Proceedings of the Second IASTED Africa Conference
Power and Energy Systems (AfricaPES 2008)
September 8-10, 2008 Gaborone, Botswana

EXAMINATION OF MPP ALGORITHMS FOR PHOTOVOLTAIC INVERTER CONCERNING TRANSMISSION EFFICIENCY

Jesús César Calvo, Henry Güldner, Jens Rost
Technische Universität Dresden
Lehrstuhl Leistungselektronik
01062 Dresden
Germany
henry.gueldner@tu-dresden.de

ABSTRACT
At present, the great value that is reaching renewable energy is known. The aim of the Kyoto Protocol is to reduce CO_2 emissions. Two great benefits will be reached: energy independence and reduction in the risk of the future escalation of energy costs **[1].** Photovoltaic energy will create an increasing contribution to electrical power supply all over the world.
This work will analyse in depth the algorithms Perturb and Observe (P&O) **[2], [3], [4],** Incremental Conductance (Inc) **[2], [3], [4]** and Constant Voltage (CV) **[2], [5]** with some changes proposed (for example an approximation of the Incremental Conductance is mixed with the Constant Voltage getting a more robust structure). Also the Newton Raphson (NR) algorithm will be analysed based in the numerical method of Newton Raphson (fast convergence and goodness to gain non-linear equation make one of the best).

KEY WORDS
Photovoltaic (PV); Maximum Power Point trackers (MPPT); Efficiency; Newton Rapshon tracker (NR); Solar Energy.

1. Introduction
In order to increase the output efficiency of a grid-connected photovoltaic system it is important to have an efficient Maximum Power Point Tracker (MPPT). The total efficiency is defined as: **[6]**

$$\eta_{total} = \eta_{PV} \cdot \eta_{MPP_{track}} \cdot \eta_{inverter} \tag{1}$$

η_{total} = Total efficiency of the PV system
η_{PV} = Efficiency of the photovoltaic array.
$\eta_{inverter}$ = Efficiency of the PV inverter.
$\eta_{MPP_{track}}$ = Efficiency of the MPPT algorithm

Therefore, the efficiency of the solar panel is deeply connected with its ability to track the maximum power point. In this study only $\eta_{MPP_{track}}$ is analysed. Many MPPT algorithms have been proposed in past research. The best research include the Perturb and Observe algorithm **[2], [3], [4],** Incremental Conductance algorithm **[4]** and Constant Voltage **[2], [5]** algorithms.They have been analysed before in different irradiation conditions without one clear organization. The efficiencies provided are given sometimes in high irradiation and sometimes in low irradiation.
The goal in this work is to become aware of their behaviour in different weather conditions and distinguish the advantages from the disadvantages. An efficiency analysis of the MPP tracking will be done also. At the end, a table with all advantages and disadvantages about the algorithms will be included.

2. Simulation Conditions

2.1 Equivalent Circuit
There are several equivalent circuits proposed in the bibliography. In this work, the circuit used by DGS [7] is analysed, this is illustrated in *Fig.1*.

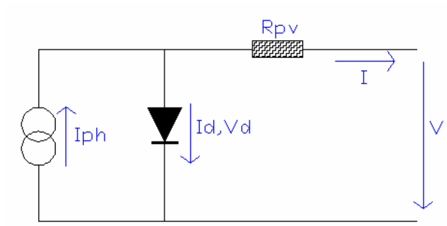

Figure 1. Solar Panel Equivalent Circuit

The correspondent equations can be seen in the following, coming from Yusof, et.al **[8]** and Yu, et.al **[9]:**

$$I_{ph(G,T)} = \left(I_{sc_{(G_0,T_0)}} + \tau \cdot (T - T_0)\right) \cdot \frac{\lambda}{100} \tag{2}$$

$$I_{(G,T)} = I_{ph(G,T)} - I_{s_{(T)}} \cdot \left(e^{\frac{V}{A \cdot V_t \cdot n}} - 1\right) \tag{3}$$

$$I_{s_{(T)}} = I_{s_{(T_0)}} \cdot \left(\frac{T}{T_0}\right)^3 \cdot e^{\left(\frac{q \cdot E_G}{k \cdot A} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right)} \tag{4}$$

where:

$R_{PV(G_0,T_0)}$: Resistence of the solar model **[7]**

$V_{T_{(G,T)}}$: The thermal voltage in this model

$I_{s_{(G,T)}}$: Saturation current diode

$I_{ph(G,T)}$: Photocurrent.

n is the number of cells connected in series

A is a coefficient that takes values since 1 until 2 and it determines the cell deviation from the ideal p-n junction characteristics **[8]**

$I_{sc(G_0,T_0)}$: Short current in reference temperature and radiation;

τ temperature coefficient in short circuit current (0.0015 A/°C); **[9]**

λ/100 solar radiation in mW/cm2 (it can be checked that when landa is divided by 100 mW/cm2, $\lambda/_{100}$ is made as a no dimensional factor).

T is the absolute temperature of the p-n junction

q is the magnitude of charge on an electron

k is Boltzmann's constant.

$q = 1.6 \cdot 10^{-19}\, Coul$

$k = 1.38 \cdot 10^{-23}\, J/K$

E_G it is considered band gap for Silicon (1.1 eV) monocrystalline and polycrystalline **[5]**

E_G it is considered band gap for Silicon (1.6 eV) amorphous thin film **[6]**

The thermal voltage is:

$$V_t = \frac{k \cdot T}{q} \quad (5)$$

The resistance is calculated according to DGS **[7]** :
Standard conditions are fixed like: ***Go*** = 1000 W/m2 ; ***To*** = 298 K

$$R_{PV(G_0,T_0)} = -M_{(G_0,T_0)} \cdot \frac{I_{sc_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}} + \frac{V_{MPP_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}} \cdot \left(1 - \frac{I_{sc_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}}\right) \quad (6)$$

$$M_{(G_0,T_0)} = \frac{V_{oc_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}}} \cdot \left(k_1 \cdot \frac{I_{MPP_{(G_0,T_0)}} \cdot V_{MPP_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}} \cdot V_{oc_{(G_0,T_0)}}}\right) + k_2 \cdot \left(\frac{V_{MPP_{(G_0,T_0)}}}{V_{oc_{(G_0,T_0)}}}\right) + k_3 \cdot \left(\frac{I_{MPP_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}}}\right) - k_4 \quad (7)$$

$k_1 = -5.411; k_2 = 6.450; k_3 = 3.417; k_4 = -4.422$ **[7]**

2.2 Weather Conditions

It is known that the tracker will work differently when changes in low radiation are produced during the day (sunset or sunrise), an algorithm with constant voltage is expected to work better. When changes in high radiation occur, in the middle of the day, an Incremental Conductance tracker, Perturb and Observed and Newton Rapshon are expected to work better (**[2],** p.3). The technology must work with high radiation as well as low radiation. The current versus voltage curve is flatter in low radiation and that makes it more difficult to track the MPP (*Figure 3*). Also the algorithms behave in different ways when big or small variations of irradiance are produced. For example, Perturb and Observe algorithm is not expected to reach high efficiencies with big variations. Therefore irradiance changes, season radiation (high and low radiation) and size of radiation (big and small variations) will be carried out (A.- A clear sky in high irradiances, B.- A clear sky with some clouds in high irradiances, a covered sky, a clear sky without clouds, a partly cloudy sky…E.- Covered sky with some clears in low irradiances, are some examples). Some changes in radiation are simulated as steps and other ones are simulated as a polynomial equation that represents the steps of irradiation as a parabolic shape (radiation versus time).

The temperature starts increasing during the first hours of the day and continues until the middle of the day when it starts decreasing. Although the irradiance could fluctuate, the tendency is to increase until the middle of the day. Therefore temperature is usually increasing when irradiation does. Temperature follows the same pattern, however not as many fluctuations can be observed (K.- A summer day with a clear sky in high irradiances; M.- A winter day with a clear sky in low irradiances…). The temperature changes are simulated as in an actual day. These increase during the day in a polynomial curve of fifth grad (11). Temperature and irradiance simulations have been made separately and together. In the following section, the case B.- A clear sky with some clouds in high irradiances and case A.1.- A clear sky in high irradiation considering polynomic representation were cjoosen among the others to be compared. Section 5 contains the data coming from the other studies.

In the following graphs (*Fig. 3* and *4*), the behaviour of solar panel curves, when the temperature keeps constant and irradiance increases and viceversa, can be observed. It will be used in the MPP sections to make some considerations.

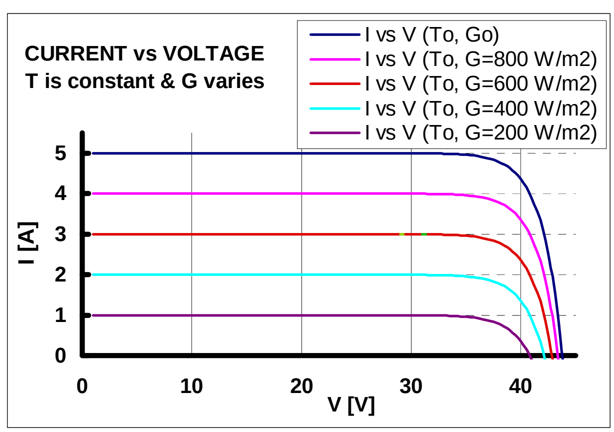

Figure 3. Current versus voltage in cell with T constant

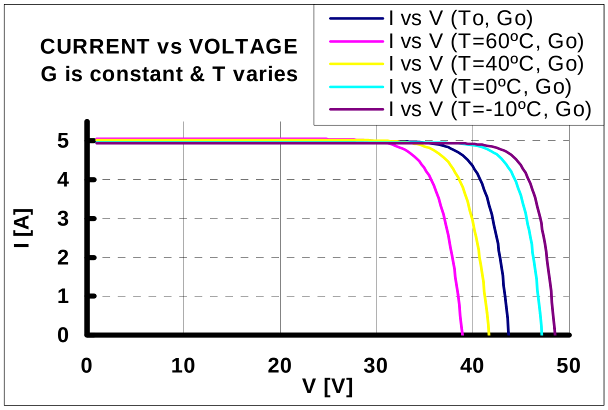

Figure 4. Current versus voltage in cell with G constant

3. MPP Trackers

The algorithms that will be explained later can be grouped into two categories: Indirect algorithms estimate the MPP voltage by means of simple measurements and direct algorithms, the optimum operating voltage is consequent from measured currents, voltages or the power of the PV generator (to be able to respond to quick changes) **[1].** Here the *Figure 5* represents the algorithm analysed in this work within the categories previously named before. The Flexible Area is a mix between these two categories. Here Flexible Area and Newton Rapshon are analysed in depth. Flexible Area uses concepts similar to Incremental Conductance and Constant Voltage.

CATEGORIES OF TRACKERS	
INDIRECT	**DIRECT**
Constant Voltage	**Newton Rapshon**
	Perturb and Obseve
	Incremental Conductance
Flexible Area	

Figure 5. Categories of the trackers

3.1 Perturb and Observe Algorithm

The Perturb and Observe algorithm has been explained in detail in different papers **[2], [3]** and **[4].** The algorithm shows the changes when the irradiation or temperature varies, however the proportion of change cannot be determined (*Fig.6 and 7*). The P&O does not work well when the irradiances rapidly change. This is one of the disadvantages because the P&O depends on the configured step voltage and only compares the present power versus the previous one (*Fig.7*).

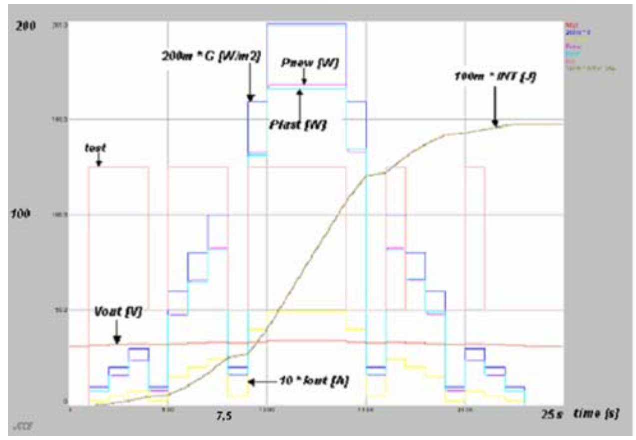

Figure 6. P&O Simulation of a clear sky with some clouds in high irradiances (P&O, B.-)

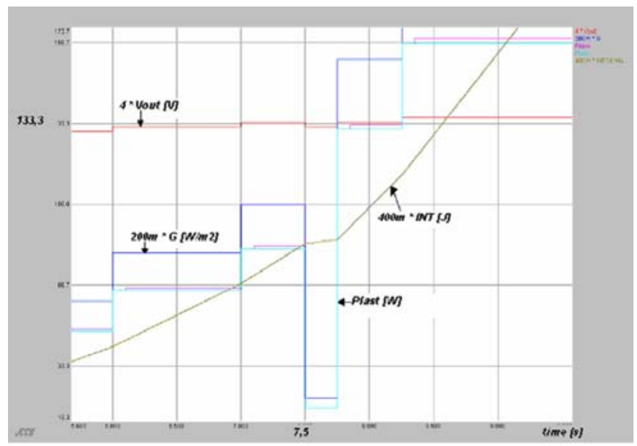

Figure 7. Depiction of Figure 6 in detail

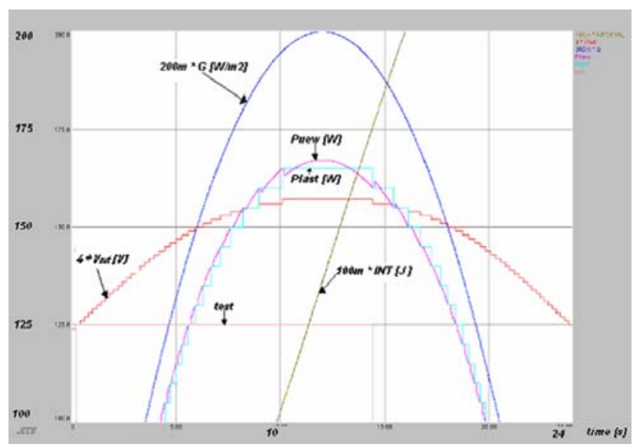

Figure 8. P&O Clear Sky in High Irradiances in parabolic representation (P&O, A.1.-)

3.2 Newton Rapshon Algorithm

The Newton Rapshon algorithm is a mathematic algorithm that finds approximations to the roots of a function. Here, it is used to find a minimum or maximum of a function, by finding zero in the function's first derivative **[10].** It is easy to understand the method: It starts as an initial value close to the root, then the function is approximated by its tangent line. This tangent line cross the X axe at a point which could be known by mathematic equations. Therefore, this point or approximation to the root, will be better every time the algorithm is repeated by iterating. NR tracker uses Rapshon iterative method to obtain the voltage in the maximum power point.

$$f'(V) = \frac{\partial^2 P}{\partial V} \tag{8}$$

$$f'(V) = -I_s \cdot \frac{\alpha}{n} \cdot \left(e^{\frac{\alpha \cdot V}{n}} \right) \cdot \left[2 + \frac{\alpha \cdot V}{n} \right] \tag{9}$$

P is the power;

$$\alpha = \frac{q}{A \cdot k \cdot T} \tag{10}$$

V is the array voltage.

Newton Rapshon iterative method is defined as (using $f(V)$):

$$V_{n+1} = V_n - \frac{f(V)}{f'(V)} \tag{11}$$

n here is the iterations steps

The next box diagram, *Fig.9*, indicates how the simulation was obtained. Some changes in notation were made, ***fn_p*** means $f'(V)$, for example.

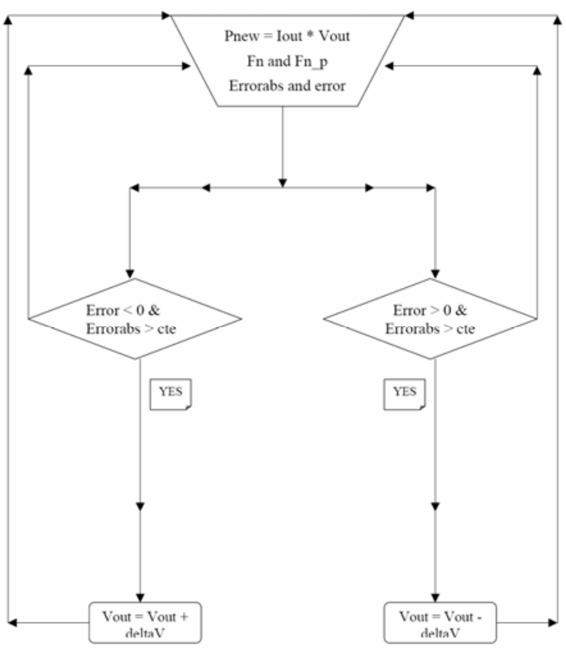

Figure 9. N&R Flow Chart

Fn : The first derivative to the Power.

Fn_p : The second derivative to the Power.

Error: It is the ***deltaV*** which as closest the root is as taking the zero value.

Errorabs: It is the absolute error to Error. ***DeltaV:***

$$\Delta V = \frac{|f(V)|}{|f'(V)|} = \frac{|f(V)|}{\frac{|f(V)|}{\Delta V}} \tag{12}$$

If the error is negative, that means that the actual voltage out is situated at the left side of the MPP, therefore Vout is increased. If the error is positive, that means that the actual voltage out is situated at the right side of the MPP, therefore Vout is decreased. It can be observed by calculating the tangents on the $f'(V)$ vs the ***V*** curve.

The most important advantage is that the proportion of the irradiation jump can be seen by the N&R algorithm, this means the ability to relate the change in the PV array power to the change in the atmospheric conditions (*Fig.10 and 11*). The error on the graph clearly represents this situation. In *Fig.10* it can be observed that the algorithm NR doesn't compare Powers, it compares ***error*** or ***deltaV***. Therefore NR has the flexibility to increase a constant step voltage or a voltage depending on this error. As a result, the MPP is acquired faster (*Fig.12*)

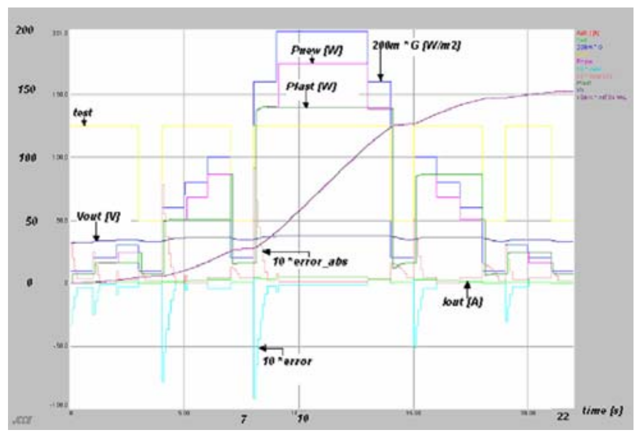

Figure 10. N&R in High radiation with some clouds (N&R, B.-)

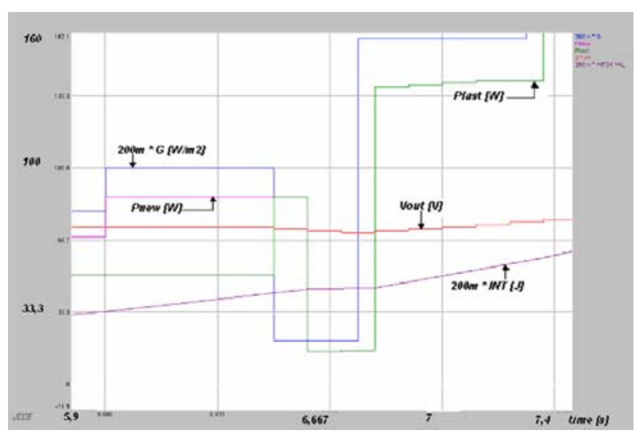

Figure 11. Depiction of the Figure 7 in detail.

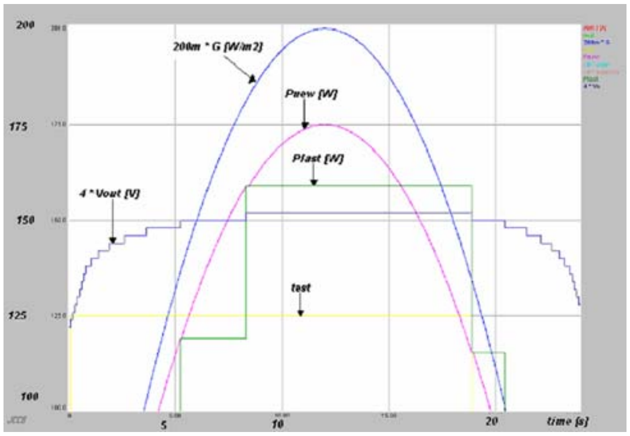

Figure 12. NR Clear Sky in High Irradiances in parabolic representation (NR, A.1.-)

3.3 Flexible Area Algorithm

A maximum power point tracker, using similar concepts from Constant Voltage **[2], [5]** and Incremental Conductance **[2],** is introduced here. It can be checked in some tests **[2], [8], [9]** how the maximum power point and the open circuit voltage (among other parameters) are moving on a current versus voltage diagram when radiation fluctuates. Also, some of these diagrams are provided when temperatures change **[2].**

When all these diagrams are examined carefully it can be emphasized that open circuit voltage movements are similar to maximum power point voltage movements (*Fig.3* and *4*). If the temperature is increasing, both of the open circuit voltage and MPP voltage movements are moved toward the left side. However, if the irradiation is increasing, they will move towards the right side. It was also checked that these movements, ***ΔVoc*** and ***ΔVmpp,*** are made in approximately the same proportion in temperature changes and irradiation changes. That can be taken to approximate the area where the maximum power point voltage is located (***ΔVoc = ΔVmpp → Vout= Vout + ΔVoc).***What happens when ***ΔVoc*** is almost zero? For example, when the temperature is kept constant and a light change of irradiation occurs. Here ***dI*** is observed, if ***dI*** is increasing, for example, the ***Vmmp*** moves slightly to the right side and viceversa. Then the voltage of reference here (voltage out) should be increased. But, how much should this reference voltage be increased? The arrangement is to fix a ***ratio*** between voltage and current and the product of ***ratio*** and ***dI*** is added to voltage out (***Vout= Vout + dI * ratio)***. That means an approximately flexible area or variable area would be configured in each cycle.

$$ratio = \frac{(V_{oc})_{G=1000W/m2} - (V_{oc})_{G=5W/m2}}{(I_{sc})_{G=1000W/m2} - (I_{sc})_{G=5W/m2}} \qquad (10)$$

The most important advantages are the simplicity and the speed where the maximum power point is located (*Fig.13 and 14*). Power losses could not be avoided because only an approximation of the area where the MPP voltage is located was calculated. In *Fig.15* peaks of power loss can be observed.

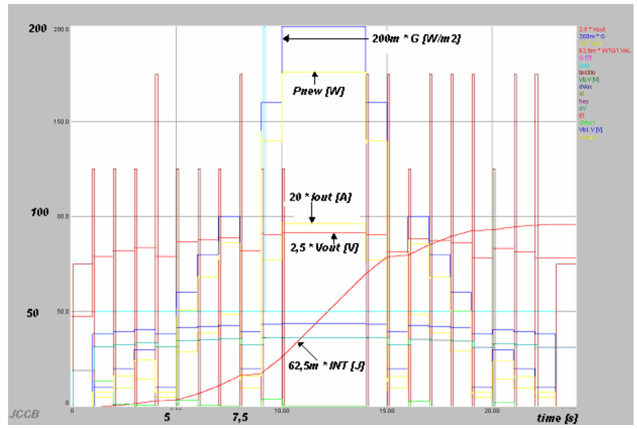

Figure 13. FA in Clear Sky High Irradiation with some clouds (FA, B.-)

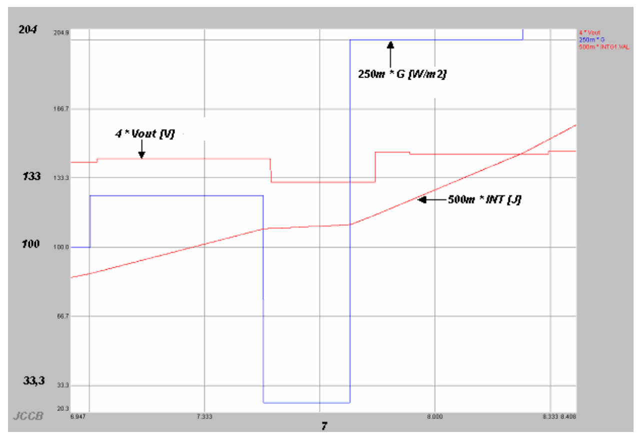

Figure 14. Depiction of Figure 10 in detail.

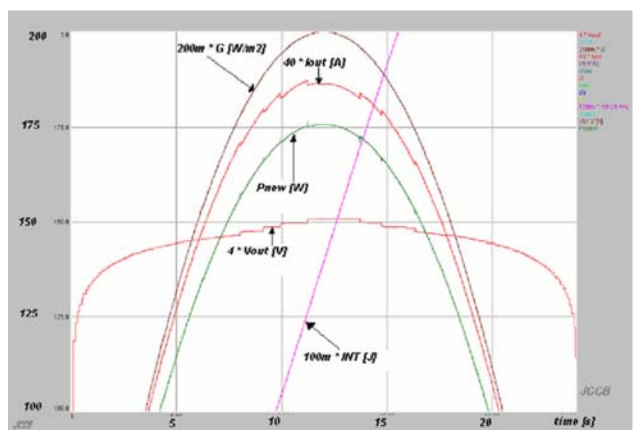

Figure 15. FA Clear Sky in High Irradiances in parabolic representation (FA, A.1.-)

3.4 Comparison of Algorithms

The MPP is tracked in different ways by the algorithms explained above when the irradiance drops or during a complete day where the irradiation slowly increases, among other cases. In P&O just one change in voltage is done (*Fig.6 and 7*) because it only compares present with previous power. The previous power is bigger, in this case, and the voltage is decreased. However, in the next step the previous power took the same value as the present one. Therefore when the irradiation remains constant, P&O will not be able to make new changes in voltage. The irradiation change is a step, as a result, in the next cycle no values in the middle of the irradiation can be found. If irradiation was a ramp, it would have as many changes of voltage as of cycles during the irradiation change. NR compares errors –***delta V*** (*Fig.10*) and FA only make an approximation between CV and INC (*Fig.13 and 14*), therefore, this disadvantage is avoided. That is to say, NR is more accurate than FA. In P&O an adjustment is made to avoid the algorithm from moving continually around MPP without settling down on it. However the dependence with the voltage step can not be avoided in P&O (*Fig.8*). If the step voltage increase is bigger, the MPP voltage is located quickly, but without precision and when the voltage increase is smaller, viceversa. FA gets an approximate MPP quicker than NR, however, it has more losses of power (peaks of *Fig.15*). The most important characteristic obtained in NR is the relationship between irradiance changes and error. Irradiation changes are proportional to error changes. Just making a relation between this error calculated by NR and how much the voltage should be increased, the MPP voltage is quickly obtained. In the parabolic depiction in *Fig.12*, above 900 W/m2 the tolerance is larger than MPP voltage changes, therefore there is no change.

4. Efficiency Analysis

The Energy Conversion Efficiency of the Tracker ($\eta_{MPP_{track}}$) or Mean Power Conversion Efficiency (calculated as the energy divided by the time which is taken to measure this energy) is the ratio between the output energy extracted using the tracker and the theoretical energy that the solar panel could provide if the MPP tracker would track the maximum power point perfectly. In this work the output energy extracted using the tracker is given by an integrator (it can be seen in all graphs as ***INT.***) fixed in Simplorer **[11]** with the algorithm and the circuit equivalent running out according to temperature and irradiance conditions described in section 2.2. An example explaining these files is introduced here. The selected case was the K.- Irradiation and Temperature changes in a Clear Sky in High Irradiances.

The changes in irradiation are introduced in Simplorer by states and transitions as steps. The temperature condition is introduced as an equation (***K:=function (t)***). In this example:

$$K = 2\cdot 10^{-15}\cdot t^5 + 0{,}0007t^4 - 0{,}0341t^3 + 0{,}3666t^2 + 1{,}0239t + 290{,}33 \qquad (11)$$

$$R^2 = 0{,}9971$$

K is the Temperature in Kelvin

T is the time.

R^2 is closer to 1 as better approximation.

Theoretically the power is calculated multiplying the MPP current by the MPP voltage in every irradiance and temperature.

Now the confidence interval is introduced. This interval uses ***alfa*** (0,05 means 95 % of probability), ***desv*** is the standard deviation and the sample size is ten. This function returns a value used to construct a confidence interval. This value comes from a normal distribution knowing the standard deviation (***desv***), the ***mean (promedio)*** and the size of the sample (***size***). The error voltage in the MPP can have 95 % percent confident within the interval which takes as minimum value ***LOW*** and as maximum value ***HIGH*** **[12].** Therefore, the maximum power point voltage in the different irradiances given by *K.*- would be within: **[*Vmpp* – 0'19 , *Vmmp* – 0'02].** *In a 95 % probability for* ***G*** *= 1000 W/m2 and the* ***T****= 311 K, the* ***Vmmp*** *is within the interval* **[36'39 , 36'48].** Then all Energy data coming from the Integrator of Simplorer (***INT***.) are introduced and the effciency is calculated. All cases mentioned in section 2.2 are linked in *Table 1*. Thus the correct interpretation of all efficiency data is within interval. ***PO: [91'3 ; 96'3]; NR: [96'1 ; 98]; FLEX A : [93,2 ; 98,3]*** as represented in *Fig.16***.**

Fig.16 shows that the Newton Rapshon algorithm is the most efficient. It can be observed NR has the narrowest volatility or margin with just less than two. The next one more efficient is the FLEX A, using Incremental Conductance and Constant Voltage concepts, because the volatility is the same compared with Perturb and Observe (around 5) and the mean efficiency is bigger.

Table 1
Efficiency analysis all cases

	EFFICIENCY		
CASE	PO	NR	FLEX A
A.-	87,1	96,9	88,0
B.-	93,4	96,6	98,2
C.-	96,3	95,5	97,4
D.-	97,4	98,1	96,1
E.-	93,9	97,6	98,0
F.-	98,4	99,9	100,0
G.-	96,5	96,6	97,2
H.-	95,7	96,8	97,4
K.-	87,1	98,2	88,5
M.-	92,3	94,1	96,7
Mean	93,8	97,0	95,8
desv	3,98	1,57	4,10
alfa	0,05	0,05	0,05
size	10	10	10
conf.interv	2,47	0,97	2,54
LOW E	91,3	96,1	93,2
MEAN	93,8	97,0	95,8
HIGH E	96,3	98,0	98,3

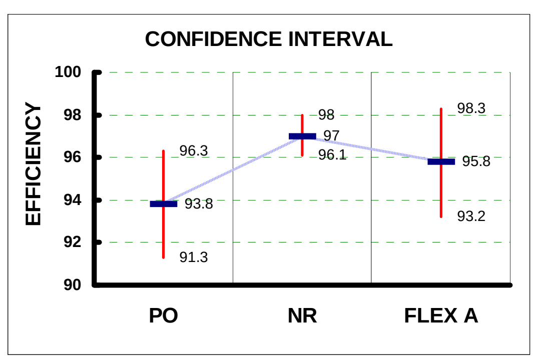

Figure 16. Confidence Interval of Efficiency

5. Conclusion

The efficiency of the solar panel is deeply connected with its ability to track the maximum power point. The most significant advantages and disadvantages among the MPP trackers analysed are shown in the following table:

Table 2
Advantages and disadvantages of the trackers

Alg.	ADVANTAGES	DISADVANTAGES
Const Volt.	Easy to implement in circuitry	Power losses when charge is disconnected
Incremental Conductance	Good performance under rapidly changing atmospheric conditions	The condition **dP/dV=0** seldom occurres. It can be solved with marginal errors (**E**) in the conditions.
Flexible Area Algorithm	Simplicity and the area where the maximum power point is located is fixed quickly. *(Fig.14)*	Peaks of current could happen if the Voc is measured at the same time that the Power increases.
NR	Irradiation and temperature effects are considered good together.	In low irradiances, the algorithm cannot see the changes perfectly.
	The proportion of the jump in irradiation can be seen. *(Fig.11)*	
	It maximizes the power from the solar array in most cases (*Fig.12*)	
Perturb and Observe	Robustness and simplicity	It does not always correctly consider irradiation and temperature effect together.
		It can see the irradiation change but it cannot appreciate the proportion of this change *(Fig.7)*.
		Doesn´t work so well when the radiation varies rapidly, for example, according to fast changing atmospheric conditions. (*Fig.8*)
		Power losses when the algorithm is moving continually around MPP without settling down on it.

The efficiency analysis results show that the best efficiencies are reached with N&R [96,1;98] in comparison with P&O [91'3, 96'3] or the FLEXA [93,2 ; 98,3]. Therefore the Newton Raphson Algorithm is suggested to implement in DSP **[13].** Also the mean value of efficiency is more centered than the other ones **[14]**, **[15].**

References

[1] Antonio Luque and Steven Hegedus, *Handbook of photovoltaic science and engineering* (NJ: John Wiley & Sons,Ltd; 2003).

[2] Cristinel Dorofte, Uffe Borup and Frede Blaabjerg, A combined Two-Method MPPT Control Scheme for Grid-Connected Photovoltaic Systems, *Power Electronics and Applications, 2005 European Conference*, 11-14 Sept. 2005, Page(s):10 pp.

[3] K.H.Hussein, I.Muta, T.Hoshino and M.Osakada , Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. *Generation, Transmission and distribution, IEE Proceedings*, *142*(1), Jan 1995,59-64

[4] C.Hua, J.Lin and C.Shen, Implementation of a DSP-controlled photovoltaic system with peak power tracking Industrial Electronics, *IEEE Transactions*, *45*(1), Feb.1998, 99-107.

[5] C.Hua, C.Shen. Comparative study of peak power tracking techniques for solar storage system. *Applied Power Electronics Conference and Exposition. APEC 98. Conference Proceedings 1998, Thiteenth Annual*, (2), 15-19 Feb. 1998, 679-685

[6] M.Jantsch, M.Real, H.Häberlin, C.Whitaker, K.Kurokawa, G.Bläaser, P.Kremer and C.W.G.Verhoeve, Measurement of PV maximum power point tracking performance. *Proc. Of the 14th European photovoltaic solar energy conference and exhibition, 1997. PV Systems, Technical Committee 82: Photovoltaic, Netherlands Energy Research Foundation ECN.*

[7] German Solar Energy Society (DGS), *Planning and Installing Photovoltaic Systems: a guide for installers, architects and engineers* (London, NJ: James&James, 2006).

[8] Yushaizad Yusof, Siti Hamizah Sayuti, Muhammad Abdul Latif and Mohd. Zamri Che Wanik, Modelling and simulation of maximum power point tracker for photovoltaic system, *Power and Energy Conference, 2004. PECon 2004, Proceedings. National*, 29-30 Nov. 2004, Pages: 88-93.

[9] G.J.Yu, Y.S.Jung, J.Y.Choi, I.Choy, J.H.Song and G.S.Kim. A novel two-mode MPPT control algorithm based on comparative study of existing algorithms, *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty_Ninth IEEE. 19-24,* May 2002, 1531-1534

[10] Endre Süli and David Mayers, *An Introduction to Numerical Analysis* (NJ: Cambridge University Press)

[11] Simplorer 7 *www.ansoft.com/products/em/simplorer*

[12] Robert Boardman, *Analyzing business data with excel* (NJ: O'Reilly).

[13] Roger A. Messenger and Jerry Ventre, *Photovoltaic Systems Engineering* (NJ:CRC Press).

[14] F. Benecke, H. Güldner, Equivalent circuit based algorithm-A new proposal for control of solar generators, *6th IASTED International Multi-Conference, Power Generation and Renewable Energy Sources*, 13-15 May, 2002.

[15] R. Teodorescu, PV Inverter Topologies and Control Structures, *39th Annual Power Electronics Specialists Conference, Tutorials*, 15-19 June, 2008.