An Optimal PID Control of Wind Generation based on Matrix Converter

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Abstract-**The paper proposes a novel wind energy generation scheme, which is based on an indirect matrix converter(IMC) and a permanent magnet synchronous generator(PMSG). This method is different from the ones concerned in the past literatures due to its unique system configuration and easy-to-implement control strategy with more degrees of freedom to be exploited. Sensorless MPPT, which is based on the combination of climbing hill searching and bisection method, is applied. Based on the particle swarm optimization(PSO) algorithm, the optimal control for the PMSG is presented, taking both output saturation and parameter uncertainty into consideration. The proposed scheme and its feasibility are verified by the simulations.**

I. INTRODUCTION

It is no denying fact that energy issue emerging with the associated problems, such as a worldwide food crisis, becomes a more and more important problem and needs an immediate settlement. Utilizing clean and cheap resources is an excellent and alternate way of alleviating the huge and increasing energy demand. Wind energy is such a kind of resources. According to the European union report, the electricity demand will increase by 12% expected before Year 2020[1]. With the development of the power electronics technology, the variable speed constant frequency(VSCF) generation system[2,8,9] is capable of tracking the maximum power point[8~11], and becomes the main trend nowadays. Meanwhile, the costs deduction and the performance enhancements of the magnetic materials [3] make the wind energy conversion system (WECS) equipped with the permanent magnet synchronous generator (PMSG) a focus in recent years [1,12]. Conventional power electronic components applied in the WECS comprise of uncontrollable AC/DC/AC converters, back-to-back voltage-source converter, and a cost-efficient power converter, which is composed of a uncontrollable rectifier, a boost loop between it and an inverter [12].

Matrix converter [4~8] is a kind of green and AC/AC power electronics device with the features such as the compact size and the absence of the bulky energy storage device . Multi-polar permanent synchronous generator [1] with the elimination of the heavy gearbox is energy efficient in small size. As a result, the integration of the matrix converter and the PMSG is the best choice under some special circumstances.

Maximum power point tracking (MPPT) is one of the basic problems to the WECS and it is the basic feature of variable speed constant frequency generation, another problem is the efficiency of generation system. In essence, the two problems belong to the same one. In this paper, a hill-climb and bisection method based sensorless maximum power point tracking approach is presented in the paper. Additionally, the maximum efficiency control of PMSG is also concerned. Meanwhile, a particle swarm optimization (PSO) algorithm [13~15] based optimal and robust PID control is explored to achieve a better dynamic response.

A. The Configuration of the Proposed WECS

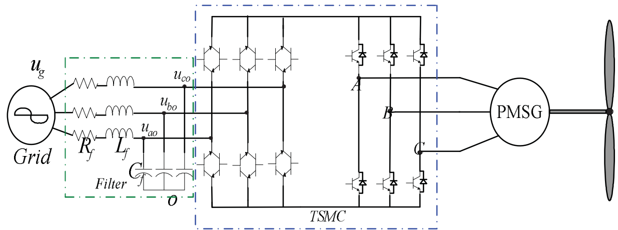


Fig. 1 The system configuration of the WECS

The whole system is composed of a wind turbine, an indirect matrix converter, an input filter, and the power grid. As shown in Fig.1, the PMSG is directly driven by the wind turbine without the bulky and heavy gearbox. The inverter side of the indirect matrix converter is connected to the PMSG, while the rectifier of matrix converter is connected to the power grid via an input filter, which is used to filter the harmonics caused by the matrix converter. The reason why such a configuration is adopted is that the control the PMSG is much easier than the scheme presented in [2] and more degrees of freedom could be utilized efficiently.

B. The Mathematical Model of PMSM

Oriented on the synchronous reference frame of the rotor, the model of the PMSG [1] can be written as

$$L_d \frac{di_{sd}}{dt} = -R_s i_{sd} + L_d \omega i_{sq} + u_d \tag{1}$$

$$L_q \frac{di_{sq}}{dt} = -R_s i_{sq} - L_q \omega i_{sd} - \omega \psi_{PM} + u_q \tag{2}$$

$$T_e = 1.5 n_p [\psi_{pm} i_{sq} + (L_d - L_q) i_{sd} i_{sq}] \tag{3}$$

Where, u_d and u_q denote the voltage on the direct axis and quadrature axis, respectively. i_{sd} and i_{sq} represent the current on the direct axis and quadrature axis, respectively. n_p is the number of the pole pairs. ψ_{PM} represents the permanent magnet, and L_d and L_q denote the direct and quadrature inductance, respectively.

II. OPTIMAL EFFICIENCY OPERATION

The power generation efficiency is one of the most important performance indexes of the WECS. Due to the elimination of the gearbox, the mechanical loss can be ignored. And the main factors affecting the system efficiency are below: the conversion efficiency of the matrix converter η_m, the efficiency of the PMSG η_p, the conversion ratio of the wind energy η_w, and the transmission efficiency of the energy η_T. Because the system is connected in cascade, the overall efficiency is

$$\eta = \eta_m \cdot \eta_w \cdot \eta_T \cdot \eta_p \tag{4}$$

Since the efficiency of the MC can be up to 93%, its exact expression is a function of the switching frequency, the modulation coefficient and the load and the modulation strategy. The details of the MC's efficiency are complicated. The focus of this section is to optimize the efficiency of the generator and the energy transmission with the wind energy conversion efficiency depicted in the next section.

The R_f in Fig.1 is the sum of the transmission resistance and the filter resistance. And the energy transmission efficiency can be reformulated to minimize the reactive power injected to power grid, so the goal is to make the following expression null, i.e. the reactive reference current is zero.

$$Q_{inj} = 1.5\bar{u}_s \otimes \bar{i} \tag{5}$$

Where, $\bar{u}_s$ is voltage vector of power grid, $\bar{i}$ is the current carried by transmission line.

The efficiency of the PMSG is more complicated than the issue above. The PMSG loss includes cooper loss, iron loss, stray loss and mechanic loss, but for the the sake of simplicity, only copper loss is considered here

$$P_{Cu} = R_s(i_{sd}^2 + i_{sq}^2) \tag{6}$$

From the energy's point of view, the $i_{sq}$is related with the active power, while $i_{sd}$is concerned with reactive power. So we just need to null the i_{sd} to maximize the efficiency of PMSG. Up to now, we have got the optimal efficiency reference. And the conversion ratio of the wind energy will be discussed in details later.

III. *THE PROPERTY OF THE WIND ENERGY*

According to the Betz's theory[10], the maximum wind power captured by the wind turbine in the unit time can be expressed as:

$$P_{me} = 0.5C_p \rho A v_w^{\ 3} \tag{7}$$

Where, ρ is the air density (kg/m3); A is the blade-swept area; v_w is the wind speed; C_p is the conversion ratio reflects the efficiency of transferring the wind power to the mechanical power, the expression is :

$$C_p = 0.5(\frac{RC_0}{\lambda} - 0.022\beta - 2)e^{-0.255\frac{RC_o}{\lambda}} \tag{8}$$

Where, λ is the tip-speed ratio, β is the pitch angle and R is the radius of the wind blade, the definition of λ is $\lambda = R\omega_m / v$ (w_m denotes the mechanical angular speed of the wind turbine)

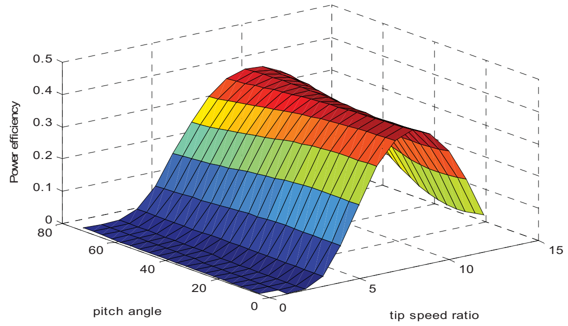


Fig. 2 The power character of the wind turbine

From Fig. 2, with the constant pitch angle and certain wind speed, there is only one maximum wind power (Pmax) to correspond with. And this feature is adopted by the maximum power point tracking, which controls the tip-speed radio under some wind to achieve the maximum wind power output. However, the present engineering method is to draw a precise curve to describe the exact relationship between the λ and the Pmax and make it as a look-up table for use. Later in practice, sample the wind speed and make corresponding adjustments to achieve the optimal power output. Nevertheless, in the physical implementations, the scenarios may be very complicated, and the mathematic relationship may not work very well as we wish. So a novel Sensorless maximum power point tracking is proposed with detailed descriptions below.

IV. *HYBRID SEARCHING METHOD FOR MPPT*

The maximum power point tracking(MPPT) is one of the two basic problems of the WECS. And the paper use hill-climbing method to realize the maximum power point tracking under the condition of Sensorless environment

The essence of Hill Climb Searching(HCS) is making use of the property of maximum power output curve witch is a mono-peak function to the wind speed. Hill Climb Searching as a series of strategies to search the optimal value is quite effective and robust to uncertainty due to varying environment. The disadvantage of Hill Climb Searching is that the rate of convergence is slow. In order to overcome this shortage, a hybrid approach, which combines Hill Climb Searching and bisection method, is proposed. The motivation is to make use of the fast convergence of bisection as well as the robustness and simplicity of hill climb searching.

Here are the implementation steps:

Step 1: Acquire few samples within the autocommissioning period of the PMSG;

Step 2: Adjust the motor's angular speed by bisection method, see whether the convergence becomes slowly if so, forward to Step 3 ; if not, recycle;

Step 3: change the searching method with hill climbing.

Its flow chart is shown in Fig.3.

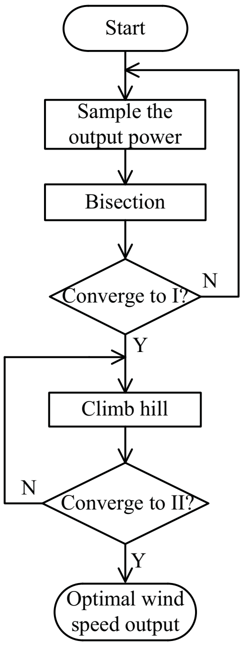


Fig. 3 The flowchart of MPPT

V. SYSTEM CONTROL

A. The block diagrams of the WECS

The overview of the control system is shown in Fig.4, and it mainly consists of three parts: the MPPT implementation, the modulation for the indirect Matrix Converter and the optimal control of the PMSG.

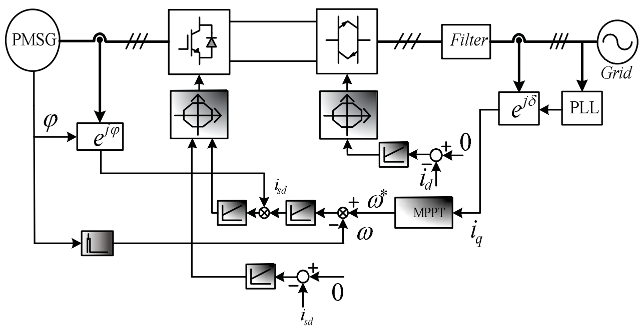


Fig. 4 Block diagrams of the control system

The optimal wind estimation is given with the MPPT module. And the calculation of the Equation 5~6 is to make the adjustments of currents on the D axis and Q axis. The current loop is classic PI controller and field oriented.

B. The modulation strategy for the matrix converter

There are many kinds of modulation strategies [5,6] for the matrix converter, which have been fully studied in the past literatures. The space vector modulation is so widely used that it becomes almost the industrial standard method. It is composed of the input current modulation and the output voltage modulation.

The process of the input current modulation, the first step is to partition the input voltage sectors. Usually, the input voltage sectors partition(time domain) is shown in Fig. 4. But in the space vector's point of view, this voltage sector assignment is shown in Fig. 4, which is like the voltage space vector modulation. The second step is to calculate duty ratios. The indirect matrix converter must satisfy the positive intermediate DC voltage to make it suitable for the operation of the inverter. So the range of controllable power factor should be limited within a certain scale.

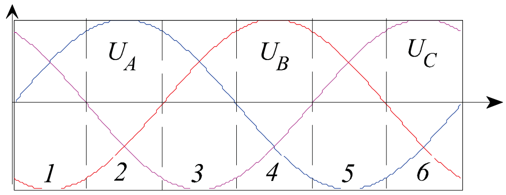


Fig. 5 Sectors separation of the intermediate dc voltage

The reference of the input current space vector is given by the unit power factor controller which could guarantee the minimum transmission loss.

The modulation of matrix converter is almost the same as the conventional SVPWM. However, the main difference between them is that the modulation in the paper consists of two steps, which share the same intermediate DC link but different DC voltage levels(Fig. 5). In addition, the synchronization between the rectifier and the inverter, which is also very important, must be guaranteed.

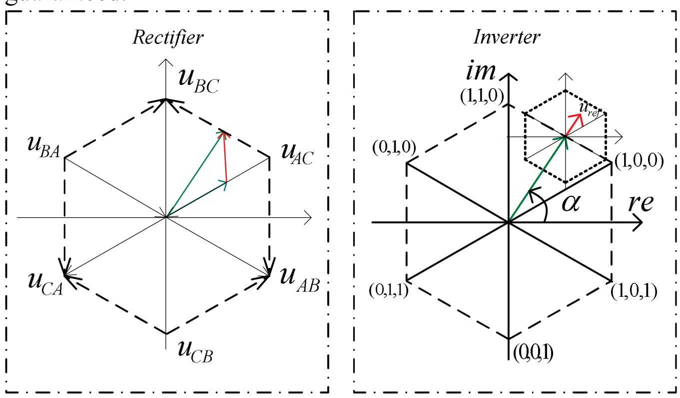


Fig. 6 Space vector modulation in rectifier and inverter

C. The Optimal Control of the PMSG

After eliminating the crossing terms in EQU.1 by directly decoupling, the current equations of PMSM in the rotor synchronous reference frame could be written as follows.

$$L_d \frac{di_{sd}}{dt} = -R_s i_{sd} + u_d^1 \tag{9}$$

$$L_q \frac{di_{sq}}{dt} = -R_s i_{sq} + u_q^1 \tag{10}$$

Where u_d^1 and u_q^1 are

$$u_d^1 = u_d + L_d \omega i_{sq}$$

$$u_d^1 = u_q - L_q \omega i_{sd} - \omega \psi_{PM}$$

In order to design an optimal controller, with the uncertain in parameters and the output saturation for preventing over-current of the inverter feeding PMSM taken into account, the conventional optimization for acquiring the optimal PID parameters is hard to apply here. So an optimal PID controller, which is based on particle swarm optimization approach, is proposed instead.

Usually, the cost functions for dynamic system have the following selections: integrated absolute error (IAE), integrated squared-error (ISE) and integrated of time-weighted-squared-error (ITSE) [13]. In all above performance index, ITSE is the best choice in this application. The cost function is defined as

$$ISTE = \int_0^{\infty} te^2(t)dt \tag{11}$$

$$\text{S.T. } \sqrt{u_d^2 + u_q^2} \le u_m$$

$$R_s \in (R_o - \varepsilon, R_o + \varepsilon)\ , \varepsilon > 0$$

Where, u_m is the maximum capacity of the inverter, ε is the boundary of the parameter perturbation.

The proposed PID structure is

$$k_P + \frac{k_I}{s} + \frac{k_D s}{T_D s + 1} \tag{12}$$

The low pass filter $1/T_D s + 1$ is introduced to avoid the measurement noise, which degrades the performance of system. The goal of the optimization problem is to acquire the optimal parameters—— $k_P\ k_I\ k_D\ T_D$.

D. PSO Algorithm

Similar to the genetic algorithm (GA) and other evolutionary algorithms, the PSO is also inspired by the nature. However, the philosophy it contains is different. For GA, survival is the best. But what the PSO adopts is to cooperation with each other. With the interesting features, such as few parameters and less operators compared with GA, the PSO algorithm is adopted.

The standard PSO with inertia weight:

$$v_{id} = wv_{id} + c_1 rand()(p_{id} - x_{id}) + c_2 rand()(p_{gd} - x_{id}) \tag{13}$$

$$x_{id} = x_{id} + v_{id} \tag{14}$$

Where, d=1,2,⋯,n ;i=1,2, ⋯m, m is the population size; t is the current run, *rand()* and *Rand()* are random numbers with value span[0,1]; c_1 and c_2 are accelerating constants; w is the inertia weight, which is calculated with the expression below:

$$w = w_{\max} - (w_{\max} - w_{\min})t/t_{\max} \tag{15}$$

Where, w_{max} and w_{min} denote the maximum and minimum in w, respectively; t and t_{max} represent the current epochs of the run and the maximum epochs, respectively.

With the calculated uq and ud shown in Fig.4, and uq, ud are supposed to be constant within the time interval between two neighboring samplings. The problem can be derived to choose the best parameters for the PID controller(the modes of the equation are the same one order except for the different parameters between L_d and L_q).

The structure of the adjustment scheme is shown below:

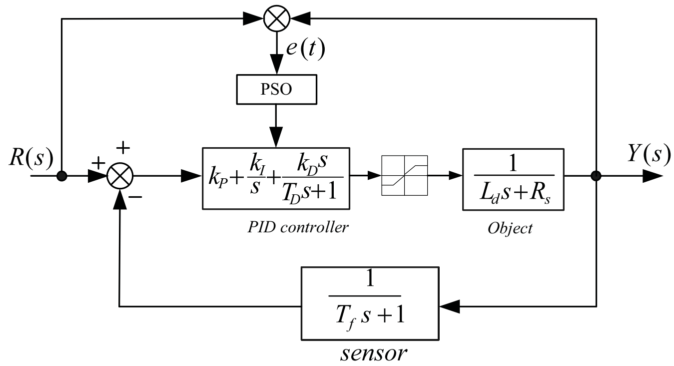


Fig. 7 Block diagram of the controller

VI. SIMULATION VERIFICATION

The simulation parameters are: MC: R_f =0.1 Ohmn, L_f =0.2mH, C_f =60uF, f_s =5kHz; PMSM: R_s =1.875Ohmn, L_d =8.5 mH, L_q =8.0 mH, Φ_{pm} =0.175, J=0.8×10^{-3}, n_p=4.

Based on the guidelines[17], the parameters in the PSO algorithm are set as: population size=30, inertia weight linearly decreases from 0.9 to 0.4 within the run about 100 epochs. C1 and c2 are the same, 2.05. An error criterion is 1e-3. The sampling period is 2e-2s.

Parameter settings: maximum generations: 2000, initial scale of PID and T_D : [0,200;0,20;0,20;0,0.01], sampling frequency: 1e-4, samples: 400, the upper and lower bound: -10 and 10.

With different parameter uncertainty, the performances of the PID controller are shown below.

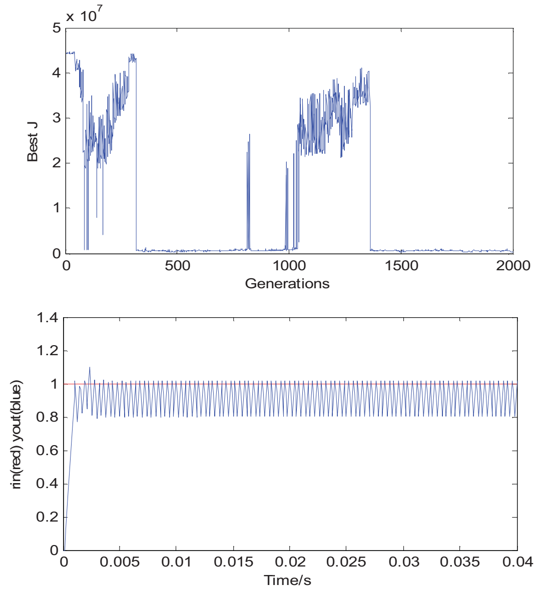


Fig. 8 The parameter uncertainty equals with the R_S

The optimal parameters for PID and T_D are 144.8674, 15.99046, 0.01622675 and 0.0012.

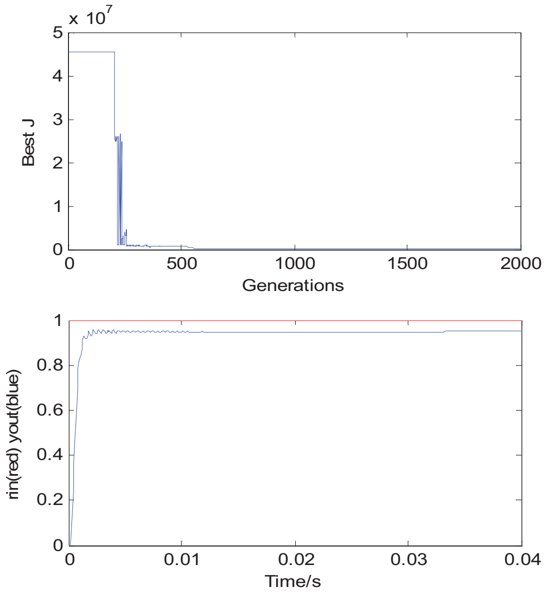


Fig. 9 The parameter uncertainty equals with 1/10 of R_S

The optimal parameters for PID and T_D are 35.5645, 13.9221, 0.00547491 and 0.0013.

It is quite natural to find out that with minor uncertainty(Fig. 8), it is easier for the system to rapidly converge to the optimal value and without much fewer vibrations. That means, it is very important to set a good initial scale, which is very close to the real value.

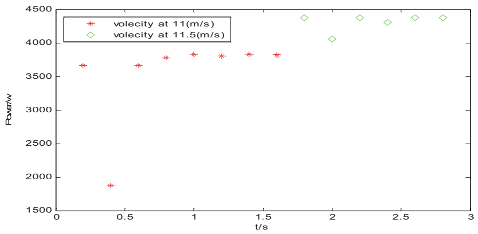
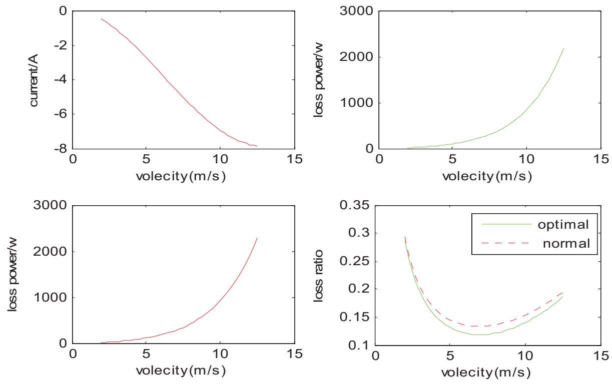
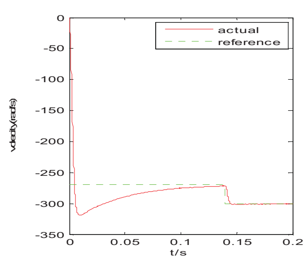


Fig. 10 Sensorless maximum power point tracking

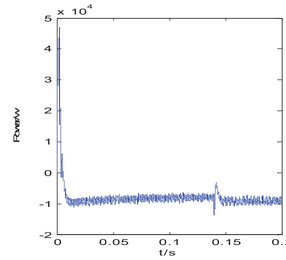


a.(upper left)Id under minimum power loss；b.(upper right)minimum power loss c. (lower left) power loss when i_{sd}=0；d. (lower right)minimum power loss ratio VS normal power loss ratio

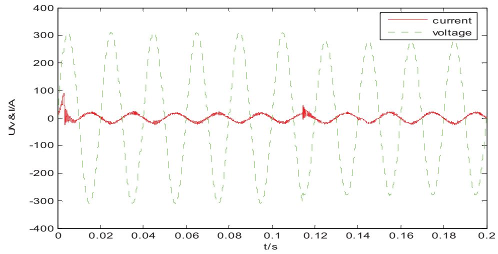
Fig.11 Efficiency optimization of the PMSM



a. Speed response



b. output power response



c. The input voltage and current response of the MC

Fig. 12 The system response

Fig. 10 depicts the optimal wind tracking process, and the first 1.5 seconds are under the wind speed of 11 m/s, the later 1.2 seconds are 11.5m/s, the sampling period of the algorithm is 0.2s, and the power output can return to the normal within this period.

As shown in Fig.11-a, the minimum power losses control method is verified under different wind speeds. Fig.11-b and Fig.11-c take the minimum loss and power loss under i_{sd}=0, respectively.

The system response under the external disturbance is shown in Fig.12, in 0.11s, a three phase symmetric sag occurs in the grid. However, the intermediate dc voltage can be sampled, and the output voltage can be immune to the disturbance(such as unbalanced power supply, power sag and power swell) on the input side as a result. From Fig. 12-a and Fig. 12-b, it is easily learned that the PMSM has no the interference, while a large transition occurs on the input current of the matrix converter. At 0.14s, the given speed is suddenly changed, within a short period, the system returns to the steady state. A less short term distortion is on the input current (Fig. 12-c).

VII. Conclusion

A novel system topology applied in the wind energy conversion system is presented. It fits some special circumstances with the feature that the elimination of gearbox and bulky electrolytic capacitor. Taking output saturation and parameter uncertainty in to consideration, the PSO-based optimal PID controller shows excellent dynamic performance and robustness in the light of simulations. Sensorless MPPT also exhibit the desired response. And the overall control system is verified. The easy-to-implement control scheme will make the physical practice easier.

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