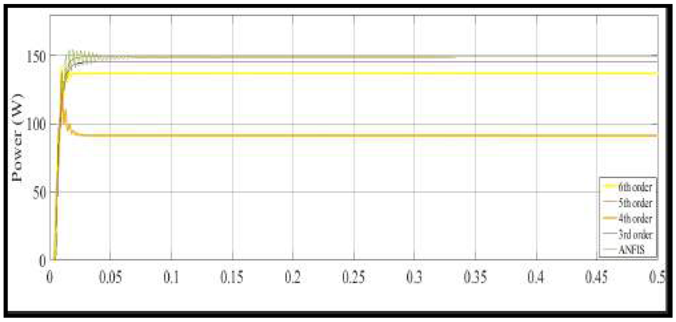

Fig. 14: Graph of 1STH-215-P Power output at (G=800W/m^2, T= 47.4°C)

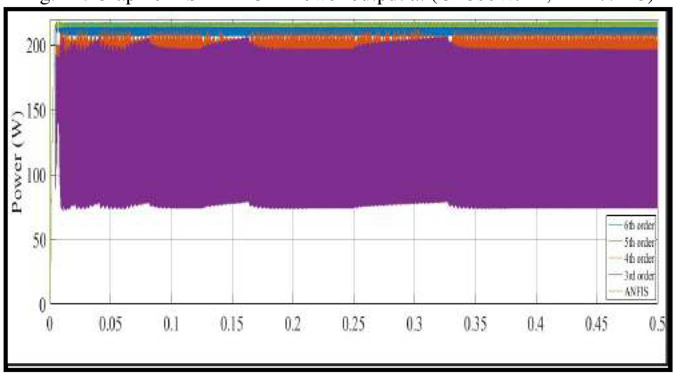

Fig. 15: Graph of 1STH-215-P Power input at (G=1000W/m^2, T= 20 °C)

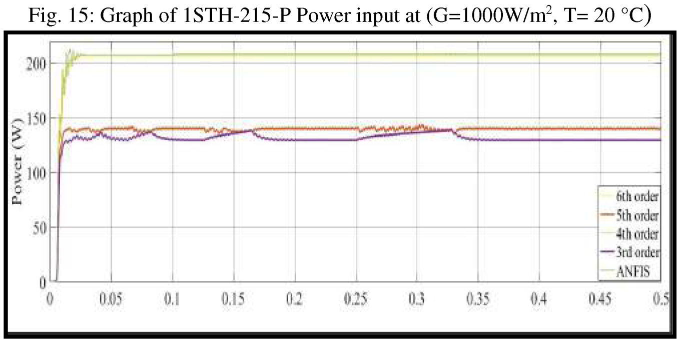

Fig. 16: Graph of 1STH-215-P Power output at (G=1000 W/m^2, T= 20 °C)

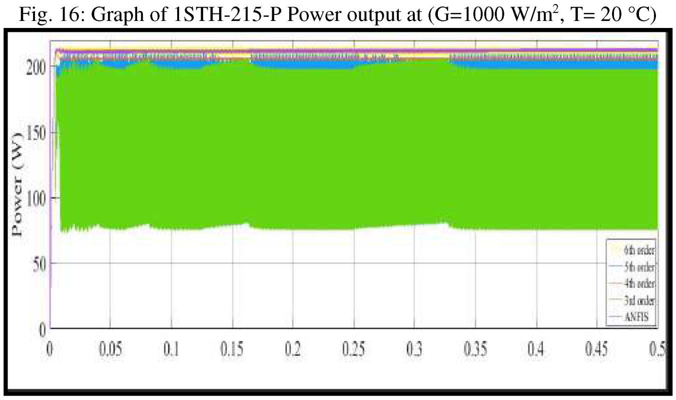

Fig. 17: Graph of 1STH-215-P Power input at (G=1000 W/m^2, T= 25 °C)

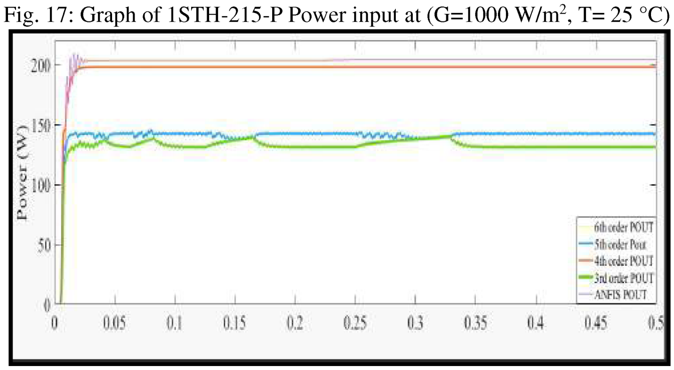

Fig. 18: Graph of 1STH-215-P Power output at (G=1000 W/m^2, T= 25 °C

TABLE VI: MPPT EXPERIMENTAL RESULTS AT DIFFERENT WEATHER CONDITIONS

G=0.6 $\frac{W}{m^2}$	**VALUES**	**ANFIS**	**6th**	**5th**	**4th**	**3rd**
	Ipv (A)	4.334	4.472	4.69	3.881	4.702
	Vpv (V)	29.18	28.33	22.59	30.61	18.34
	Io (A) load	-2.458	-2.462	-2.177	-2.383	-2.078
	Vo (V) load	-49.16	-49.24	-43.54	-47.65	-41.56
T=30 (°C)	Power in (W)	126.8	127.5	120.6	119.1	119.4
	Pout (W)	120.9	121.2	94.78	113.5	86.35
	Efficiency wrt mpp	**59.49**	**59.82**	**56.58**	**55.88**	**56.02**
	Efficiency wrt load	56.72	56.86	44.47	53.25	40.51
G=0.8	Ipv (A)	5.736	6.09	6.207	5.699	6.209
T=20	Vpv (V)	30.45	28.02	19.13	30.56	18.19
	Io (A) load	-2.894	-2.859	-2.437	-2.892	-2.352
	Vo (V) load	-57.89	-57.18	-48.73	-57.83	-47.04
	Power in (W)	175.2	173.6	144	174.9	137
	Pout (W)	167.6	163.5	118.7	167.2	110.6
	Efficiency wrt mpp	**82.20**	**81.45**	**67.56**	**82.06**	**64.27**
	Efficiency wrt load	78.63	76.71	55.69	78.44	51.89
G=0.8	Ipv (A)	5.844	5.013	6.06	3.128	6.231
T=47.4	Vpv (V)	26.63	28.5	25.72	30.66	24.3
	Io (A) load	-2.73	-2.615	-2.73	-2.139	-2.692
(NOCT)	Vo (V) load	-54.6	-52.31	-54.61	-42.78	-53.83
	Power in (W)	156.1	143.1	156.8	95.86	153.5
	Pout (W)	149.1	136.8	149.1	91.49	144.9
	Efficiency wrt mpp	**73.24**	**67.14**	**73.56**	**44.97**	**72.02**
	Efficiency wrt load	69.95	64.18	69.95	42.93	67.98
G=1 T=20	Ipv (A)	7.181	7.576	7.756	7.039	7.759
	Vpv (V)	30.18	28.11	19.00	30.57	17.94
(PTC)	Io (A)	-3.228	-3.203	-2.64	-3.218	-2.547
	Vo (V)	-64.57	-64.05	-52.8	-64.35	-50.95
	Power in	217.4	212.96	207	215.18	196.8
	Pout (W)	208.4	205	139.4	207.1	129.8
	Efficiency wrt mpp	**101.68**	**99.91**	**97.12**	**100.95**	**92.33**
	Efficiency wrt load	97.77	96.18	65.40	97.16	60.90
G=1 T=25	Ipv (A)	7.199	7.489	7.796	6.723	7.799
	Vpv (V)	29.51	28.31	18.94	30.61	18.02
	Io (A) load	-3.196	-3.194	-2.667	-3.146	-2.560
(STC)	Vo (V) load	-63.92	-63.88	-53.34	-62.91	-51.21
	Power in	213.05	213.14	205.7	206.2	197.9
	Pout (W)	204.3	204	142.3	197.9	131.1
	Efficiency wrt mpp	**99.95**	**99.99**	**96.51**	**96.74**	**92.85**
	Efficiency wrt load	95.85	95.71	66.76	92.85	61.51

For the second experiment, Fig. 19 and Fig. 20 show the results for the 6th order and ANFIS average power input, and power output from Jan. to Dec. 2016. Table VII shows the results, with the aim of determining how much power can be extracted from the PV system in a year and estimating the payback time and amount that can be saved using ANFIS MPPT and the 6th order curve fitting technique. It can be seen from Fig. 7 and Fig. 8 from the simulation model setup that in real life scenario, a rise in the ambient temperature usually arises with a rise in the irradiance from the sunlight.

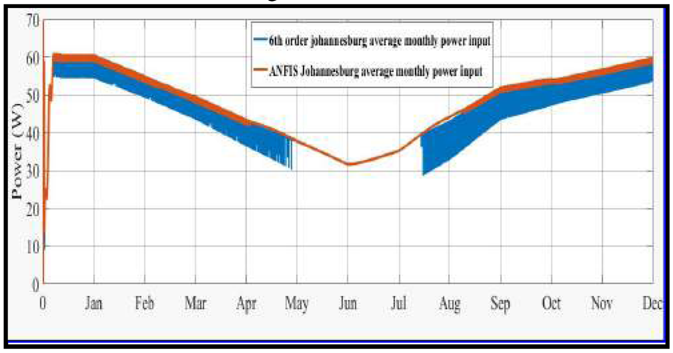

Fig. 19: Average Johannesburg Monthly PV Power from Jan. to Dec. 2016.

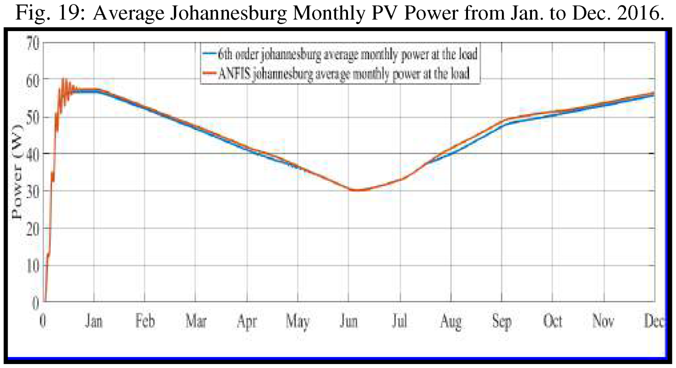

Fig. 20: Average Johannesburg Monthly Load Power from Jan. to Dec. 2016.

TABLE VII: YEAR 2016 AVERAGE MONTHLY CLIMATIC FOR JOHANNESBURG AND POWER SAVED USING A MODULE OF 1Soltech 1STH-215-P

Season	Month	Average daily insolation per month $\frac{kWh}{m^2 \cdot day}$	Average daily insolation per month $\frac{W}{m^2}$	Temp (°C)	Average Monthly Power ANFIS (W)	Average Monthly Power 6th order (W)
Summer	Jan.	6.70	279.17	22.23	60.00	60.2
Summer	Feb.	6.10	254.17	22.11	55.33	54.99
Autumn	Mar.	5.46	227.15	21.07	49.30	49.67
	Apr.	4.77	198.75	18.66	43.80	43.10
	May	4.21	175.42	15.25	39.60	37.95
Winter	Jun.	3.80	158.33	11.61	32.30	32.33
	Jul.	4.08	170.00	11.46	34.30	35.18
	Aug.	4.78	199.17	14.61	43.10	42.97
Spring	Sep.	5.69	237.08	18.50	51.80	51.30
	Oct.	5.98	249.17	20.20	53.90	53.80
	Nov.	6.29	262.08	20.85	56.50	56.55
Summer	Dec.	6.62	275.83	21.36	59.64	59.65
Total estimated power obtained from a PV in a year					17.67 kW	17.62kW
Power unit in a year (Energy) (kWh)					424.2kWh	423kWh
Cost of 1kWh energy in Johannesburg, South Africa					R1.73	R1.73
Amount saved in a year using 1STH-215-P PV Module					R734.87	R731.39

V. CONCLUSIONS

From the two experiments, it can be seen that, as the order of polynomial is increasing, the efficiency of the PV panel is also increasing. From Table VI, and under PTC condition ($G=1000W/m^2$, T= 20 °C), it was observed that the output power of the ANFIS and the 6th order output power was higher than Manufacturer's STC rated power (213.15 W). This could be due to the MPPT controller performing better at a lower temperatures as the voltage tends to be higher at lower temperatures, thereby resulting in a higher power supply. Also, from the plotted graphs, it was observed that when using odd order (3rd & 5th order) curve fitting polynomials, the maximum power keeps oscillating around the peak and the efficiencies using the proposed 6th order MPPT are very much close to the results obtained from ANFIS in both experiments.

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