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Maximum Power Point Tracking Algorithms for the Wind Energy Systems

Ersagun Kürşat YAYLACI [1] (ekyaylaci@sakarya.edu.tr)
İrfan YAZICI [2] (iyazici@sakarya.edu.tr)

[1]*Sakarya University, Elec.& Electronics Department, 54050 Sakarya, Turkey*
[2]*Sakarya University, Elec.& Electronics Department, 54050 Sakarya, Turkey*

Abstract – Wind energy is one of the renewable energy sources and its share in energy production is increasing every year. Therefore, many research topics about the wind energy occur with the spreading wind energy sources. The maximum power point tracking is the one of these topics which is considered as efficiency study in wind energy because of the fact that there is just one optimal rotating speed assured maximum power from the wind for every wind speed. For this reason, the rotating speed should be controlled continuously according to the changing wind speed. Nowadays, many works about this topic are still made in order to contribute to the literature. In this paper, the literature works made about the maximum power point tracking are analyzed in detail. The most widely used maximum power point tracking methods dedicated to the wind energy systems are compared to each other according to the advantages or disadvantages.

***Keywords** -*
Maximum power point tracking, wind energy systems, renewable energy.

1. Introduction

Electrical energy demands of the humanity continue to increase by the developing technology and the growing world’s population every year. Considering the negative effects caused by the fossil fuels, the renewable energy sources (RES) have more attention in response to the increasing energy demand. The renewable energy sources can be classified as wind energy, solar power, geothermal, hydroelectric and biomass. The wind energy systems (WES) have an important share among the RES [1].

By using power electronic converters, the WES is operated with variable or constant speed. The constant speed WES has some advantages such as low cost and easy controllable structure. On the other hand, the variable speed WES has maximum power point tracking

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[1]***Corresponding Author***

(MPPT) capability, less fluctuating and less mechanical stresses [2]. To get an efficient energy capacity, variable speed WES should be used because of the fact that variable speed WES may be extracted more electrical energy approximately %40 at the same wind conditions [2].

The MPPT algorithms assure to extract maximum energy from the wind in spite of the changing wind speed by operating the wind turbine with optimal rotating speed. Three known MPPT methods such as power signal feedback (PSF), tip speed ratio (TSR) and hill climb searching (HCS) are used for the WES.

This paper represents an extension/update of the paper presented at the conference, EEB2016, and contained in the Proceedings of that conference.

In this paper, the MPPT methods related to the WES are analyzed in terms of the advantages or disadvantages according to the each other. Also, the WES model is established by using MATLAB/Simulink. The performances of the MPPT algorithms are evaluated with the MATLAB model. The remainder of this article is organized as follows.

Section 2 gives the knowledge about the WES model used in this paper. Section 3 gives account of previous work about the MPPT algorithms in the literature. Finally, Section 4 gives the simulation results.

2. Wind Energy Systems

Although the WES can have many different topologies, generally, it has a wind turbine, generator, power electronic converters and load. The energy conversion has three stages for the WES as given Figure 1.

Figure 1. Energy conversion stages for the WES

Aerodynamic wind energy is converted to the mechanical energy in terms of the blades of the wind turbine. The mechanical energy is converted to the electrical energy by using an electric generator. The electrical energy is transferred to the power electronic devices in order to arrange according to the grid connection rules and also MPPT control Finally, the electrical energy is delivered to the grid or autonomous loads. The wind energy absorbed by the blades of the wind turbines is given as

$$P_t = \frac{1}{2}\rho A V_w^3 c_p \tag{1}$$

which P_t is the power absorbed by the wind, ρ is air density, A is swept area by the turbine, V_w is wind speed and c_p is the performance coefficient of the wind turbine. According to the Betz rule, the maximum value of the c_p is theoretically about 0.59 while it is about

0.35-0.40 for practical applications [3]. According to the mechanical structures of the blades, the c_p values change from turbine to turbine. Also, its value is a function of the TSR value as given follows

$$c_p(\lambda,\beta)=c_1\left(\left(\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}\right)c_2-c_3\beta-c_4\right)\times e^{-\left(\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}\right)c_5}+c_6\lambda \tag{2}$$

where β is the blade pitch angle, λ is the TSR and c_1, c_2 .... c_6 are the constant coefficients depended on the mechanical structure of the blade and the values of them can be given as 0.5176, 116, 0.4, 5, 21, 0.0068 respectively for this study. For the MPPT control region, the β value should be selected zero and so the equation (2) is rearranged as below

$$c_p(\lambda,0)=c_1\left(\left(\frac{1}{\lambda}-0.035\right)c_2-c_4\right)\times e^{-\left(\frac{1}{\lambda}-0.035\right)c_5}+c_6\lambda \tag{3}$$

Therefore, the TSR is the only parameter that can be used to provide maximum power from the wind and described as follow [4]

$$TSR=\lambda=\frac{\omega_m R}{V_w} \tag{4}$$

where R is the rotor radius and ω_m is the rotational speed of the blades.

3. The MPPT Algorithms

To provide MPPT, the c_p should be brought the maximum value. As given (2), it is possible to get maximum value of the c_p by changing the λ value. Likewise, the λ value should only be changed by modifying the rotational speed of the blades as given (4). So, the aims of the all MPPT methods modify the rotational speed and bring them the optimum values. The relationship between the power generated by the turbine and mechanical speed is given Figure 2. As it can be seen from the Figure 2, there is only one optimal rotational speed to assure maximum power from the wind for a particular wind speed.

The most popular MPPT methods; TSR, PSF, and HCS methods are explained with the subsections as below.

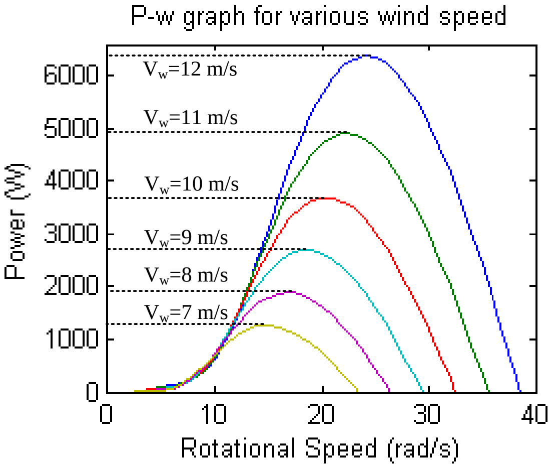

Figure 2. P-w_m graph for various wind speed

3.1. TSR Method

The optimum value of the TSR satisfied the MPPT is a constant value and does not depend on the wind velocity. This value which is only related to the mechanical structure of the wind turbine can be found in terms of the theoretical or experimental studies. The TSR method aims to provide the optimum value of the TSR for the MPPT. The control block diagram of the TSR method can be given as Figure 3. The reference mechanical speed can be obtained by using the measured wind speed and pre-known optimal values of the TSR. It can be concluded from the Figure 3 that the mechanical sensors are needed to measure both wind velocity and rotational speed. Also, the optimum value of the TSR can be known for used wind turbine. On the other hand, the MPPT can be provided very quickly because of the fact that the reference point of the mechanical speed is produced directly from the equation (4).

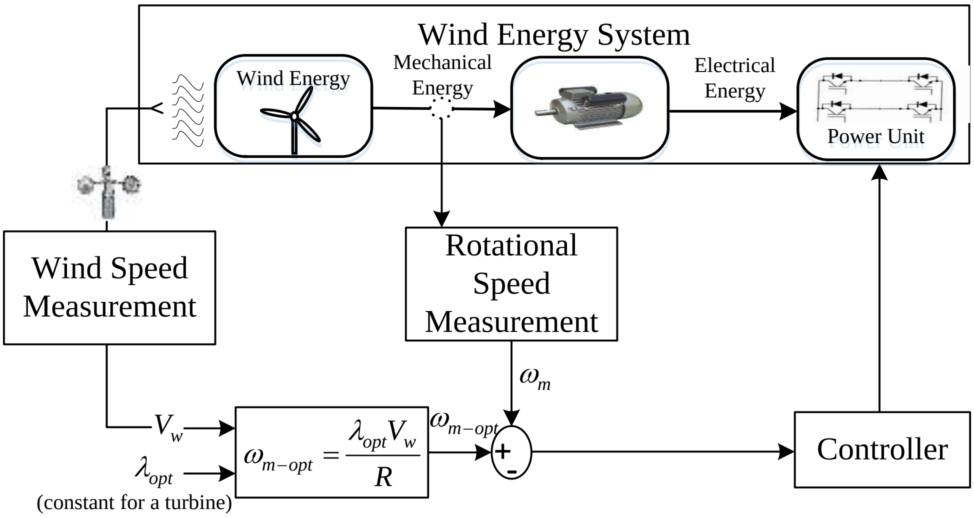

Figure 3. The control block diagram of the TSR method

3.2. PSF Control

The PSF control can be obtained mathematically by using (1) and (4) as follow

$$P_t = \frac{1}{2}\rho\pi R^2 \left(\frac{\omega_m R}{\lambda}\right)^3 c_p \tag{5}$$

The maximum power can be found by substituting the maximum value of the c_p and the optimum value of the TSR at (5)

$$P_{\max} = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3} c_p = K_{opt}\omega_m^3 \tag{6}$$

$$K_{opt} = \frac{1}{2}\frac{\rho\pi R^5}{\lambda_{opt}^{\ 3}} c_{p-\max} \tag{7}$$

It can be concluded from equation (6) that the maximum power is proportional to the cube of the mechanical speed. The K_{opt} called maximum power coefficient can be obtained by using $c_{p\text{-max}}$ and λ_{opt}. The control block diagram of this method is given as Figure 4. The optimal power curve which is consisted of the electrical power and rotational speed can be obtained with the experimental study or by using knowledges of $c_{p\text{-max}}$ and λ_{opt} [5]–[7]. The optimal power curve is also need a measured mechanical speed to produce the reference of the maximum power point. The error produced by comparing the measured turbine power and reference turbine power is delivered to the controller. Therefore, the WES is controlled according to the directive from the controller.

The different parameters such as dc bus voltage-power [8] or turbine power and rotational speed [5] used to establish the optimal power curve in the literature.

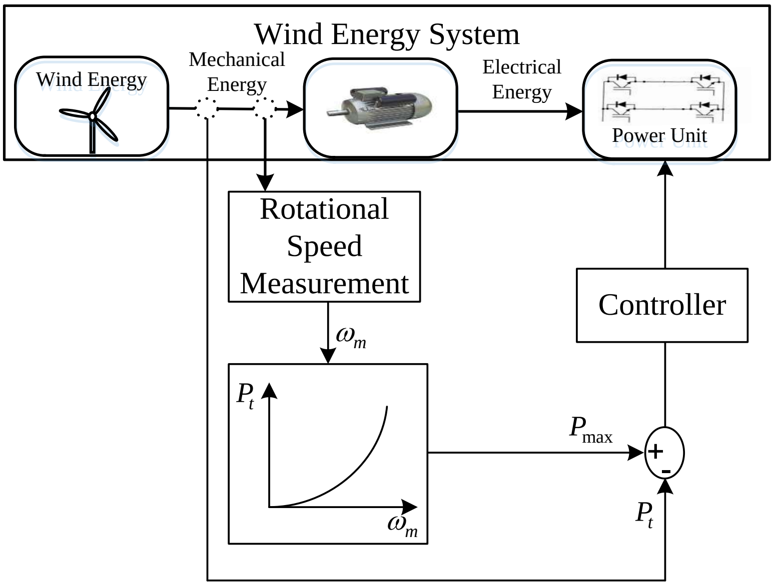

Figure 4. The control block diagram of the PSF method

3.3. P&O Control

P&O method is a mathematical optimization technique that it is used for searching the local maximum point. First of all, the control and output parameters are selected according to the controlled system. Then, the control parameter is perturbed and output parameter is observed. This action is continued until the slope becomes zero as given Figure 5. For the WES, the control parameter (ω) is increased if the slope is positive. Otherwise, it is decreased. In the literature, it is seen that duty cycle, input current and/or input voltage of the converter can be selected as the control parameter for this method [9]–[14].

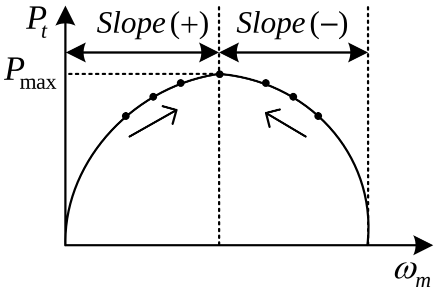

Figure 5. P&O method graph

4. The Simulation Results

The Matlab/Simulink is used to simulate the WES which is consisted of the wind turbine, permanent magnet synchronous generator, uncontrolled rectifier, dc-dc boost converter and resistive load for this paper as given Figure 6.

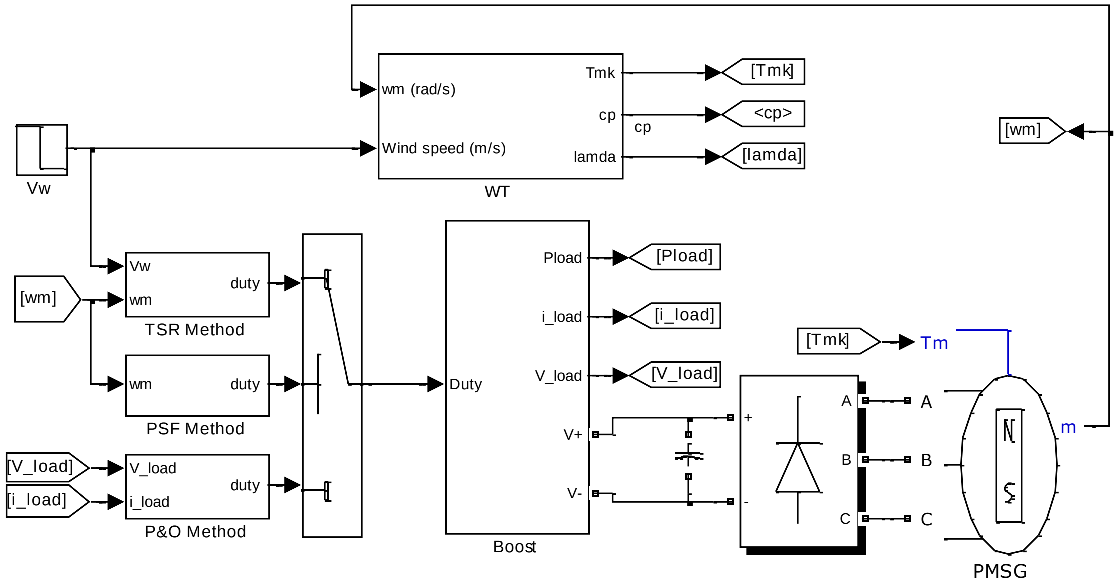

Figure 6. Simulink model of the WES

The performances of the three most used MPPT algorithms are evaluated according to the each other. The MPPT algorithms are deactivated first 0.12 seconds in order to accelerate wind turbine for all simulation studies. The optimum value of the TSR and the maximum value of the performance coefficient used in this paper are 8.1 and 0.48 respectively because of the fact that wind turbine model of the Simulink is used directly. In this paper, the simulation studies are carried out for two scenarios which are constant wind speed and varying wind speed.

Actually, the MPPT algorithms can be compared with each other according to some criterions such as the efficiency, reliability, additional cost and necessity of the pre-knowledge about the system.

Efficiency: The performances of the MPPT methods are related to the efficiency directly. The reaching time of the maximum power point is especially important for the efficiency. As given Figure 7a, the MPPT is assured quickly by the PSF algorithm when the MPPT algorithm is activated at 0.12 second. The wind speed is decreased from 12 to 10 m/s at 0.4 for the PSF algorithm. Still, the PSF algorithm tracks the maximum power point very quickly as given Figure 7b. The TSR algorithm has also good performance given as Figure 8a and 8b. Although the wind speed is changed from 12 to 10 m/s at 0.4, the MPPT is provided by the TSR algorithm in a short time.
The WES has high inertia according to the change in wind speed. The PSF method uses only rotational speed as feedback signal. However, the sudden change in wind speed does not cause the sudden change in rotational speed because of the inertia. So, the PSF method

is slower than the TSR method because of the fact that the TSR method uses both the rotational speed and wind speed as feedback signals in order to produce the MPPT reference. According to the TSR and PSF algorithms, the P&O algorithm has not good performance for the WES as given Figure 9a and 9b. Also, the oscillation is shown around the maximum power point which is not desired for the WES. The P&O algorithm can provide the MPPT in a short time when the wind speed is changed from 12 to 10 m/s at 3,5. However, the performance of the P&O is still bad according to the TSR and PSF algorithms.

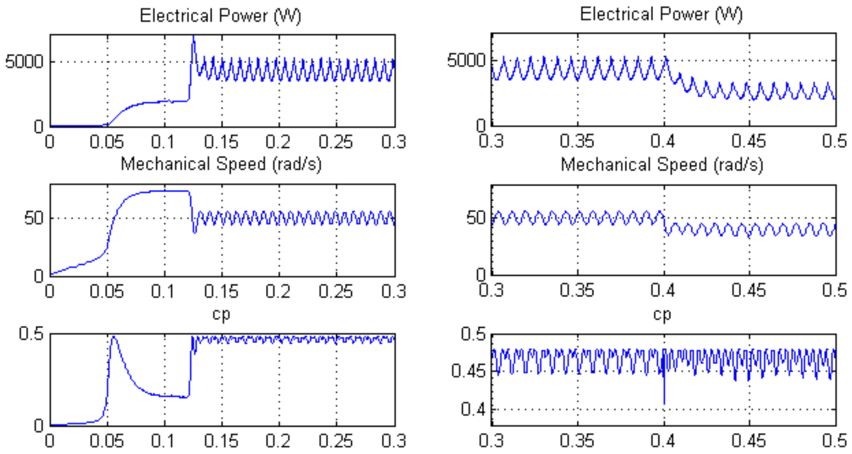

Figure 7a and 7b. The performance of the PSF algorithm according to the constant wind speed and varying wind speed respectively

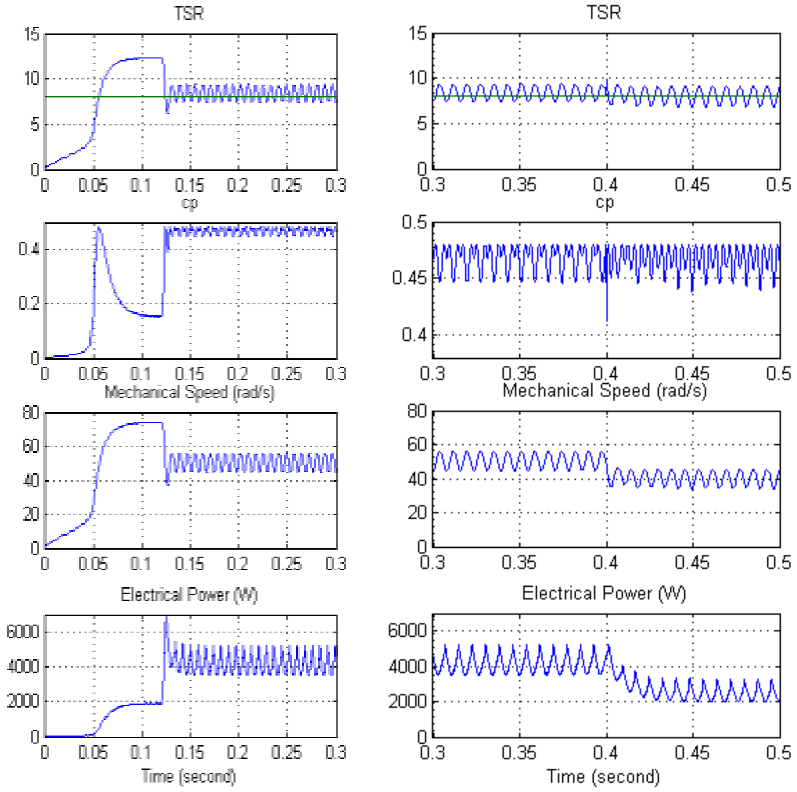

Figure 8a and 8b. The performance of the TSR algorithm according to the constant wind speed and varying wind speed respectively

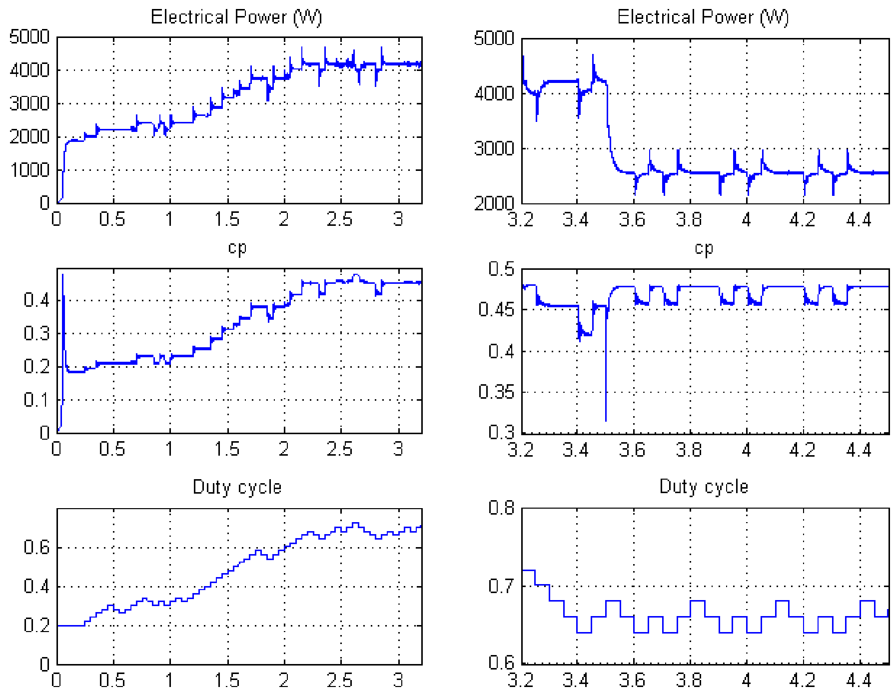

Figure 9a and 9b. The performance of the P&O algorithm according to the constant wind speed and varying wind speed respectively

Reliability: The reliability of the WES is adversely affected by the usage of the mechanical sensor. Although, the TSR method needs two sensors to measure wind speed and rotational speed, the PSF method needs only one sensor to measure rotational speed. Another perspective, the wind speed measurement can be inaccurate especially for the large size wind turbines due to the fact that the anemometer can measure only where it is located. Additionally, the wind measurement located on the hub may be incorrect for both upwind and downwind structures because of the interaction between the rotor and wind [15]. However, the P&O method does not need any sensor necessity but the electrical measurement devices. Therefore, the most reliable method is the P&O algorithm according to the other methods.

Additional cost: The requirement of the mechanical sensor brings also additional cost to the system. Therefore, it increases cost of the system which is not desired especially for small scale wind turbine systems. Thus, the P&O algorithm is cheaper than the other methods.

Pre-knowledge about the system: The TSR and PSF methods need to knowledge about the system which is not desired for any system because of the necessity of the experimental or theoretical studies. The optimal power curve can be obtained before the installation of the system. Also, these two methods based on look-up table cannot update the optimum values used for MPPT. This approach is not true because of the fact that the optimum values can shift due to the some reasons such as gradient of the air density, ageing and non-constant efficiencies of the generator and converter subsystems. The extracted power from the turbine is a function of the air density as given (1). So, the optimum values stored in look-up table should be updated according to the seasons. Additionally, the ageing of the components of the system should be considered for a period of time. The non-constant efficiencies of the system are the other important barrier for these methods due to the fact that the system is consisted of the generator and power electronics converter. It must be also considered for this reason while the look-up table methods are used [15].

The HCS method, which is a simple and flexible control method, does not need to pre-knowledge of the wind turbine. However, the first barrier of the HCS method is that it has good performance for slow varying system as PV energy systems. Another important barrier of the HCS method is the selection of the perturbation step size. The performance of the HCS method can be slow when the perturbation step size selects small. In this case, the HCS method may not track the maximum power point under the rapidly change in wind speed. The oscillation increases around the maximum power point and so the efficiency will be worst when the large perturbation step size is selected [14, 16]. Also, one of the barrier of the HCS method is that the sign of the perturbation signal is judged according to the current and previous values of the observed signal. However, the HCS algorithm can apply wrong decision in case of the change in wind speed in this time interval. Therefore, the efficiency of the HCS can be deteriorated directly if the wrong decision is dictated by the HCS algorithm to the system. There are many works made about the HCS method in order to eliminate all these barriers [10, 11, 13, 14, 16, 17]. For instance, the HCS method supported with the adaptive perturbation size, which is updated the perturbation size according to the operating point, is one of these works. The perturbation size is increased if the operating point is far away from the maximum power point. Otherwise, the perturbation size is decreased. Therefore, the oscillation around the maximum power point is decreased and also the MPPT is achieved in a shorter time. The comparisons of the MPPT methods given above are summarized at Table 1.

Table 1. The comparison of the MPPT methods

Methods	Efficiency	Additional cost	Reliability	Pre-knowledge
TSR Method	very good	two sensor	weak	needed
PSF Method	good	one sensor	not strong	needed
P&O Method	bad	no sensor	strong	non-needed

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