Milestone of the most used maximum power point tracking in solar harvesting system

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ABSTRACT

Solar harvesting system with photovoltaic (PV) is one of the most desirable renewable energy sources because of its prominent advantages. However, low efficiency due to fluctuating output power is a major problem for PV systems. A technique used to maximize power extraction known as maximum power point tracking (MPPT) has been proposed by various literature to deal with this problem. One of the most widely developed MPPT methods due to its ease of implementation is perturb and observe (P&O). Since the initial discovery of the principle, the P&O method has been extensively modified including the fixed step-size: step-size variables, partial shading, threshold module current, three-point-comparison, maximization of dynamic performance, minimization of dynamic performance, bandwidth of $P-V$ curve, decoupling, observation of dV, dI, and dP, datasheet parameters, curve fitting, voltage hold P&O, and observation of dV and dP. This paper presents the development of the P&O method from the initial principle to the end as a reference source for readers. The hope is that a new easy and robust P&O method as a complement to the implementation of the MPPT technique is developed in the solar harvesting system.

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1. INTRODUCTION

Renewable energy sources are experiencing rapid development. This is due to the policies of many countries in an effort to make the earth healthier. Therefore, renewable energy sources in the production of electrical energy play an important role in reducing emissions and achieving sustainable power generation [1]–[3]. In the last decade, from various types of renewable energy, solar energy based on solar harvesting systems with photovoltaic (PV) achieved the most widespread application because of its most prominent advantages [4]. Easy installation with high security, quiet, and environmentally friendly are some of the advantages offered [5]. Furthermore, because the operation of the PV system does not require a drive unit, this system is able to operate for a long time due to minimal maintenance [6]. Moreover, the recent decline in production costs has increasingly made PV systems the most promising candidate for renewable energy systems [7].

However, fluctuations occur in the output power of the PV system due to intermittent weather conditions due to solar irradiation and rapidly changing ambient temperature [8]–[11]. Fluctuations in output power due to variations in irradiation obtained by PV might lead to the undesirable performance of the electric network. This variation can occur due to clouds covering the solar irradiation to the PV, which can cause the output power of the PV system to drop to zero. Therefore, the efficiency generated by the system. Therefore, a technique used to maximize power extraction known as maximum power point tracking (MPPT) was introduced to deal with this problem by controlling the PV system so that it always operates at its maximum point. To date, various MPPT methods have been introduced. One of the most widely used methods is perturb and observe (P&O) [12], [13]. The P&O method is a favorite because it offers easy and inexpensive implementation, and has even been widely applied to commercial products [14].

There have been many studies in the form of review papers specifically reviewing the performance of the MPPT method that can be taken into consideration by researchers. Belhachat and Larbes [15], Li *et al.* [16], Dileep and Singh [17], Ahmad *et al.* [18], Lyden and Haque [19], Mohanty *et al.* [20], Mohapatra *et al.* [21], Saravanan and Babu [22], Tajuddin *et al.* [23], Danandeh and Mousavi [24], Bollipo *et al.* [25], Karami *et al.* [26], Mao *et al.* [27] described the advantages and disadvantages, or the merits, and demerits of each method. Other article review such as Subudhi and Pradhan [8], Verma *et al.* [28], Esram and Chapman [29], Ali *et al.* [30], Kamarzaman and Tan [31], Bendip *et al.* [12], Gupta *et al.* [32], Podder *et al.* [33] describes a review and classification of MPPT techniques with their development variables.The aim of this paper is to provide an unbiased review of the key steps in the development and establish the state-of-the-art of P&O method in MPPT technique. The final goal is that the reader is expected to be able to understand the various development strategies of the P&O method so that it can be a reference in modifying and perfecting it.

2. DEVELOPMENT OF MAXIMUM POWER POINT TRACKING

In theory, the principle of operation of MPPT is maximum energy transfer [34]. The basic purpose of the MPPT method is to find the maximum power by finding the operating point of the PV system. When the output impedance of the PV cell and the load impedance are the same, the maximum power can be obtained. Therefore, the MPPT technique works by matching the output impedance of the PV cell with the load impedance. When the PV system is implemented in the field, and therefore the output impedance of the PV cell is affected by environmental factors, the MPPT control is carried out in real-time. Under different conditions, the PV system produces an $I-V$ characteristic curve as Curve 1 and Curve 2 are shown in Figure 1. Load 1 and Load 2 are load curves, while A and B are points of the maximum power output of the PV system under different irradiation. The maximum power output at point A will change to A' if the PV gets a sudden increase in irradiation. In this situation, the PV system must work at point B to provide maximum power. Therefore, for the load characteristics to be a Load 2 curve, the external PV circuit must be controlled.

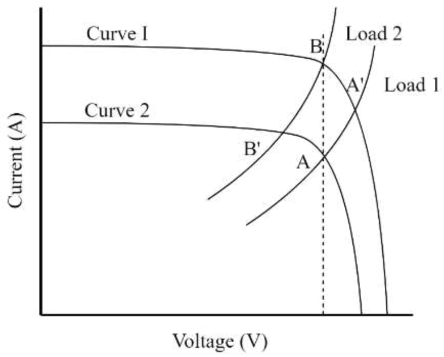
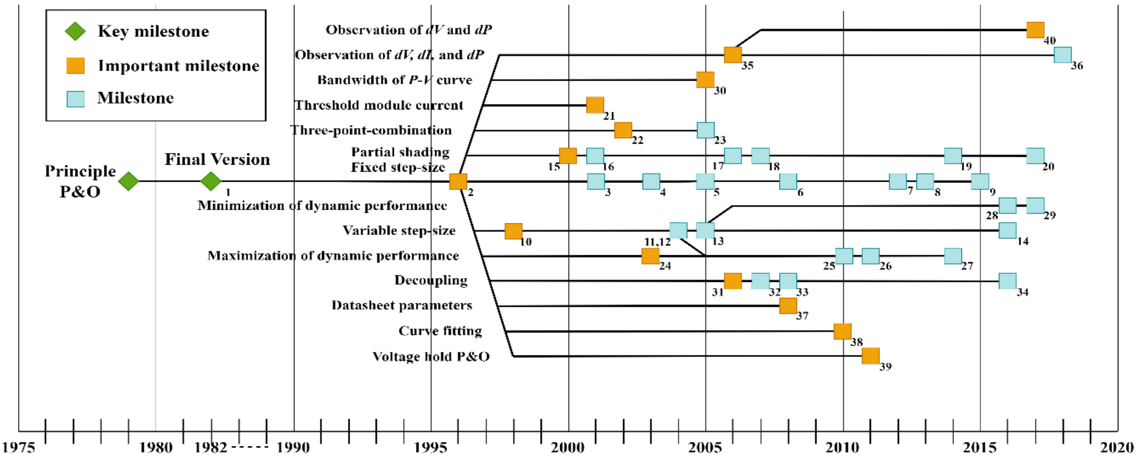


Figure 1. MPPT at $I-V$ curve

3. HISTORICAL DEVELOPMENT OF P&O METHOD

The most robust P&O principle was proposed in 1979. At the beginning of its introduction, P&O was introduced from the basic techniques of hill-climbing using mathematical optimization. Until 1982, Schoeman *et al.* refined the initial P&O ideas into the final version [35]. Since then, the P&O method has been developed into several bases. The development journey of P&O as a method in MPPT on PV systems is packaged in a milestone shown in Figure 2.

The P&O method developed rapidly, starting from the fixed step size introduced by Atlas Atlas *et al.* [36]. Since then, various method developments have shown variations, such as adjustable step size. Then followed the need to handle partial shading and different other requirements. The developmental methods include fixed step-size; step-size variables; partial shading; threshold module current; three-point-comparison; maximization of dynamic performance; minimization of dynamic performance; bandwidth of $P-V$ curve; decoupling; observation of dV, dI, and dP; datasheet parameters; curve fitting; voltage hold P&O; and observation of dV and dP will be explained in more detail.



1. Schoeman *et al.* 1982 [35]
2. Atlas *et al.* 1996 [36]
3. Yeong-Chau *et al.* 2001 [37]
4. Noguchi *et al.* 2003 [38]
5. Salas *et al.* 2005 [39]
6. Liu *et al.* 2008 [40]
7. Gomathy *et al.* 2012 [41]
8. Moore *et al.* 2013 [42]
9. Killi *et al.* 2015 [43]
10. Al-Amoudi *et al.* 1998 [44]
11. Liu *et al.* 2004 [45]
12. Xiao *et al.* 2004 [46]
13. Femia *et al.* 2005 [47]
14. Husain *et al.* 2016 [48]
15. Irisawa *et al.* 2000 [49]
16. Veerachary *et al.* 2001 [50]
17. Kobayashi *et al.* 2006 [51]
18. Amrouche *et al.* 2007 [52]
19. Qi *et al.* 2014 [53]
20. Alik *et al.* 2017 [54]
21. Hua *et al.* 2001 [55]
22. Hsiao *et al.* 2002 [56]
23. Jiang *et al.* 2005 [57]
24. Hua *et al.* 2003 [58]
25. Baek *et al.* 2010 [59]
26. Elgendy *et al.* 2011 [60]
27. Mamarelis *et al.* 2014 [61]
28. Zakzouk *et al.* 2016 [62]
29. Sher *et al.* 2017 [63]
30. Jung *et al. 2005* [64]
31. Sera *et al.* 2006 [65]
32. Yafaoui *et al.* 2007 [66]
33. Sera *et al.* 2008 [67]
34. Mamatha *et al.* 2016 [68]
35. Kim *et al.* 2006 [69]
36. Abdel-Salam *et al.* 2018 [70]
37. Azab *et al.* 2008 [71]
38. Khatib *et al.* 2010 [72]
39. Abdalla *et al.* 2011 [73]
40. Devi *et al.* 2017 [74]

Figure 2. Milestone of P&O as MPPT method on PV system

3.1. Fixed step-size

The tracking speed of the method and the oscillations around the MPP that occur due to the P&O method become a trade-off problem that was discussed in 1996. by Atlas *et al.* [36]. In that case, a fixed step-size is used to increase the speed of finding the MPP and reduce the oscillations around the MPP. Although the results show that the tracking speed is increasing, the oscillations that occur cannot be completely suppressed. Problems related to solar irradiation that varied and suddenly became a concern and tried to be overcome in 2001 by Kuo *et al.* [37]. The experiment was carried out using a fixed step-size and optimizing it by adding an irradiation sensor. As a result, dynamic efficiency increases, but costs and complexity also increase due to the dependence of the system on the irradiation sensor. Still to solve the trade-off problem, in 2003, Noguchi *et al.* make modifications by adding a PI controller [38]. The resulting performance shows oscillations can be reduced, but tracking speed is the same as classic P&O. The correct MPP was obtained under suddenly varying solar irradiation in 2005 by Salas *et al.* by proposing a fixed step-size tested under steady-state and dynamic conditions [39]. The results obtained showed satisfactory efficiency, which reached 97%. However, in this case, the variation of the solar irradiation slope is not considered.

For grid-connected PV systems, the P&O method was implemented and compared with hill climbing in 2008 by Liu *et al.* [40]. Both methods succeeded in getting the MPP estimation well. The P&O results show fast dynamic performance and a well-regulated PV output voltage. The P&O method was modified and simulated in MATLAB/Simulink in 2012 by Gomathy *et al.* [41]. Modifications are made with a fixed step-size and result in better tracking speed. Another modification was made and applied to the street lighting system in 2013 by Moore *et al.* [42]. Simulations and experimental results are presented for design validation. The results show the tracking speed of MPP seeking and efficiency at steady-state increases. However, the resulting dynamic efficiency cannot exceed 84%. The P&O method often drifts. This phenomenon occurs due to wrong decision making in the first step change in duty cycle when there is a rapid increase in irradiation in the classical P&O method. Modifications were made taking into account current changes (dI) to avoid drift problems in 2015 by Killi *et al.* [43].

3.2. Variable step-size

The classic problem arising from the fixed step-size P&O method is the selection of the right step size length which results in the tracking speed and oscillations around the MPP. To overcome this problem, a step-size variable was proposed in 1998 by Al-Amoudi *et al.* [44]. A new scheme was proposed by calculating the direction of the next perturbation in 2004 by Liu *et al.* [45]. This scheme uses peak current control and instantaneous value for DC-DC boost converter. Based on the step-size variable, the modified adaptive hill-climbing (MAHC) technique was proposed in 2004 by Xiao *et al.* [46]. This modification updates the voltage step-size on-line to suit sudden changes in exposure levels. The experimental results show the steady-state efficiency of 97.3%, and the dynamic efficiency of 96.3%. To overcome the problem of oscillations around the MPP, the P&O method was optimized based on the step-size variable in 2005 by Femia *et al.* [47]. The experimental results show steady-state accuracy is better than the classical method because the tracker step size is adaptive matches the location of the operating point. However, the trade-off problem between MPP tracking speed and accuracy has not been solved. Fast mutable duty (FMD) was proposed approaching MPP quickly and then supported by variable dD in 2016 by Husain *et al.* [48] in 2016. A limited search area for tracking characterizes this method. The step size mutates automatically based on the distance of the operating point. Fast convergence and low oscillations are generated during a steady state.

3.3. Partial shading

Under field conditions, the PV system is operated under various environmental effects such as under uniform or non-uniform irradiation. The PV system operating under non-uniform irradiation produces several points of maximum power on the $I-V$ curve which causes serious problems in the MPPT technique. To overcome this problem, the method using cell monitoring to get the right operating starting point and the dV/dI method was proposed in 2000 by Irisawa *et al.* [49]. Using load voltage information, the process of tracking the maximum power point using an interleaved dual boost (IDB) converter was proposed in 2001 by Veerachary *et al.* [50]. The experimental results show that more power extraction is produced. A two-stage MPPT control technique to track the maximum power point occurring under partial shading was proposed in 2006 by Kobayashi *et al.* [51]. The performance of this control concept was evaluated in simulation using PSIM and LabView software. A modification by combining the classic P&O method with artificial neural network (ANN) to solve problems related to partial shading was proposed in 2007 by Amrouche *et al.* [52]. Although ANN is very helpful in determining the global MPP, it inevitably increases the complexity. MPPT technique strategies that can handle under partial shading conditions with classical methods continue to be developed because of their low complexity. Improving the performance of classic MPPT by adding a change detection procedure under partial shading and global peak area search was proposed in 2014 by Qi *et al.* [53]. Modification of the P&O method by adding a checking algorithm was proposed in 2017 by Alik *et al.* [54]. The results obtained indicate that the maximum power point can be tracked both in uniform and non-uniform conditions. However, this strategy is still under simulation test and has not considered the effect of temperature.

3.4. Threshold module current

To deal with problems related to the effects caused by sudden variations in solar irradiation, a technique based on extra loops combined with classical techniques was proposed in 2001 by Hua *et al.* [55]. Variation of irradiation level is detected by threshold current parameter which is the loop of the proposed method. The experimental results show that the steady-state and dynamic efficiency can reach 83.6%.

3.5. Three-point-comparison

To avoid the problem of perturbation oscillations, a three-point weight comparison method was proposed in 2002 by Hsiao *et al.* [56]. The experimental results show superior performance compared to the classical method. To overcome similar problems and the effects caused by sudden variations in solar irradiation, a three-point weight comparison technique was used in 2005 by Jiang *et al.* [57]. The steady-state efficiency from the experimental results reaches 97%, while the dynamic efficiency reaches 92%.

3.6. Maximization of dynamic performance

The P&O method was modified to maximize dynamic performance, in this case maximizing tracking speed. The large and small-signal model and transfer function was developed based on the principle of energy conservation carried out in 2003 by Hua *et al.* [58]. The experiment was carried out under sudden variations in solar irradiation. The results show the tracking speed can improve in dealing with suddenly changing exposure levels. Combination of P&O with fractional open-circuit voltage (FOCV) was proposed in 2010 by Baek *et al.* [59]. FOCV technique is used only at the start-up tracker to interrupt the output current. Then the open circuit voltage is recorded by the tracer with the subsequent loss of power in the PV system. A comparison of the perturbation of P&O implementation was carried out in 2011 by Elgendy *et al.* [60]. The reference voltage perturbation can respond to irradiation and temperature transients quickly, but the stability decreases when operated at high perturbation levels. On the other hand, direct duty ratio control has good stability in slow transient response, but poorer performance in the fast change of irradiation. To improve P&O performance at steady-state, P&O was modified by implementing small perturbation of the controlled variable in 2014 by Mamarelis *et al.* [61]. With this scheme, tracking at constant irradiation only consists of three operating points, i.e., the center point is close to MPP while the other two are on the side of MPP.

3.7. Minimization of dynamic performance

P&O modification was carried out by varying the perturbation step during a sudden change in ambient temperature, especially to reduce oscillations around the MPP, in 2016 by Zakzouk *et al.* [62]. This modification scheme depends on the dV, dP, and dP/dV. The experimental results show the steady-state and dynamic state efficiency of 99.8%. The P&O method is modified to detect dynamic weather conditions faster which is based on the fractional short circuit current (FSCC) method in 2017 by Sher *et al.* [63]. The experiments carried out reduce offline measurements (short circuit current) so that energy utilization is better.

3.8. Bandwidth of $P - V$ curve

The P&O method was modified based on the bandwidth of the $P - V$ curve in 2005 by Jung *et al.* [64]. This method is based on the hysteresis band and auto-tuning perturbation step. Experimental was conducted on the digital signal processor (DSP), and the results show an increase in tracking speed, but not an increase in dynamic efficiency, and tracking is complicated.

3.9. Decoupling

Modification of the P&O method with voltage perturbation is decoupled was developed due to extreme variations in irradiation and ambient temperature sudden changes. Classic P&O dynamic performance modified based on dP-P&O by decoupling the change in PV output power due to the effect of weather changes from the power change effect due to perturbation of the voltage, then in the middle of the step perturbation an additional measurement is recorded in 2006 by Sera *et. al.* [65]. The value of steady-state and dynamic efficiency resulting from the experiment is 99.6%. A similar modification of the P&O was proposed in 2007 by Yafaoui *et al.* [66]. Even though, the scheme of this method depends on the estimation process of each perturbation step. The experimental results show steady-state efficiency of 97.5%, dynamic efficiency of 95%, but the tracking speed decreases due to delay in the estimation process. An additional power measurement without perturbation was used in the dP-P&O method and utilizing this information to decoupling the perturbation from environmental effects was proposed in 2008 by Sera *et al.* [67]. Simulation and experimental results provide fast and accurate tracking in rapidly changing environmental conditions. Modifications based on the decoupling of changes in PV output power due to voltage perturbations and changes in irradiation levels were also proposed in 2016 by Mamatha *et al.* [68]. The experimental results show that the steady-state and dynamic efficiency can reach 94.8%.

3.10. Observation of dV, dI, and dP

Current and voltage is sensed, then the polarity of current changes and the corresponding power change is observed as a modification of the classic P & O method in 2006 by Kim *et al.* [69]. The resulting performance is better than the classic P&O, however the current sensor is expensive. Another P&O modification is to utilize the polarity of the PV current change dI corresponding to voltage change dV and dI/dV to direct tracer to MPP in 2018 by Abdel-Salam *et al.* [70]. Steady-state efficiency increases up to 99.48%, while dynamic efficiency is 98.03%.

3.11. Datasheet parameters

The maximum power obtained from the PV module datasheet was used as the basis for modification of the P&O method in 2008 by Azab *et al.* [71]. The maximum known power is used as the control reference value. The buck chopper is operated so that the PV operates at maximum power. Its steady-state and dynamic efficiency is up to 95%.

3.12. Curve fitting

Curve-fitting-based techniques to improve classical P & O performance were proposed in 2010 by Khatib *et al.* [72]. This modification is done by determining the optimal voltage module approaching the maximum power (V_{mpp}) according to the PV module datasheet. Furthermore, classical P&O method are employed with small step-size to reach the actual MPP. However, based on the experiments carried out on average efficiency cannot exceed 89.2%.

3.13. Voltage hold P&O

To track MPP correctly under the irradiation changes, modification based on the voltage-hold Perturbation and Observation was proposed in 2011 by Abdalla *et al.* [73]. The voltage across a capacitor because of changes in the output of PV currents due to irradiation level dependence is considered in this method. The operating voltage perturbation under irradiation changes is not carried out, but perturbation is done before exceeding the MPP voltage and directly forces the voltage to the capacitor. Based on the experimental results, the value of efficiency in established and dynamic conditions is 91%.

3.14. Observation of dV and dP

Classical P&O modifications to solve problems that occur related to sudden irradiation changes using the polarity of voltage mining (dV) and power change (dP) ere proposed in 2017 by Devi *et al.* [74]. The ΔV and ΔP are taken into account and multiplied together to decide where the next perturbations are directed.

4. CONCLUSION

Milestone The development of the P&O MPPT technique in the solar harvesting system has been described. Since the beginning, the principle was stated in 1979 and the final version of 1982, until now various modifications have been developed from the derivative of the P & O method. Modification of the P & O method with a fixed step-size model; variable step-size; Partial Shading; Threshold Module Current; Three-point-comparison; Maximization of Dynamic Performance; Minimization of Dynamic Performance; Bandwidth of $P - V$ Curve; decoupling; Observation of dV, dI, and dP; datasheet parameters; Curve fittings; Voltage Hold P&O; And the Observation of dV and dP is part of an effort to maximize PV power conversion systems. Through consideration and inner studies, it is expected that a new modification-based P&O method will be born to perfect the MPPT technique at solar harvesting system.

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