OUTPUT MAXIMIZATION CONTROL FOR VSCF WIND ENERGY CONVERSION SYSTEM USING EXTREMUM CONTROL STRATEGY

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Abstract: The energy conversion optimization control strategy is presented for a family of horizontal-axis variable-speed fixed-pitch wind energy conversion systems, working in the partial load region. The system uses a variable-speed wind turbine (VSWT) driving a squirrel-cage induction generator (SCIG) connected to a grid. A new maximum power point tracking (MPPT) approach is proposed based on the extremum seeking control principles under the assumption that the wind turbine model and its parameters are poorly known. The aim is to drive the average position of the operation point close to optimality. Here the wind turbulence is used as search disturbance instead of inducing new sinusoidal search signals. The discrete Fourier transform (DFT) process of some available measures estimates the distance of operation point to optimality. The effectiveness of the proposed MPPT approach is validated under different operation conditions by numerical simulations in MATLAB/SIMULINK. The simulation results prove that the new approach can effectively suppress the vibration of system and enhance the dynamic performance of system.

Key words: wind energy conversion systems; maximum power point tracking; extremum control strategy; discrete Fourier transform

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INTRODUCTION

Nowadays one of human's endeavors is to cope with the energy crisis. Because wind power is free, clean and endless, it is a very good choice. Furthermore, the cost of the electricity produced by wind turbines is fixed once the plant has been built and it has already reached the point where the cost of the electricity produced by wind is comparable with that produced by some of the conventional and fossil based power plants. Therefore, compared with other renewable energy technologies, wind energy conversion system (WECS) is the most promising one.

Wind is highly variable, both in space and in time. The importance of this variability becomes critical since it is amplified by the cubic relation of the available energy. The speed-control criterion leads to two types of WECS: Fixed-speed and variable-speed wind turbines. Variable-speed wind turbines are currently the most used WECS. Compared with fixed-speed wind turbines, their advantages are numerous. First of all and most importantly, the decoupling between the generating system and the grid frequency makes them more flexible in terms of control and optimal operation. And the high controllability offered by the variable-speed operation is a powerful advantage in achieving higher wind energy penetration levels[1-2]. Moreover, the variable-speed operation

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allows the rotational speed of the wind turbine to be continuously adapted (accelerated or decelerated) in such a manner that the wind turbine operates constantly at its highest level of aerodynamic efficiency. Furthermore, variable-speed operation allows the use of advanced control methods, with different objectives: Reduced mechanical stress, decreased acoustical noise, increased power capture, and so on[3].

Obviously, how to realize the output maximization control of WECSs is a challenging problem. Therefore, advanced automatic control methods are imperatively required. The maximum power point tracking (MPPT) means roughly to extract the maximum power available in the wind stream, irrespective of the wind regimes, and takes place in the partial-load region. In fact, the traditional MPPT approach employs the hill-climbing method for dynamically driving the operating point to the optimal regimes characteristic (ORC). In order to obtain gradient estimations of some measurable variables, some probing signals are used[4-5]. And the traditional MPPT approach has some drawbacks. The main ones are the significant estimation errors and important high-frequency power fluctuations, which will influence the reliability of the system. In order to cancel the impact of the above effects, the MPPT algorithms employing fuzzy control techniques are used[6-8]. Although the techniques are easy to be extended and more flexible, they should have much more requirement on the system model.

Extremum seeking control (ESC) is one of the methods to maximize or minimize a cost function which denotes efficiency, benefit, loss, and so on[9]. Thus, a new approach to MPPT employing an extremum search algorithm is proposed in the paper. The algorithm uses the wind turbulence as a probing signal to obtain gradient estimations of some measurable variables, such as the electrical power, the wind speed, the rotational speed, and so on. Thus it can drive the operation point to ORC dynamically.

In this paper, the operation characteristics of WECS and the wind speed model are given, and the traditional MPPT approach to WECS is analyzed. Moreover, a new approach to MPPT based on the extremum seeking control principles is presented. The numerical simulations are realized using MATLAB and the effectiveness of the proposed scheme is validated under different operating conditions by simulation results.

1 OPERATION CHARACTERISTICS OF WECS

1.1 Operation characteristics of wind turbine

As shown in Fig. 1, the wind turbine operates from the cut-in wind speed to the cut-out wind speed with different dynamics. That is to say, four zones may be identified in the static operation of WECS depending on the wind speed.

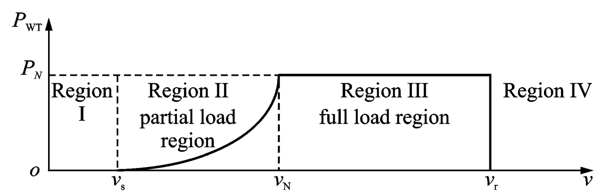

Fig. 1 Output power vs. wind speed characteristic

Obviously, the mechanical power P_{WT} extracted by a wind turbine must be limited to the rated one P_N in the full load zone. Thus, the interest focused on the partial load zone is output energy maximization control.

The mechanical power P_{WT} is expressed as

$$P_{WT} = P_A \cdot C_P(\lambda, \beta) = \frac{\pi}{2}\rho \cdot R^2 \cdot v^3 \cdot C_P(\lambda, \beta) \tag{1}$$

where P_A is the total power of a delimited moving mass of air, ρ the air density, R the blade radius, v the wind speed, and $C_P(\lambda, \beta)$ the power coefficient defining the aerodynamic efficiency of the wind turbine rotor. Usually it is a function of the tip speed ratio λ and the blade pitch angle β.

Because of the fixed-pitch wind turbine, β is constant here. The tip speed is defined as the ratio between the peripheral speed of the blades and the wind speed. It is denoted by λ and computed as

$$\lambda = \frac{R\Omega_l}{v} \tag{2}$$

where Ω_l is the rotor rotational speed.

Fig. 2 presents the C_P-λ performance curve. For control purposes, the useful information arising from the Fig. 2 is the fact that the power conversion efficiency has a well determined maximum for a specific tip speed ratio, denoted by λ_{OPT}.

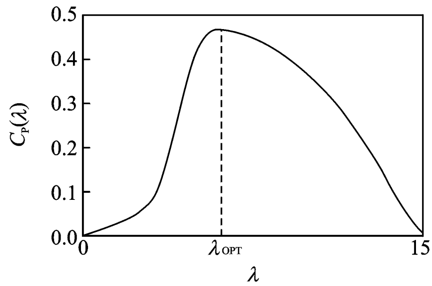

Fig. 2 C_P-λ curve of typical horizontal axis wind turbine

The corresponding power characteristics parameterized by the wind speed are shown in Fig. 3. Obviously, for each wind speed, there is a certain rotational speed at which the power curve of a given wind turbine has a maximum (C_P reaches its maximum value). And all these maxima compose what is known in the literature as the optimal regimes characteristic (ORC).

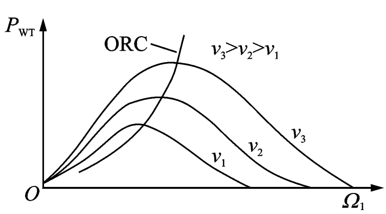

Fig. 3 Power characteristics parameterised by wind speed

Therefore, the energetic optimization is equivalent to tracking λ_{OPT} irrespectively of the wind speed. In the case of the fixed-pitch wind turbines this can be achieved by appropriately torque/rotational speed controlling the electric generator[10].

1.2 Wind speed modeling

From a system point of view, the wind speed represents the main exogenous signal applied to WECS and determines its behaviour. Its erratic variation, highly dependent on the given site and on the atmospheric conditions, makes the wind speed quite difficult to model. Reviewing literatures, the wind speed model used in current dynamic simulation for VSCF wind turbine is usually reduced to three kinds of typical wind speed, that is, gust, random wind and gradient wind. This approach is more in line with reality. In view of focusing on the energetic optimization of the energy conversion system, wind speed is modelled in the literature as a non-stationary band-limited random process, yielded by superposing two components[11]

$$v(t) = v_s(t) + v_t(t) \tag{3}$$

where $v_s(t)$ is the low-frequency component (or seasonal component) describing long term variations and $v_t(t)$ the turbulence component corresponding to fast and high frequency variations. In a word, $v_s(t)$ determines the average position of the operation point on the wind turbine characteristic and $v_t(t)$ generates the high frequency variations around this point.

The turbulence is mathematically described as a zero average normal distribution, whose standard deviation, σ, depends on the current value of the hourly average, $v_s(t)$. The turbulence intensity is a measure of the global level of turbulence, depending on the ground surface roughness and is defined as

$$I = \frac{\sigma}{v_s} \tag{4}$$

Here Fig. 4 presents a wind sequence with the average speed of about 7 m/s and a medium turbulence intensity of $I = 0.15$, obtained by using the von Karman spectrum in the IEC standard.

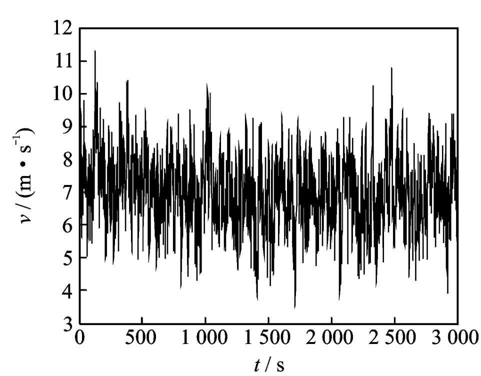

Fig. 4 Model of wind speed (v=7 m/s, I=0.15)

2 MPPT BASED ON ESC

While the aerodynamics and drive train models are not fully available, that is to say, only few constructive parameters are known and few variables are available for measure, the new version of MPPT based upon poor knowledge about the system must be developed. But the basic idea of any MPPT algorithm is to maintain the optimal operating point, denoted as

$$\frac{\partial P_{WT}}{\partial \Omega_l}=0 \tag{5}$$

2.1 Traditional MPPT approach

Fig. 5 illustrates the traditional MPPT approach employing the hill climbing method. Therefore, the operation point position and its moving trend (the sign of $\partial P_{WT}/\partial \Omega_l$) determine the wind turbine speed reference together. The wind turbine power P_{WT} is estimated based on the measured active power P. Also, the rotational speed Ω_l of low speed shaft (LSS) is estimated from measuring the generator speed Ω_h.

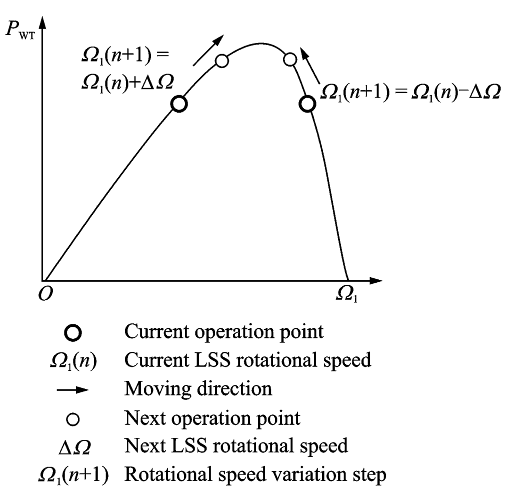

Fig. 5 Principle of traditional MPPT

The significant estimation errors and the important high frequency power fluctuations are the two main drawbacks of this method, which are harmful for the overall reliability. In order to avoid the first drawback, one can use heuristic methods needing wind speed estimation, along with power coefficient curve identification[12]. As for the second drawback, some extensions of the MPPT algorithms, for example, fuzzy control techniques, lead to more flexible, but also quite context dependent controllers[8].

2.2 New MPPT approach based on adaptive extremum control

Extremum control strategy (ECS) has been evolved since 1950 along with optimization theory, adaptive control theory and nonlinear control theory. And several design methods have been discussed to construct ECS in the last few years. Especially, Krstič's method using averaging technique attracts a lot of interest[9].

(1) Principle of single-parameter extremum seeking control

The ESC method relies upon finding the extremum of some unimodal function dynamics by exciting the plant with sinusoidal probing signals. The basic idea of this control method is illustrated in Fig. 6, where the controller performs a modulation/demodulation operation and its output has a harmonic component called the probe signal. It usually contains a washout filter, a demodulator, a low pass filter and an integrator for obtaining the average component of the control input, and a summation with the probing signal block.

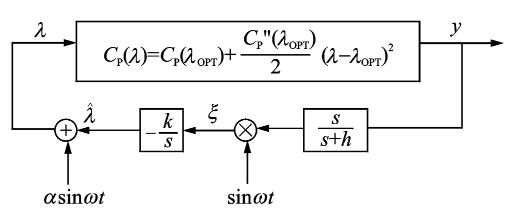

Fig. 6 Principle of single-parameter extremum seeking control

The power characteristic has a maximum at λ_{OPT} for each wind speed in the partial load region. Then the Taylor series of this function around its maximum, $C_P(\lambda_{OPT})$, is denoted as

$$y=C_P(\lambda)=C_P(\lambda_{OPT})+\frac{C_P''(\lambda_{OPT})}{2}(\lambda-\lambda_{OPT})^2 \tag{6}$$

The purpose of the algorithm is to make $\lambda-\lambda_{OPT}$ as small as possible, so that the output y is driven to its maximum $C_P(\lambda_{OPT})$. The perturbation signal $a\sin\omega t$ fed into the plant helps to get a measure of gradient information of the map $C_P(\lambda)$. Parameter $\hat{\lambda}$ in Fig. 6 denotes the estimate of the unknown optimal input λ_{OPT}. Let $\tilde{\lambda}=\lambda_{OPT}-\hat{\lambda}$ denote the estimation error, thus

$$\lambda-\lambda_{OPT}=a\sin\omega t-\tilde{\lambda} \tag{7}$$

Replacing Eq. (7) in Eq. (6) and expanding it further can result in that

$$y=C_P(\lambda_{OPT})+\frac{C_P''}{4}a^2+\frac{C_P''}{2}\tilde{\lambda}^2-aC_P''\tilde{\lambda}\sin\omega t+\frac{C_P''}{4}a^2\cos 2\omega t \tag{8}$$

The washout filter $\frac{s}{s+h}$ applied to the output serves to remove $C_P(\lambda_{OPT})$. Then the signal is demodulated by multiplication with $\sin\omega t$, giving

$$\xi=\frac{C_P''}{2}\tilde{\lambda}^2\sin\omega t-aC_P''\tilde{\lambda}\sin^2\omega t+\frac{C_P''}{4}a^2\cos 2\omega t\sin\omega t \tag{9}$$

Note that λ_{OPT} is constant and the last two rows are high frequency signals. When the two rows pass through an integrator, we have

$$\dot{\tilde{\lambda}}\approx-\frac{k\cdot a\cdot C_P''}{2}\tilde{\lambda} \tag{10}$$

Since $kC_P''>0$, this is a stable system. Thus concluding that $\tilde{\lambda}\rightarrow 0$, converges to within a small distance of λ_{OPT}. Therefore, the searching process is convergent. The excitation frequency, ω, must be sufficiently large to ensure stability of the closed loop system, and the washout filter parameter, h, depends on this frequency[9].

(2) New MPPT method

According to the above analysis, this principle can be used in a WECS optimal control application. Thus, an already existing perturbation, wind turbulence, is used here instead of sinusoidal probing signals. In this case, the modulation process is naturally achieved by means of high frequency (non harmonic) wind speed variations.

The stated scope of the control can be achieved by changing the tip speed ratio λ. And the linearized variation of λ is expressed as

$$\Delta\lambda=\frac{R}{v}\cdot\Delta\Omega_l-\frac{\lambda}{v}\cdot\Delta v \tag{11}$$

Based on the basis of Eq. (3), Δv may be simplified as Δv_t. At the time, $\Delta\Omega_l$ is neglected because the time interval is very small.

Thus

$$\Delta\lambda=-\frac{\lambda}{v}\cdot\Delta vt \tag{12}$$

In Eq. (12), $\Delta\lambda$ can be used instead of $\sin\omega t$ feeding the system because the wind turbulences have high frequency variations. As a result, they induce some power coefficient variations, ΔC_P, which are non harmonic, but have a bounded spectrum.

From the ESC principle discussed above, the integrator input is expressed as

$$\frac{d\bar{\lambda}}{dt}=k\cdot\Delta C_P\cdot\Delta\lambda \tag{13}$$

Consideration of the change of wind speed is a random process, and the separation of sinusoidal exciting signals is the key and difficult task. In this paper, the discrete Fourier transform (DFT) is used for extracting the phase of each harmonic component of $\lambda(t)$ and $C_P(t)$, and then computing the phase lag of each component. An average of these values gives the angle denoted by $\theta(t)$, which contains the average position information of operation point. If operation point is on the left (rising) slope of the C_P curve, the values of $\theta(t)$ will get closer to 0. Otherwise, the values of $\theta(t)$ will get closer to π in the right case. This is illustrated in Fig. 7.

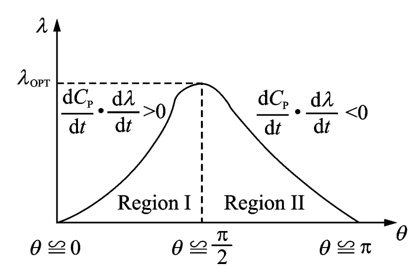

Fig. 7 Relationship between operation point and θ

Here the applied method is based upon deducing the average phase shift, denoted by $\theta(t)$. As a result, the position of operation point will be separated into two zone characterized by $\pi/2$.

(3) Control law

Fig. 8 presents the control structure including an information processing block and a rotational generator speed reference block[13].

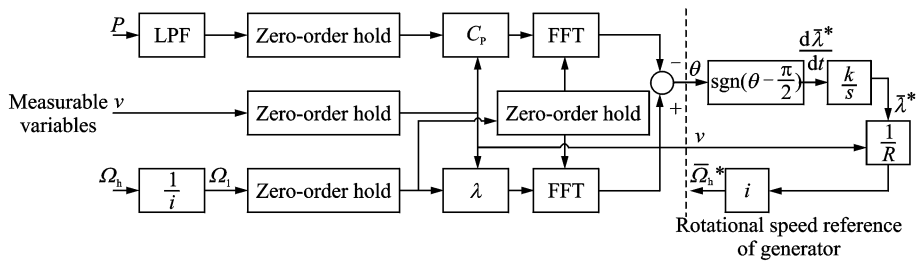

Fig. 8 Control structure of new MPPT appoach

From Fig. 8, $C_P(t)$ and $\lambda(t)$ are obtained using the electrical power with wind speed and the rotational speed with wind speed respectively. These signals are fed to a FFT algorithm for obtaining their phase spectrum and the corresponding average position signal, $\theta(t)$.

On the right side of Fig. 8, the augment or reduction of tip speed reference can be achieved by integrating a nonlinear function of average phase information, $\mathrm{sgn}(\theta-\pi/2)$. Finally the rotational generator speed reference is obtained.

3 SIMULATION RESULT AND ANLYSIS

The numerical simulation and result analysis are given in the section. A 6 kW fixed-pitch horizontal-axis variable-speed WECS operating in the partial load region is used as case study for the above proposed MPPT approach. The rotor of turbine and the squirrel-cage induction generator (SCIG) are coupled by a rigid drive train. Its main parameters are given as follows.

Turbine parameters: $R=2.5$ m, $v_s=9$ m/s, $v_r=15$ m/s.

SCIG parameters: $R_s=1.265\ \Omega$, $R_r=1.43\ \Omega$, $L_m=0.139\,7$ H, $L_s=0.145\,2$ H, $L_r=0.145\,2$ H, $P=2$.

The power coefficient can be described by a polynomial function of the tip speed ratio, λ[14], that is

$$\begin{aligned}C_P(\lambda)&=a_7\cdot\lambda^7+a_6\cdot\lambda^6+a_5\cdot\lambda^5+a_4\cdot\lambda^4+\\&\quad a_3\cdot\lambda^3+a_2\cdot\lambda^2+a_1\cdot\lambda=\\&\quad -4.54\times10^{-7}\lambda^7+1.302\,7\times10^{-5}\lambda^6+\\&\quad 6.541\,6\times10^{-5}\lambda^5-9.747\,7\times10^{-4}\lambda^4+\\&\quad 0.008\,1\lambda^3-0.001\,3\lambda^2+0.006\,1\lambda\end{aligned}\tag{14}$$

Therefore it has the following optimal parameters

$$\lambda_{OPT}=7,\quad C_{P\max}=0.476\tag{15}$$

The simulations by MATLAB/SIMULINK only concern the partial load region for medium wind turbulence and no wind gusts.

In Fig. 9, the C_P-λ performance curves based on the traditional MPPT approach vs. the new version of MPPT using ECS are compared. As a result, the standard deviation of the power coefficient in Fig. 9(b) is much smaller than that in the case of the classical MPPT control on the left. The controller gain k in Fig. 9(b) is 0.03.

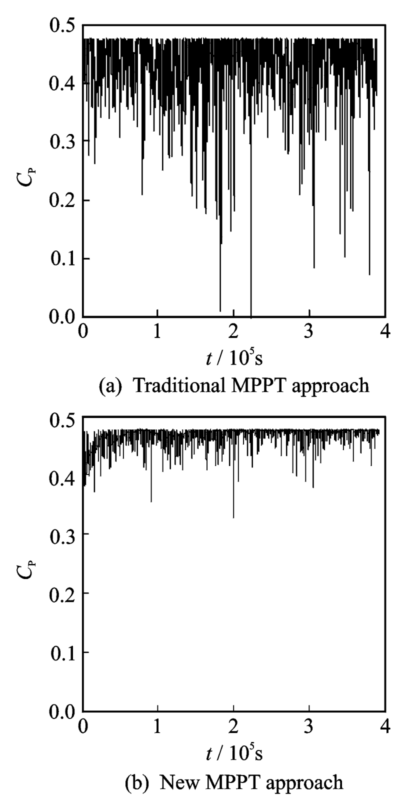

Fig. 9 C_P-λ performance curves based on two MPPT approaches

Similarly, in Fig. 10 the energy optimization curves using speed-power plane based on the two MPPT approaches are compared. Obviously, the

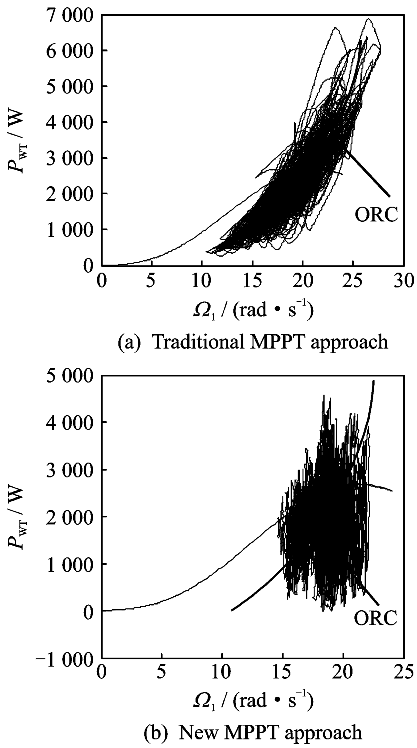

Fig. 10 Energy optimization curves based on two MPPT approaches

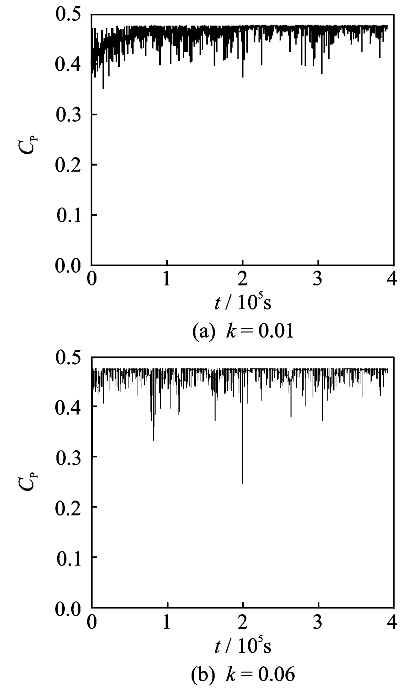

Fig. 11 Influence of control gain k on C_P-λ performance curves based on new MPPT approach

operation point distribution around ORC in Fig. 10(b) on the right is more easy to be remarked than the case in Fig. 10(a) on the left. ORC is explained in Fig. 3. Therefore, compared with the classical MPPT version, the new MPPT version based on ESC has a better performance.

Fig. 11 shows the simulation results with different values of the control gain k. From Fig. 11, it can be deduced that the control gain k is smaller, and the standard deviations of the C_P-λ performance curves are smaller. Therefore if the system has been in steady-state regime, better performance can be realized by a small value of k.

4 CONCLUSION

The paper deals with a wind power system using a variable-speed wind turbine driving a squirrel-cage induction generator connected to the grid through power converter.

Classical MPPT has some drawbacks such as requiring real time computation of gradients. A new MPPT control approach based on the extremum seeking control for variable-speed WECS is presented in this paper. When the plant is not sufficiently and precisely known, the new approach proves its efficiency. Moreover, the control strategy has higher flexibility because the information of $\theta(t)$ is included in the control gain k.

Compared with the classical MPPT, the proposed MPPT approach shows better control performances. This is validated by simulations results in MATLAB/SIMULINK. The most valuable feature of the presented approach is the use of minimal knowledge about the state and parameters of system. And it has the advantage of employing very few parametric and feedback information in the controller construction.

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