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Review of the Best MPPT Algorithms for control of PV Sources
RUCA Tracking Algorithm

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Keywords: Maximum Power Point Tracking, Perturb and Observ algorithm (PO), IncCond, Hill Climbing, Boost converter, Robust Unified Control Algorithm (RUCA).

Abstract: Renewable energies, has generated more and more interest of research in control of the HyRES. Thousand of papers deal with MPPT (Maximum Power Point Tracking) to optimize harnessing solar energy. The intent of this paper is to review the most interesting Algorithm and to propose a Robust Unified Tracking Algorithm.

1 INTRODUCTION

The conversion systems of renewable energy sources, as they include commutations and discontinuities, are VSAS (Variable Structure Automatic Systems) and highly dependent on variations in climate parameters, such as temperature and irradiation (Schaefer, 1990).

A great variety of MPPT methods have been proposed by the researchers and competition between the algorithms to be implemented continues. A good classification will help future applications in PV systems and give a convenient reference on the required system features.

In this paper, we present a review of the existing methods, propose a classification and try to find the best of them. Three categories of MPPT schemes exist: open loop, closed loop and hybrid methods; They can also be classified with regard to model based methods or robust optimisation. Then we propose a new technique which unify and robustify the algorithms. The Robust Unified Control Algorithm is proposed to track the maximum power point (VSAS-MPPT) based on Variable Structure Automatic Systems approach.

The purpose of this study is also to analyze and compare execution efficiency for the proposed RUCA-MPPT algorithms to well known power control type MPPT methods, including Perturbation and Observation (P&O), Incremental Conductance (InCond) and Hill Climbing (HC) methods, simulated in Matlab/Simulink environment in order to compare their performance (Yu and Shen, 2009; Tavares et al., 2009).

The paper is organized as follows. The second section presents standard photovoltaic system equations and features. Section three reviews the different control algorithms proposed for tracking the maximum power point (MPP) and then in section four the analysis and discussion lead us to introduce our new algorithm. After VSAS-MPPT definition, we compare the results of the RUCA with the widely used MPPT algorithms; the performance is evaluated on the energy point of view, in simulation, considering different actual solar irradiation measured variations. Finally, a conclusion summarizes the work and proposes perspectives.

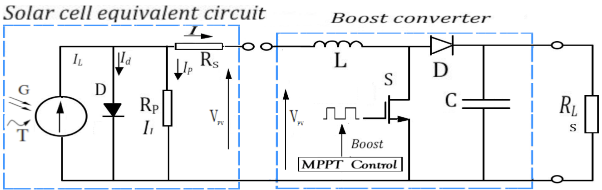

Figure 1: Equivalent circuit model of PV panel

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PV modules (panels) are composed by combination of several solar cells, connected in series and in parallel circuits, to generate higher power (Liu et al., 2008).

The equivalent circuit of the general model, as illustrated in left of figure 1, consists of a photo-current, diodes, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow.

The PV circuit is connected to the load (R_L) trough a DC-DC converter in order to adjust (adapt) the operating voltage and current of the PV panel at optimal values to maximize the harnessed power. The control of the boost has to tracks the Maximum Power Point (figure 2).

Mathematical description of I(V) Input/Output characteristics for a PV cell has been studied for over the past four decades. The PV system exhibits then a nonlinear I(V) characteristic which depend on the temperature and the solar radiation which vary during a day. The PV characteristics (I = f (V) and Ppv = f (V)) are represented by the figure 2 under constant temperatures (Ta=10, 30, 50 and 70°C) and irradiation Gs=1000 w/m2.

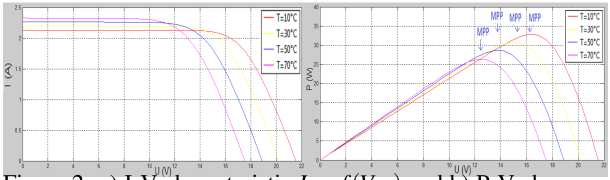

Figure 2: a) I-V characteristic $I = f(V_{pv})$ and b) P-V characteristic curve $P_{pv} = f(V)$ of PV module

Te DC-DC converter is used as a power interface circuit between the PV panel and the load or battery. This circuit consists, in its simple way, of only a switch (typically a MOSFET), an inductor, and a capacitor connected as shown in figure 1. To achieve the optimum matching and track the power Maximising point, a good control of the DC-DC is necessary.

3 THE MPPT CONTROL

3.1 The Open Loop Methods for MPPT

3.1.1 Fixed Operating Point

The problem is to find the voltage V_{MPP} or the current I_{MPP} at which the PV array delivers the maximum power under a given temperature T and irradiance G. Then the method automatically puts the PV in this condition. The first remark was that the MPP varies in a small region and that on the left part of the P-V characteristic, the slope P/V is roughly constant.

Fractional Open-Circuit Voltage The first method uses the observation that, the ratio between array voltage at maximum power V_{MPP} to its open circuit voltage V_{OC} is nearly constant. $\frac{V_{MPP}}{V_{OC}} \approx k_1$. The factor k_1 is not constant but, has been remarked to be between 0.71 and 0.78. Once the constant k1 is known, V_{MPP} can be computed.

This method consists in measuring V_{OC} periodically and then fixing $V_{MPP} = k_1 V_{OC}$.

The implementation is simple and cheap, but the tracking efficiency is relatively low due to inaccurate values of the constant k_1 in the computation of V_{MPP}.

Fractional Short-Circuit Current This method is based on the remark that the current at maximum power point I_{MPP} is approximately proportional to the short circuit current I_{SC} of the PV array. $I_{MPP} \approx k_2 . I_{SC}$

The factor k_2 is not constant but, has been remarked to be between 0.78 and 0.92. Once the constant k1 is known, V_{MPP} can be computed.

The accuracy of this method and its tracking efficiency depend on the accuracy of knowledge of k_2 and the periodic measurement of short circuit current I_{SC}.

3.1.2 Artificial Neural Networks, ANN for MPPT

ANN are well known to provide universal approximators providing non-linear models which are complementary to the conventional modeling techniques. Back propagation ANN are used as pattern classifier or as non-linear layered feed-forward networks to give a global approximations to a non-linear input-output mapping (Reisi et al., 2013). The first application of ANNs to MPPT, has been proposed by Hiyama et al (Hiyama and Kitabayashi, 1997).

In general a three layer structure, i.e. input layer, hidden layer and output layer are used with the back propagation. After a good learning, ANN are able to make generalizations in regions of the phase space where little is known or no data are available. The Neural network is composed by neuron cells, placed in 3 layers (or may be more) connected to all neurons through weights see figure below. The input variables are PV parameters like V_{OC} and I_{SC}, atmospheric data (Irradiance and Temperature). The output of ANN gives reference signals, like the reference voltage or the duty cycle signal used to drive the power converter to operate at or close to the MPP.

The three layers of neural network have a hyper tangent sigmoid function (Noguchi et al., 2002). The algorithm used for training is back-propagation. The back-propagation training algorithm needs inputs and the desired output to adapt the weight by MSE.

The characteristics of a PV array are nonlinear and time-varying, this implies that the neural network has to be trained to guarantee accurate tracking of MPP. This is a time consuming process. Note also that it can use as inputs the voltage and current measurement, to become a closed loop method or a combination of both.

3.1.3 Fuzzy logic method (FL)

Fuzzy logic controllers offer the advantage of working capability with imprecise inputs, and do not need an accurate mathematical model. They can handle nonlinearities, and have fast convergence. Their learning ability and accuracy depend on the number on the fuzzy levels and the the membership functions. The decision-making uses rules specified by a set of IF–THEN statements to define the control which produce the desired behavior. The defuzzification stage, operates the reverse function to get numerical variables for analog control using the membership function.

In order to track MPP, the error is computed based on irradiance and temperature or instantaneous values such as power and voltage (Algazar et al., 2012). The output signal is either the duty cycle itself, or V_{MPP} and I_{MPP} reference to generate the duty cycle.

The membership function associated with fuzzification and defuzzification, as well as the antecedent and the consequent fuzzy rules are determined by trial and error. This can be time-consuming. This method can be used in open loop or in closed loop when using as feedback (in real time) the output variables like current, voltage and the power.

3.2 The Closed Loop MPPT

3.2.1 Perturb and Observe Methods

The most commonly used MPPT algorithm is the Perturbation and Observation (P&O) due to its easy implementation. It uses the P-V characteristics $P_{pv} = f(V)$ of the PV module shown in figure 3 (b). Note that the point of maximum power P(n)=V(n)I(n) is obtained when the condition $\frac{dP}{dV} = 0$ is accomplished, regardless of the sun irradiance magnitude (Kim et al., 2001). In actual experiments, the system oscillates aroumd the MPP. To minimize the oscillations amplitude, we can reduce the perturbation step size. However, small step size slows down the convergence of the MPPT.

The Modified Enhanced Perturb and Observe (MEPO) algorithm uses and adaptive step adjustment gain and simplify the implementation using on commutation functions. This algorithm have been revisited, its rationale behind have been clarified and then implementation obviated using commutation functions (Msirdi and Nehme, 2015).

3.2.2 Incremental Conductance Methods

The incremental conductance (IncCond) (Femia et al., 2004), method is based on the fact that the slope (or the PV conductance $G = \frac{dI}{dV}$) of the PV array, in the power curve is zero at the MPP and it is positive (constant) on the left of the MPP. The slope becomes negative on the right of th MPP.

3.2.3 Hill Climbing Method

The basic idea of the HC (Hill Climbing) method is the same as P&O method. It tests if P(n) is greater than P(n-1) or not, to reach MPP. The PO method uses instead a test on dP/dV to determine whether the maximum power point has been found or not. However, the HC method uses a test condition on P(n)-P(n-1).

3.2.4 Extremum Seeking Control method (ESC)

Krstic et al. (Ariyur and Krstic, 2003), from automatic control community interested on robust and adaptive control techniques, proposed an adaptive ESC methodology which has been proved to be robust against parametric uncertainties for non linear dynamic uncertain systems. It is based on theories namely averaging theory, adaptive control and singular perturbation techniques. This real-time optimization ESC method has been successfully applied in various systems and has been specifically adapted for PV systems in order to track MPP (**?**; **?**). Extension to ESC by Newton Like optimisation has been also considered and compared to other ESC based methods (Zazo et al., 2012). The objective of ESC is to rapidly reach the MPP despite uncertainties and disturbances on the PV panel and the load.

The reference current is perturbed by a sinusoidal modulation. The power got at the output of the PV system is high pass filtered, to get only effect of the perturbation ($\triangle P(t)$) on the obtained power $P(t)$. Then, after the ripple demodulation to get the produced power perturbation observed ($\xi(t)$), integration with an adaptive gain $C(p)$ of this effect gives the reference current. The adaptation gain $C(p)$ is adjusted by a theoretical study to get fast convergence to the optimum power (MPP). The controller will, therefore, adjust the reference current until MPP is reached.

The main advantages of ESC are that the power optimization is got by a dynamic adaptation-based feedback for a sinusoidal perturbation and convergence to the MPP is guaranted. This approach does not require any parametrization or structural formalization of the modeling uncertainty. The disadvantage of ESC is its complexity and the implementation difficulties regard to PO and MEPO.

3.2.5 RSMCA: Robust Sliding Mode Control Algorithm

A lot of algorithms have been proposed based on Sliding Mode. The most of them are not very precise when defining the objective of the algorithm and chosing the sliding surface. They simply has been develop as alternative to use of a standard regulator like PID controller. This reduces the efficiency of the Sliding Mode Approach and does not tackle the robustnes problem. The most of them use a sliding surface to reach the MPP. The best choice seems to be given by the proposed criteria in equations (1 and 2).

In the following we propose an MPPT based on the VSAS and the Lyapunov theory which generalizes all the previous algorithms. The desired objective to get is that the MPP reached when the maximum power is obtained $\frac{dP}{dt} = 0$.

Note that the optimization is done versus time because P varies during time in function of the voltage V and the current I. Only if current I (respectively the voltage V) is maintained constant we can consider P(V) (respectively P(I)) characteristic. Note also that in real weather condition the Operating Point do not moves on a unique (P-V) characteristic. If the irradiation or the temperature changes the MPP varies from one curve to another one.

Then as $P(t) = V(t).I(t) = f(V,I,t)$, the power is function of the voltage, the current and time, then the required Maximum Power Point to Track is really defined by the following objective function which we propose to take as the generic sliding surface:

$$\frac{dP}{dt} = \frac{dVI}{dt} = I\frac{dV}{dt} + V\frac{dI}{dt} = 0 \tag{1}$$

Let us consider the control in case of discrete time, like do all the above presented algorithms, with the previously defined variables (see equation 5) the fetched MPPT may be defined by $\Delta P(k) = 0$, then as $\frac{dP}{dt} = 0$ can be approximated by $\Delta P(k) = (I(k)\Delta V(k) + V(k)\Delta I(k)).\triangle t$

The objective function that we propose in (M'Sirdi et al., 2014) becomes then:

$$\Delta P(k) = I(k)\Delta V(k) + V(k)\Delta I(k) = 0 \tag{2}$$

The control variable is either, in the first case, $u_1(k) = \triangle V(k)$, which means that the voltage perturbed and the current is fixed $u_2(k) = \triangle I(k) = 0$, or in the second case, the control variable is $u_2(k) = \triangle I(k)$, the current is pertubed and the voltage is fixed $u_1(k) = \triangle V(k) = 0$. In control context, the previously presented **MPPT controllers use only one control variable u_1 or u_2 and impose the second to zero**. Let us consider the MPP reaching condition $\frac{dP(t)}{dt} = 0$ and note that the maximum power is always $P_{max} \geq P(t)$ every where and at any time. We can choose as Sliding Surface $s(t) = P_{max} - P(t)$ which goes to zero (or at least to its minimum) when $P(t) = P_{max}$ (Msirdi and Nehme, 2015). We can also take zero instead of a positive constant $P_{max} = 0$.

Let us then consider the Lyapunov like function $W(t) = s^2 = [P_{max} - P(t)]^2 > 0$ which is strictly positive every where except at the MPP where it goes to zero. Lyapunov based control design is well known to give robust algorithms.

The derivative of this Lyapunov function $W(t) = s^2 > 0$, is $\dot{W} = s\dot{s} = -[P_{max} - P(t)].\frac{dP(t)}{dt}$.

This term is negative when $-\frac{dP(t)}{dt} = -I\frac{dV}{dt} - V\frac{dI}{dt}$<0. This equation is similar to the proposed Sliding Surface equations (1 2 **??**). Please note also the similarity with the InCond equation (**??**). This means obviously that we only need, from control, to make $\frac{dP(t)}{dt} > 0$, to reach the MPP.

as we impose $\frac{dI}{dt} = 0$, we get $\dot{W} = -I\frac{dV}{dt}$

It can be made negative by choosing the appropriate control laws $u_1(k) = \triangle V(k)$ and $u_2(k) = 0$. Note that this can be reached by choosing the sign of $u_1(k) = V(k)$, such as to get $\dot{W} < 0$.

Choosing $u_1(k) = \triangle V(k) = \triangle P(k).\alpha.sign(\triangle V(k))$ and knowing that we impose $u_2(k) = \triangle I(k) = 0$ like in the control algorithm, we have previously proposed MEPO (Msirdi and Nehme, 2015). This gives us $\triangle W = -\alpha.\triangle P(k).sign(\triangle V(k))I(k)$. If the gain parameter α is positive constants, we then get a negative derivative

$$\triangle W = -\alpha.\Delta V(k).sign(\triangle V(k))I^2(k) < 0 \tag{3}$$

This method, called MEPO (Modified Enhanced Perturb and Observ) gives an enhanced and variable step size algorithm. The step size is adjusted in proportionally to the power variation produced in the previous step. The step adjustment gain $K = \alpha.\triangle P(k)$ is used for weighting this adjustment step. It may be useful for oscillation avoidance and noise sensitivity.

This proves, theoretically the convergence of the RSMC algorithm and shows that Robust Sliding Mode Control is equivalent to the MEPO algorithm got by enhancement of the P&O.

We propose, as a modified PO Algorithm which will be more robust, the reference voltage is given by

$$Vref = Vk + \alpha.\triangle P.sign(\triangle V) \tag{4}$$

The algorithms have been tested under various operating conditions. The obtained results have proven that the MPPT is tracked even under sudden change of irradiation level.

3.2.6 RUCA: Robust Unified Control Algorithm

VSAS (Variable Structure Automatic Systems) control methodology was applied to clarify the rationale behind Maximum Power Point Tracking and get the best optimization algorithm. We have seen previously that the control is either on voltage or on current input or both. For the proposed RUCA algorithm, both controls can be used if we look for adjusting both variables (V and I), either at each control step or alternatively.

Two new algorithms can be developed, using this approach, the Modified and Enhanced Perturb and Observe Algorithm (**MEPO**) if the control input is on the voltage or the Modified Enhanced InCond (**MEInCond**) if the control input is on the current.

For the MEPO and the RSMC, we take for estimation of the power variation $\Delta P(k) = I(k)\Delta V(k)$, the current is assumed constant.

For the Modified Enhaced InCond (**MEInCond**), we consider the current as the only input control and we take $\Delta P(k) = V(k)\Delta I(k)$, the voltage is assumed constant.

The Robust Unified Control Algorithm (**RUCA**) will do both of them alternatively. Note that the hardware have to be considered in consequence. Compared to the other algorithms like Perturb and Observe (PO), Hill Climbing, Incremental Conductance (InCond) The RSMC approach it is proven more efficient and faster despite using low frequency commutation.

It can be noticed that all the previous algorithms can be considered as particular cases of this one (**RUCA**), when simplifying the proposed control method.

The implementation of the proposed **RUCA** controller can be summarised as follows:

1. The reference voltage is set be equal to the PV open circuit voltage.
2. Measurement of the of input signals (PV voltage, PV current and Load voltage).
3. Estimate the PV power at the sample time k : $P_{PV}(k) = I_{pv}(k)V_{pv}(k)$
4. Calculate the PV current and the power increments.

$$\begin{cases} \Delta I = I_{PV}(k) - I_{PV}(k-1) \\ \Delta V = V_{PV}(k) - V_{PV}(k-1) \\ \Delta P = P_{PV}(k) - P_{PV}(k-1) \\ P_{PV}(k) = V_{PV}(k).I_{PV}(k) \end{cases} \tag{5}$$

The reference voltage $V_{ref}(k)$ is calculated as below, where α is the perturbation variation step (control gain). Note that $\Delta V_{ref} = \alpha.sign(\Delta P \Delta V)$ produces exatly the same result as the classical PO algorithm with a much more simple implementation (one formula instead of an algorithm chart).

Recall that the system equations have been used also to define the classical Sliding Mode based algorithms by means of choosing a commutation (sliding) surface s. The proposed MPPT has several advantages: simplicity, high convergence speed and is independent on PV array characteristics. In conclusion let us say that **RUCA** enhances and generalizes all the best algorithms presented in litterature and suggest new algorithmes like MEPO and MEInCond.

3.3 Hybrid Tracking Methods HTM

It is well known that combination of OLM (Open Loop Method) for anticipation with robust feedback (CLM: Closed Loop Method) gives the best way to control and track trajectories of uncertain and time varying systems. In HTM, the control signal associates OLM, determined according to atmospheric conditions temperature and irradiance, and CLM based on feedcback control to track MPP. In a hybrid method consisting of two loops is proposed. In the first loop MPP is estimated based on the open circuit voltage at a constant temperature. Several authors use Neural Networks or Fuzzy Logic or combine Neuro Fuzzy Logic to anticipate on temperature and radiation effects. Tina et al proposed to use a simplified model used to evaluate the MPP power in (Tina and Scrofani, 2008). It seems to be the most efficient way to predict the MPP.

4 COMPARATIVE STUDY

In this section we present simulations based comparison between different MPPT algorithms. Several algorithms are compared the classical P&O (Perturb and Observe), the MEPO (Modified Enhanced Perturb and Observe), IncCond (Incremental Conductance), RUCA (Robust Unified Control Algorithm), and NL-ESC (Newton-Like Extremum Seeking Control).

The first step, for validation of the implementation, uses the same simulated model as in the paper of Zazo et al (Zazo et al., 2012) to compare the different algorithms. The second step is simulation with the PSIM software of the model of the experimental setup.

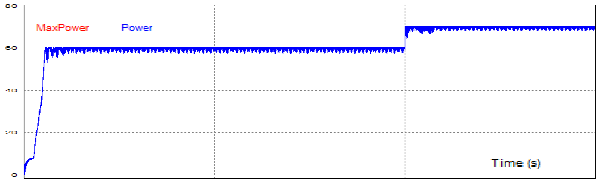

Figure 3: Power output of a PV panel with sudden variation

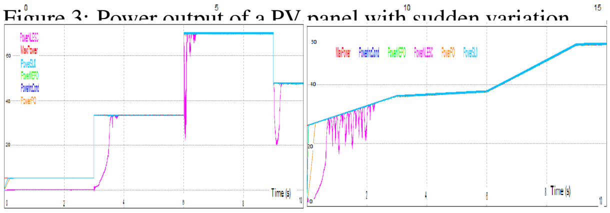

Figure 4: First order interpolation comparison of the 5 algorithms with real data.
Zero order sample and hold comparison of the 5 algorithms.

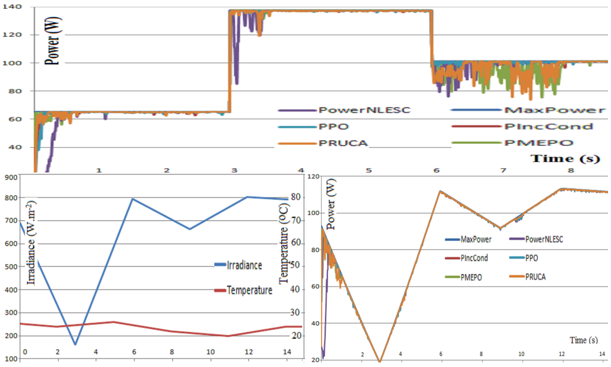

Figure 6: Simulation for change in irradiance and temperature.
Interpolated change in irradiance and temperature.

4.1 Simulations with PSIM software

The physical model of a PV panel is used with a Boost DC-DC converter using a MOSFET as a switch. The panel is considered to have 36 cells. A boost converter is built;The load is a 100Ω resistor. The algorithms are implemented in a C block and the duty cycle is calculated from Vref using another C block. The actual, measured irradiation and panel temperature, when used, are read from a txt file as input to the simulation.

We start first by retrieving all the simulation of the paper of Zazo et al (Zazo et al., 2012) and then compare to the other algorithms.

In order to compare the 5 algorithms we build under Psim software 5 identical PV systems. Each system is controlled by a different MPPT algorihm. The second simulation is done with the same input irradiance and temperature for the 5 systems. Zero order sample and hold is applied. The result is shown in figure 4.

The third simulation is done with first order interpolation and shown in figure 5. In this simulation real weather data and real PV temperature are used.

4.2 Simulation results

The simulation was performed under Psim software. The simulated process is composed of two PV panels, a DC/DC converter, and 4 batteries. Each PV panel is composed of 10 cells mounted in serie. The panel short circuit current is 5.1 A and it can generate 62W in STC. The two panels are mounted in series. The DC/DC converter is a boost (step up converter) mainly made of a capacitor, a self, a diode and a switching device. The batteries are connected in series delivering $4 \times 12 = 48V$.

In order to compare the 5 algorithms we built 5 identical simulation systems. All systems have the same irradiance and temperature inputs.

The step of the P&O algorithm is fixed to 0.1V. The step of the IncCnd algorithm is also fixed to 0.1V. The gain of the MEPO algorithm is chosen 25. The gain of the RUCA algorithm is chosen 25. The gain of the NL-ESC is 0.15 and the gain of the hessian is 3000.

For the first simulation, we consider an irradiance of 1000W.m^{-2} and a temperature of 25 ^{o}C. We can see that all the algorithms reach the maximum power point in less than 0.5 seconds. The NL_ESC presents the less oscillations. The RUCA is the fastest with decreasing oscillations. Also the MEPO present the same features. The IncCnd and PO present high oscillation and takes time to reach the MPP.

For the second simulation, we consider a zero order sample and hold for the irradiance and temperature that change. The irradiance and temperature rise and fall brutally during as shown in figure 3. The simulation of figure 4 shows how all algorithms manage to reach the MPP after the brutal variation of environmental conditions. The NL-ESC presents the highest oscillation amplitude after the brutal change. The RUCA and MEPO presents oscillation before stabilizing in the MPP after the brutal change. This is explained because these last algorithms uses the gradient of power to calculate the step, and after brutal change of environmental conditions, the power gradient is high.

For the third simulation, we consider a variation in irradiance and temperature with first order interpolation. Real data are taken from measurement done on the 16/5/2012. We can see that all algorithms reaches the MPP. Oscillations do not occurs because the power gradient is low.

In summary, the simulation comparison between the 5 algorithms showed a convergence of all the algorithms. Algorithms based on fixed step as P&O and IncCond must run at high frequency in order to reach the MPP. Algorithms based on the power gradient as MEPO and RUCA can operate at lower frequencies. MEPO, RUCA, and NL-ESC present oscillations in front brutal variation of irradiance and temperature.

5 Conclusion

The best MPPT algorithms of the litterature have been reviewed and analyzed in this work. This comparison allowed us to select five of them to be compared in simulations and experimental application. The simulations was performed under PSIM software to use realistic physical models.

The analysis has shown the rationale behind MPPT and the generalization leading to a unified framework RUCA, as a Robust Unified Control Algorithm. The well known algorithms can be viewed as particular cases of the RUCA. The proposed approach RUCA generalizes the PO, the InC, the ESC and the Sliding Mode Control schemes to non linear systems with commutations. The proposed MPPT has several advantages: simplicity, high convergence speed, and is independent on PV array characteristics. The obtained results have proven that the MPPT is tracked even under sudden change of irradiation level or temperature.

The algorithms are tested under various operating conditions. Realistic simulations are used to show ease of implementation of our new algorithm, and to compare its execution efficiency and accuracy to the the studied MPPT methods.

In summary the best algorithms are those designed using the SASV-MPPT approach and Lyapunov design method considering that the PV system can move from one characteristic to another. The proposed algorithms are the most efficient despite using low frequency commutation. They are the faster converging.

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