Performance of the Global MPPT Algorithms – a brief overview and case studies

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Abstract – In this paper a general presentation of the global maximum power point tracking (GMPPT) algorithms, their classification and case studies are shown. In the first case study, the simulation of the GMPPT algorithm using perturbed-based extremum seeking control (PESC) scheme based on a band pass filter (named G1PESC scheme), and the GMPPT algorithm using PESC scheme based on two band pass filter (named G2PESC scheme) is performed. The comparative analysis of the two schemes shows that their performances are almost similar: search time of 0.2 seconds and tracking accuracy of 99.9%. For the second case study, the performances obtained with the G1PESC scheme and Perturb and Observe (P&O) algorithm is compared.

Keywords-component: Global maximum power point tracking (GMPPT); Perturbed-based extremum seeking control (PESC); tracking accuracy; tracking efficiency; tracking speed; searching resolution.

I. INTRODUCTION

Photovoltaic installations are composed of maximum power point tracking (MPPT) systems to extract the maximum power from the photovoltaic (PV) modules in any environmental conditions: temperature, solar radiation intensity [1]. The MPPT techniques are mainly classified into three groups [2]:

a) Indirect techniques (off-line) that use the technical data of the PV panels to estimate the maximum power point (MPP).

b) Direct techniques (on-line) that use the measured parameters (U, I) in real time: the Incremental Conductance algorithm (IC) or the Perturb and Observe algorithm (P&O).

c) Other methods which include a combination of these two methods or numerical calculation.

The Perturb and Observe (P&O) [3], Incremental Conductance (IC) [4], Hill Climbing (HC) [5] and other MPPT algorithms cannot find the global maximum power point (GMPP) [6–11]. Improved performance for irradiance profile with slow variation are obtained for advanced variants of the P&O [12], IC [13], and HC [14] algorithms, Theory of Reference PV String [6,15], sweep current or voltage methods [7,16], golden section [8,17], fractional methods based on short-circuit current or open circuit voltage [9,18], \(dP/dV, dP/dI\) or time-varying reactive power injection feedback control [10,19], slide control methods [11,20], and so on. The performance indicators that will be used here are the following: the tracking accuracy, the tracking efficiency, the tracking speed; and the searching resolution.

The interest to study the Global MPPT (GMPPT) algorithms increases in last year, so many GMPPT algorithms are proposed and their performance is analysed in [21,22]. Most of them are two-stage-based GMPPT methods proposed in the literature have been presented. The GMPP was located in first stage using firmware-based MPPT algorithms, and the GMPP is accurately tracked in the second stage using classical MPPT algorithms, such those mentioned above. The extremum seeking control (ESC) can be used as well [22]. The power generated by the PV system controlled with a GMPPT algorithm is higher with more than 5% in comparison with PV system controlled with a MPPT algorithm [23].

This paper is organized as follows. The second section presents global MPPT techniques. The third section deals with GMPPT algorithms based on ESC control: G1PESC and G2PESC. The simulation results for the two schemes G1PESC, G2PESC and the comparative analysis of the P&O algorithm and the G1PESC algorithm for low/high frequency, sunny/cloudy day are shown in Section 4. The last section concludes the paper.

II. GLOBAL MPPT (GMPPT) TECHNIQUES

Large photovoltaic systems are achieved by the series-parallel connection of the PV modules. Clouds, trees, buildings or other surrounding objects, cause at some of the PV modules to receive reduced sunlight intensity, phenomenon being called partial shading conditions (PSC). In these conditions the maximum power point of the I-U feature changes, being needed retrieving for extracting maximum power. To avoid hot spots during partial shading conditions, bypass diodes are incorporated into photovoltaic modules [24]. P-U characteristics of the PV systems (see Fig. 1) with bypass diodes show many local maximum power points (LMPP), and many local minimum power points (LmPP) only one of them being the
global maximum power point (GMPP) [24,25]. The GMPPPT algorithms were classified in two main classes [22]: firmware-based (FLC, ANN, EA) and hardware architecture based algorithms (micro-inverter, central inverter, multistring [26,27]). It has been found that the GMPPPT methods used are hybrid methods obtained by combining two MPPT algorithms: in the first stage it uses a firmware algorithm or hardware architectures and in the second stage uses a conventional algorithm after the GMPPPT was located in the first phase.

III. GMPPPT ALGORITHMS BASED ON ESC CONTROL

A new method for searching GMPP based on ESC control is presented: perturbed-based extremum seeking control (PESC). The ESC method is a method of adaptive closed loop control used to look for extreme values of a nonlinear function [25]. Global schemes MPPT (GMPPPT) based on the PECS method is done with high pass filter (HPF), low pass filter (LPF) or band pass filter BPF (BPF=HPF + LPF). Several PESC schemes are proposed in literature for global MPPT (GMPPPT): scalar scheme, derivative scheme and scheme based on two band pass filter (BPF) [25].

3.1. Scalar PESC scheme

Scalar PESC scheme known since 1922 is shown in Fig. 2. The structure of the filtering block includes a high pass filter (HPF) to eliminate the DC component of the probing signal and in another version a low pass filter (LPF) or a band pass filter BPF (BPF=HPF + LPF). PESC schemes based on HPF, LPF and schemes based on BPF are almost equivalent in the case that phase delays are equal in module and the rest of the tuning parameters k1, k2 are set the same [25].

3.2. Derivative PESC scheme

Derivative PESC scheme for GMPPPT is shown in Fig. 3. The loop remains the same as in the conventional ESC scheme, but the dither is multiplied with the absolute value of the probing signal:

\[ \tilde{p}_2 = k_2 \frac{dy}{dx} \sin(\omega t) \]

3.3. Global PESC scheme based on two band – pass filters

The scheme uses two filters BPF (BPF=HPF + LPF), the second filter replaces the derivative operator in the previous scheme. The global PESC scheme will be further noted as the G2PESC scheme. The principle scheme and the block diagram for G2PESC are shown in Fig. 4 and Fig. 5.

The operating equations for the scheme shown in Fig. 5 are:

\[ y = h(p), \]
\[ y_N = k_N y_N, \]
\[ \dot{y}_1 = -\omega_{h1} y_1 + \omega_{h1} y_N y_{HPF1} = y_N - y_1, \]
\[ \frac{dx}{dt} = f(x, g(x, p)) \]
\[ y = h(x) \]

Figure 2. Scalar PESC scheme (adapted from [25]).

Figure 3. Derivative PESC scheme (adapted from [25]).

Figure 4. Principle of the G2PESC scheme.
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\[ y_{BPF1} = -\omega_{h1} y_{BPF1} + \omega_{h1} y_{HPF1} \]  \hfill (3)
\[ y_2 = -\omega_{h2} y_2 + \omega_{h2} \gamma N, y_{HPF2} = \gamma N - y_2 \]  \hfill (4)
\[ y_{BPF2} = -\omega_{h2} y_{BPF2} + \omega \gamma_{HPF2} \]  \hfill (5)
\[ \omega_{h2} = \omega_{h2} \]  \hfill (5)
\[ y_{MV} = \frac{1}{T_d} \int y_{BPF2} dt, f_d = \frac{1}{T_d} = \frac{\omega}{2\pi} \]  \hfill (6)
\[ G_d = k_2 y_{MV} \]  \hfill (6)
\[ y_3 = y_{BPF1} \sin(\omega t) \]  \hfill (7)
\[ y_4 = y_3 \]  \hfill (8)
\[ p_1 = k_3 y_4, k_3 = \omega y_{sd} \]  \hfill (9)
\[ p_2 = G_d \sin(\omega t) \]  \hfill (10)
\[ p_3 = A_m \sin(\omega t) \]  \hfill (11)
\[ p = p_1 + p_2 + p_3 \]  \hfill (12)

Eqns (1)-(12) represent the static PV pattern, \( y_{BPF1} \) is the band pass filter BPF1, \( y_{BPF2} \) is the band pass filter BPF2, \( y_{HPF1} \) and \( y_{HPF2} \) are the outputs from HPF respectively BPF filter, with the corresponding index one or two, \( y_{MV} \) the average value of the output quantity of the filter BPF2.

The parameters used in the operating equations have the following meanings:

- the dither frequency, \( f_d = \frac{\omega}{2\pi} = 100 \text{ Hz} \),
- the amplitude of dither \( A_m \),
- the cut-off frequency of the HPF1, \( f_{h1} = b_{h1} f_d \), \( \omega_{h1} = 2\pi f_{h1} \),
- the cut-off frequency of the LPF1, \( f_{l1} = b_{l1} f_d \),
- the cut-off frequency of the HPF2, \( f_{h2} = b_{h2} f_d \), \( \omega_{h2} = 2\pi f_{h2} \),
- the cut-off frequency of the LPF2, \( f_{l2} = b_{l2} f_d \),
- the normalization gain \( k_2 = |p_{GMP}-p_0| \), where \( p_0 \) is the initial value for starting the search of the \( p_{GMP} \),
- the gain of the dither amplitude, \( k_2 = |p_{GMP}-p_0| \),
- the loop gain \( k_1 = \omega y_{sd} \).

## IV. SIMULATION RESULTS

4.1. For the first simulation a global PESC scheme based on a BPF filter (G1PESC) whose diagram is shown in Fig. 6 is used. The scheme contains a band pass filter BPF (BPF=HPF+LPF), the integrator block, the mediation block MV and generator of sinusoidal signal which is a disturbing signal.
The significance of the parameters from Fig. 6:
- Y-probing signal (note with y the power for a PV panel),
- X-searching signal (note with p the current for PV panel),
- \( y_{bpf} = H_4 k_2 \cdot (G_d) \) – dither gain, \( H_4 \) - the magnitude of the first harmonic,
- \( p_1 \)-component \( p_1 \) of the searching signal (p),
- \( p_2 \)-component \( p_2 \) of the searching signal (p),
- \( p_0 \)-set point of the searching signal,
- \( p \) – searching signal.

The parameters used in simulation: dither frequency (\( fd=1/T_d=100\) Hz), the cut-off frequency of the (HPF=0.1\( f_d=10\) Hz), loop gain(\( k_1=4\omega=4\times 2\pi \times 100=2512\) Hz), the sine amplitude(\( k_2=8\)), the cut-off frequency of the LPF2 (\( f_{lp2}=5.9fd=590\) Hz), maximum value of the sample signal \( Y_{\text{max}}=300\).

4.2. The second simulation is performed for the global PESC scheme based on two band pass filters BPF (G2PESC), diagram is shown in Fig. 7.

The significance of the parameters from Fig. 7:
- \( y_b \)-probing signal,
- \( p_{bpf} \)-component \( p_1 \) of the searching signal (p),
- \( y_{bpf} \cdot H_1 k_2 \cdot (G_d) \) – dither gain, \( H_1 \) - the magnitude of the first harmonic,
- \( p_0 \)-searching signal (p),
- \( p_{bp} \)-component \( p_2 \) of the searching signal (p),
- \( p_{b0} \)-set point of the searching signal.

The parameters used in simulation: dither frequency (\( fd=1/T_d=100\) Hz), the cut-off frequency of the (HPF=0.1\( f_d=10\) Hz), loop gain(\( k_1=4\omega=4\times 2\pi \times 100=2512\) Hz), the sine amplitude(\( k_2=8\)), the cut-off frequency of the LPF2 (\( f_{lp2}=5.9fd=590\) Hz), the maximum value of the probing signal \( Y_{\text{max}}=300\), the cut-off frequency of the LPF1 (\( f_{lp1}=1.5fd=150\) Hz), the cut-off frequency of the LPF2 (\( f_{lp2}=5.5fd=550\) Hz).

4.3. Comparative analysis of the simulation results for the two schemes G1PESC and G2PESC. The simulation results are shown in Fig. 8 (a), (b).

In Fig. 8(a) the generic PV model used is shown, and in Fig. 8(b) the simulation results for the two GPESC schemes are displayed. From the graphic representations the following have been deducted:

- the searching time for both schemes is 0.2 seconds,
- \( y_{bpf} \cdot y_{bpfb} \) grow rapidly during the searching phase of the GMPP, after which they are depreciated quickly,
- the tracking accuracy is defined as \( Y_{\text{max}}/Y_{\text{GMPP}} \), where \( Y_{\text{GMPP}}=h(\rho_{\text{GMPP}}) \) and \( Y_{\text{max}} \) is the maximum value that was obtained with a GMPP algorithm. The tracking accuracy for G1PESC is 99,9995% (429,998/430=99,9997%, see zoom for Y),
- the tracking accuracy for G2PESC is 99,9997% (429,999/430=99,9997%, see zoom for Yb),
- the searching resolution is defined as \((Y_{\text{GMPP}} - Y_{\text{max}})/Y_{\text{GMPP}} \) [\%]. The searching resolution for G1PESC is 0.0005% (430-429,998)/430=0.0005%). The searching resolution is limited by the tracking accuracy, the minimum value of it being (100-tracking accuracy) [%],
- the searching resolution for G2PESC is 0,0003%,
- it is noted that GMMP is located in almost 0.2 seconds, about 20 periods of oscillation.
- it can be observed that the signal „X“ search in the range [0÷100] to locate the GMPP and finally reach \( \rho_{\text{GMPP}} \) whose values for generic PV model are 410, 420 and 430.

4.4. Comparative analysis of the Perturb and Observe algorithm and G1PESC using the dynamic standard test EN 50530 (RO 50530). The dynamic standard test EN 50530 (RO 50530), defines a test procedure to measure the MPPT efficiency of the grid-connected PV systems, with a PV simulator which simulates the output characteristics of a PV source. The dynamic MPPT efficiency test under rapid
changes of weather conditions is characterized by the combination of various ramp profiles over a certain time interval. The dynamic efficiency of the MPPT ($\eta_{\text{MPPT}}$) is calculated with the following equation:

$$\eta_{\text{MPPT}} = \frac{\int_{0}^{T_M} V_{PV}(t) \times I_{PV}(t) \, dt}{\int_{0}^{T_M} P_{MPPT}(t) \, dt}$$  \hspace{1cm} (13)

where $V_{PV}(t)$ and $I_{PV}(t)$ represent the instantaneous voltage and current at the output of the PV array simulator. The $P_{MPPT}$ represents the available maximum power of the PV simulator with respect to the instantaneous $P_{MPP}$. $T_M$ represents the time duration of the whole sequence [28]. Further the EN test is used (EN 50530) to compare the performance of the two dynamic MPPT algorithms: the Perturb and Observe algorithm and the global PESC scheme based on a band-pass filters (G1PESC) (see Fig. 9). Two test sequences are used: low frequency and high frequency.

For the G1PESC algorithm the parameters used in the simulation are the following: the dither frequency ($f_d=1/T_S=100$ Hz), the cut-off frequency of the (HPF=$0.1f_d=10$ Hz), the loop gain ($k_1=4\omega=4 \times 2\pi \times 100=2512$ Hz), the sine amplitude ($k_2=3$), the maximum value of the probing signal $Y_{\text{max}}=51$, the cut-off frequency of the LPF1 ($f_{l1}=1.5f_d=150$ Hz), the cut-off frequency of the LPF2 ($f_{l2}=5.5f_d=550$ Hz).

For the Perturb and Observe algorithm (P & O) the parameters used are: the step $\Delta I=0.1A$, $T_S=0.1$ ms and the reference current $I_{\text{ref}}(0)=0.1$ A.

For low frequency the following results were
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obtained (Fig. 10):

- Perturb and Observe algorithm shows large oscillations for irradiance \( (G < 500\text{W/m}^2) \), then when a ramp signal is applied it loses control of the MPP tracking.
- P & O algorithm cannot follow the MPP in case of low irradiance and rapid changes of weather.
- G1PESC algorithm shows oscillations at the beginning of the tracking process, the efficiency obtained is 98%.

For high-frequency the following results were obtained (Fig. 11):

- P & O algorithm completely loses MPP tracking to the rapid changes of irradiance,
- G1PESC algorithm presents oscillations in MPP tracking at rapid variation of irradiance,
- the efficiency for the G1PESC algorithm is high 99.9%.

The performances for G1PESC algorithm and P&O for a real profile (a sunny/cloudy day) are also tested, the simulation results are presented in Fig. 12 and Fig. 13. The simulations for a sunny day are shown in Fig. 12:

- P & O algorithm shows large oscillations for irradiance \( (G = 500\text{W/m}^2) \),
- the oscillations for the G1PESC algorithm are small compared with P & O algorithm,
- the efficiency for the G1PESC algorithm is 98% at maximum value irradiance \( (G = 1500\text{W/m}^2) \),
- the efficiency for the P&O algorithm is 95% at maximum value irradiance.

The simulations for a cloudy day are shown in Fig. 13:

- P & O algorithm shows large oscillations at irradiance \( (G = 500\text{W/m}^2) \), and at rapid changes of weather, P & O can not track the maximum power point during rapid changes in weather (clouds on the sky);
- the oscillations for the G1PESC algorithm are reduced even in the rapid changes of weather, and maximum power point can be tracked;
- the efficiency for the G1PESC algorithm is 97% during rapid changes of weather;
- the efficiency for the P&O algorithm is 92% at irradiance \( G = 1200W/m^2 \), and shows fluctuations according to the change of solar radiation.

V. CONCLUSIONS

This paper presents two schemes for tracking and searching the global maximum power point (GMPP) based on perturbed extremum seeking control (PESC): the G1PESC scheme based on one BPF filter and the G2PESC scheme based on two BPF filters. The comparative results for the G1PESC and G2PESC schemes are the following: the searching time for both schemes is about 0.2 seconds if100 Hz dither frequency is used, the tracking accuracy exceeds 99.9% for both schemes, the searching resolution is 0.0005 and 0,0003 for G1ESC and G2PESC schemes. The behavior of the two schemes is a bit different during the searching phase, when higher oscillations appear for G1PESC scheme, and is almost identical during the stationary phase. This explains the similar performance for the two schemes analyzed.

The performance of G1PESC scheme and P&O algorithm is estimated using two irradiance sequences: pulses of low frequency and high frequency. The G1PESC scheme presents a good behavior to rapid variations of irradiance, the MPPT efficiency is 98% at low frequency and 99.9% at high frequency. The P & O algorithm fail to track the MPP or completely loses the MPP tracking to pulsed irradiance of low or high frequency. Then, the performances of the two algorithms were tested on a real profile (sunny/cloudy day). Simulation results show good results for the G1PESC scheme, resulting a high efficiency of 98% compared to the P & O algorithm which has an efficiency of 92%. The G1PESC scheme shows small oscillations for rapid weather changes, unlike the P & O algorithm has large oscillations. So, the Global PESC schemes can track the GMPP during rapid changes of the weather.

LIST OF ABBREVIATIONS

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>GMPP</td>
<td>Global maximum power point</td>
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<tr>
<td>MPPT</td>
<td>Maximum power point tracking</td>
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<td>MPP</td>
<td>Maximum power point</td>
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<td>P&amp;O</td>
<td>Perturb and Observe</td>
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<td>ESC</td>
<td>Extremum seeking control</td>
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<td>ES</td>
<td>Extremum seeking scheme</td>
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<td>BPF</td>
<td>Band pass filter</td>
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<td>LPF</td>
<td>Low pass filter</td>
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<td>HPF</td>
<td>High pass filter</td>
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<td>PV</td>
<td>Photovoltaic</td>
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<td>LMPPP</td>
<td>Local maximum power point</td>
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<tr>
<td>LmPP</td>
<td>Local minimum power point</td>
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<td>PSC</td>
<td>Partially shaded condition</td>
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<td>PESC</td>
<td>Perturbed-based extremum seeking control</td>
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<td>MV</td>
<td>Mean value</td>
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<td>GMPPT</td>
<td>Global maximum power point tracking</td>
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<td>G1PESC</td>
<td>Global PESC scheme based on one bandpass filters</td>
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<td>G2PESC</td>
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