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A MPPT Strategy Based on Fuzzy Control for a Wind Energy Conversion System

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Abstract

In order to maximize the amount of energy produced from a wind turbine according to the wind speed fluctuations, the WECS needs a controller able of ensuring its operation mode around the OPP. In this paper, a MPPT strategy is proposed, to extract a maximum power from a variable speed wind turbine based on squirrel cage induction machine drive by using fuzzy logic control. The proposed strategy is based upon the monitoring and the judgment of the power - rotational speed characteristic in the aim to find the optimum rotational speed that corresponds to the optimal produced power. The simulation results in MATLAB/SIMULINK of the entire WECS demonstrate the ability of the MPPT-FLC to extract a maximum power from the wind.

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Keywords: Maximum Power Point Tracking strategy; Fuzzy logic control; Wind energy conversion system; Squirrel Cage Induction Generator.

1. Introduction

Recently, due to global warming and climate change, the renewable energy sources especially wind energy has been paid much attention. Wind power has developed very fast during the last decades and it has achieved a large

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penetration of electricity consumption in some countries, for example 53% experienced in Spain, more than 40% in Denmark. Moreover, in 2020 the electricity consumption that will be supplied by wind power according to the setting of EUs 20-20-20 goad and Danish agreement is 50% [1]. Reliable and effective optimization of the operation mode of the installation is an essential critical issue to achieve the highlighted market. In this work our interest is made upon improving the operation of a wind power renewable source throughout elaborating an intelligent strategy of control. Three main kinds (TSR, PSF and HCS) of MPPT strategy founded in literature to control the WECS through the converter side generator, where they are reviewed in [2]. Their objective is to extract a maximum power from the wind. The TSR strategy enables to regulate the rotational speed of the generator to its optimal based on the wind speed measurement and the WT characteristic. The PSF strategy allows the WECS to track the optimum power based on the power reference curve and the WT characteristic. The wind speed measurement, the power reference cure and the WT characteristic remain a challenge issue in application of TSR and PSF strategies. A HCS strategy is very adapted to control the WECS. It enables to track the optimal OP without wind speed measurement and WECS characteristic. In this work a reliable MPPT is elaborated without wind speed measurement and requiring just poor information about the system. The proposed strategy is based on FLC which is a modern concept to control the complexes systems. It objective is to maintain the operation of the WT around the optimal regime where the power the harvested power is maximal. The efficiency of the proposed method is verified by simulation results in MATLAB/SIMULINK for a small variable speed WT model of 6 KW.

Nomenclature

WECS	Wind energy conversion system
WT	Wind turbine
SCIG	Squirrel Cage Induction Generator
MPPT	Maximum Power Point tracking
FLC	Fuzzy Logic Control
HCS	Hill climbing searching
PSF	Power signal feedback
TSR	Tip Speed Ratio
P_w	Wind turbine mechanical power [W]
P_e	Wind turbine electrical power [W]
Pn	Wind turbine mechanical power nominal
C_p	Power coefficient of the wind turbine
ρ	Air density [kg/m^3]
R	Rotor turbine radius [m]
V	Wind speed [m/s]
V_n	Rated wind speed [m/s]
λ	Tip Speed Ratio (TSR)
β	Pitch angle
Ω_l	Shaft rotor turbine speed [rad/s]
Ω_h	Shaft generator rotational speed [rad/s]
J_{eq}	The equivalent inertia of turbine and generator [kg.m^2]
T_e	Electromagnetic torque of the generator [N.m]
T_r	Turbine mechanical torque [N.m]
$\Delta\Omega_h$	Rotational speed change of the generator
ΔP_e	Electrical power change
$\Delta\Omega_h^{ref}$	Desired rotational speed change of the generator
L_s	Stator inductance [H]
L_r	Rotor inductance [H]

L_m	Mutual inductance [H]
p	Pole pairs number of the generator
ω_s	Stator field frequency [rad/s]
R_s	Stator resistance [Ω]
R_r	Rotor resistance [Ω]
v_{sd} , v_{sq}	Voltages of the stator in the dq frame [V]
Φ_{sd}, Φ_{sq}	Stator flux linkage in the dq frame [Wb]
Φ_{rd}, Φ_{rq}	Rotor flux linkage in the dq frame [Wb]
i_{dqs} , i_{dqr}	Current components of the stator in the dq frame [A]
G	Gearbox ratio
OR	optimal regime or maximum power curve in the power-rotational speed characteristic
OP	operating point
OPP	Optimal operating point
PWM	pulse width modulation

2. WECS Modeling

WECS is a renewable energy source, enables to harvest an amount of energy from the wind flow. It contains many components and each has a specific function. A WT allows transforming the motion of the wind flow into a motion of rotation available at the rotor shaft speed. A gearbox is used to adapt the rotational speed of the generator and the rotor. The machine drive is used to convert the motion of rotation available at its shaft to a power electric. A converter side electrical machine is used to control the WECS. An inverter side grid is used to control the active and reactive power between the system and the grid. The entire structure of WECS is illustrated in Fig. 1.

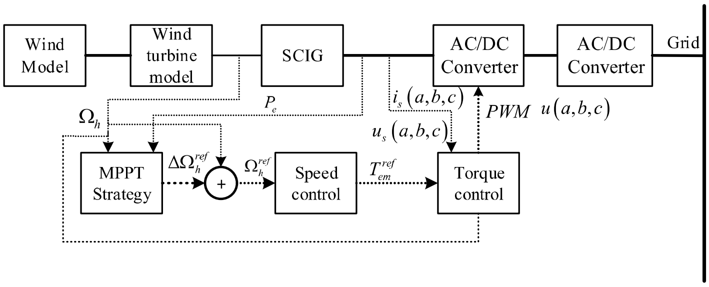

Fig. 1. WECS model and control system

2.1. WT modeling

The amount of power extracted from the wind by the WT and the aerodynamic torque are given respectively by the expressions [3]:

$$P_m = \frac{1}{2}\rho\pi R^2 C_p v^3 \tag{1}$$

$$T_r = \frac{P_r}{\Omega_l} = \frac{\rho\pi R^2 C_p}{2\lambda} v^2 \tag{2}$$

With $\lambda = \frac{\Omega_l * R}{v}$

C_p represents the ability of the wind turbine to extract a power from the wind. Its a complex function of λ and β. Different expressions of this coefficient founded in the literatures such as given in [1]. Generally, in the partial load area of the WT operation mode, the pitch angle is kept fixe at its optimal value. A value $\beta = 0$ enables to an optimum level of efficiency. In this work we use the expressions below because we interest just to maximize the produced power throughout the electromagnetic torque.

$$C_p(\lambda) = \sum_{i=0}^{6} a_i \lambda^i \tag{3}$$

2.2. Electrical drive machine and drive train modeling

The electrical machine selected to convert the motion of rotation available at the shaft speed of the rotor into the electrical power is a Squirrel Cage Induction Generator, that due to high efficiency and simple maintenance of the induction machine. The modeling of the machine in *dq* frame is given by the following voltage equation (3)-(6):

$$\begin{cases} v_{qs} = -R_s i_{qs} + \dfrac{d\Phi_{qs}}{dt} + \omega_s \dfrac{d\Phi_{ds}}{dt} \\ v_{ds} = -R_s i_{ds} + \dfrac{d\Phi_{ds}}{dt} - \omega_s \dfrac{d\Phi_{qs}}{dt} \\ v_{dr} = 0 = -R_r i_{dr} + \dfrac{d\Phi_{dr}}{dt} - \omega_s \dfrac{d\Phi_{qr}}{dt} \\ v_{qr} = 0 = -R_r i_{qr} + \dfrac{d\Phi_{qr}}{dt} + \omega_s \dfrac{d\Phi_{dr}}{dt} \end{cases} \tag{4}$$

With

$$\begin{cases} \Phi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \Phi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \Phi_{ds} = L_r i_{dr} + L_m i_{ds} \\ \Phi_{qr} = L_s i_{qr} + L_m i_{qs} \end{cases} \tag{5}$$

The produced electrical power and the electromagnetic torque are given respectively by:

$$P_e = \frac{3}{2}(v_{sd} i_{sd} + v_{sq} i_{sq}) \tag{6}$$

$$T_{em} = \frac{3}{2}\left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) \tag{7}$$

The drive train of the WT in this work is considered rigid, which represent the coupling between the WT and the electrical machine. A gearbox is, considered ideal, to adapt the rotational speed of the two parts. Its model is given by the following equation:

$$T_r = \frac{d\Omega_h}{dt} + T_e \tag{8}$$

With $\Omega_h = G * \Omega_l$

3. MPPT strategy Modeling

3.1. MPPT based on FLC

The aim of the MPPT strategy is to control the WT in the partial load of operation. In fact, when the wind speed is lower than the rated value $\left(v \prec v_n\right)$, it is important for the WT to follows quickly the wind speed change in order to provide a maximum power to the grid. In other word the OP of WT changes rapidly according to change of the wind speed, so that's why its necessary to integrate a MPPT strategy into the WT in order to maintain its OP around the optimal value, which corresponds to $\lambda_{opt} = 7$ (or $C_p^{opt} = 0.47$) of the 6KW WECS model studied , despite of the wind speed change. As shown in figure.2.b, which represents the mechanical power versus rotational speed characteristic of a WT, that for each wind speed (v_1, v_2 ,…) there exists a single point where it's marked by a small round which indicate the OPP denoted by the peer $\left(P_e^{opt}, \Omega_h^{ref}\right)$. All this point constitutes the OR of WECS operation given in Fig. 2.a. So the aim of MPPT strategy is to operate the system on this OR.

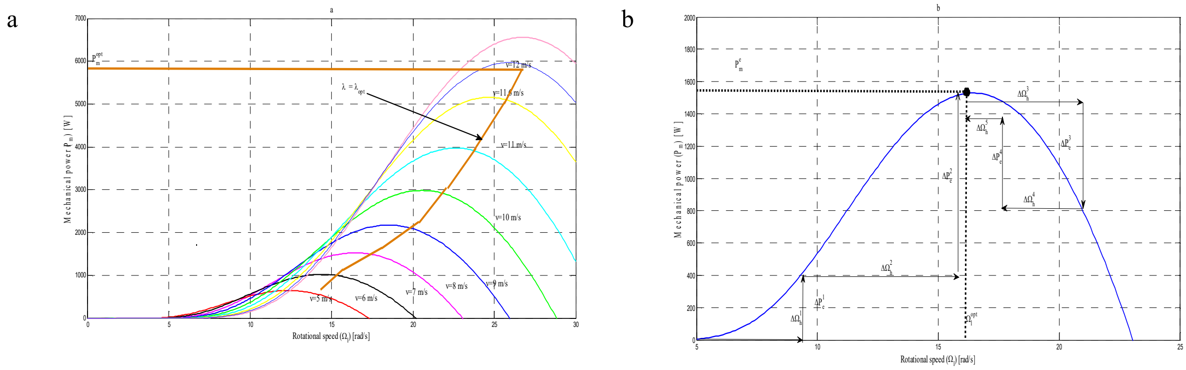

Fig. 2. a) OR of the WECS operation; b) Principe of searching the MPPT strategy

The proposed MPPT strategy structure is given in Fig.1. It has two inputs which are the electrical power change and the rotational speed change and one output which is the desired rotational speed step change, given at the k iteration as follow:

$$\Delta\Omega_h\left(k\right)=\Omega_h\left(k\right)-\Omega_h\left(k-1\right) \tag{9}$$

$$\Delta P_e\left(k\right)=P_e\left(k\right)-P_e\left(k-1\right) \tag{10}$$

FLC is a reliable tool enables to control the complexes system. It's designing is based on human experience through a set of the empirically determined design rules introduced by [4]. The MPPT strategy is based on three steps:

Fuzzification: This step consists to convert the numeric values of inputs into fuzzy values. The two inputs ($\Delta\Omega_h$ and ΔP_e) and output ($\Delta\Omega_h^{ref}$) are expressed by five variables linguistic in the universe of discourse, which are: NB (Negative Big), (NS) Negative Small, Z (Zero), PS (Positive Small) and PB (Positive Big). Each inputs/output is characterized by triangular and symmetric membership function. All the variables $\Delta\Omega_h$, ΔP_e and $\Delta\Omega_h^{ref}$ are normalized by factor scales k_Ω , k_P and k_Ω^{ref} respectively.

Fuzzy logic rules: The fuzzy rules are derived from the exact knowledge of the WECS behavior. The inputs/output is connected by the IF-THEN logic rules. Par example if $\Delta\Omega_h$ is NB and ΔP_e is NB then $\Delta\Omega_h^{ref}$ is PB. The engine rules of the MPPT strategy is given in the table.1.

Table 1: Fuzzy logic rules

$\Delta\Omega_h$	ΔP_e	NB	NS	Z	PS	PB
NB		PB	PS	Z	NS	NB
NS		PS	PS	Z	NS	NS
Z		NB	NS	Z	PS	PB
PS		NS	NS	Z	PS	PS
PB		NB	NS	Z	PS	PB

Defuzzification: This step is the inverse of fuzzification operation, consists in converting the linguistic variables of the output to a real value. The method center of gravity used in [5] is utilized in this work to obtain the crisp value of the rotational speed change.

The MPPT strategy has two tasks to establish in order to drive the OP of the WECS to its optimal point:

- Second point
- Monitoring the produced electrical power vs. rotational speed characteristic: For each wind speed the rotational speed and the electrical power produced are estimated. The estimated characteristic for a particular wind speed is given in Fig. 2.b.

- Searching and tracking the OPP: According to the assessment of the produced power-rotational speed of the generator characteristic, the MPPT strategy will increase or decrease the rotational speed until maintaining the OP on zero slope area of the characteristic (the peak of the characteristic) which corresponds to OPP. If $\frac{\Delta P_e}{\Delta \Omega_h} \succ 0$ the MPPT will increase the rotational speed by an adaptive step given at its output to attain the OPP. In the opposite case, the MPPT will decrease the rotational speed. If $\frac{\Delta P_e}{\Delta \Omega_h} = 0$, there is no act to do by the MPPT strategy.

The optimal rotational speed of the generator at the k iteration, that extracts a maximum power from the WT is given based on the previous rotational speed and the trend of change given at the output of the MPPT strategy, as follow:

$$\Omega_h^{ref}(k) = \Omega_h(k-1) + \Delta\Omega_h^{ref}(k) \tag{11}$$

4. Result and discussion

A simulation is performed in MATLAB/SIMULINK for the system of Fig.1 in the aim to investigate the performances of the presented strategy. The characteristics of the simulated system are given in table.3. The WECS is subjected to a wind profile given by Fig. 4 of 2 min of time interval; a 7 m/s mean wind speed and a medium level of turbulence. Fig. 5, 6, 7, 8 show respectively, the rotational speed, tip speed ratio, power coefficient and the produced electric power, obtained by the proposed strategy and the HCS strategy respectively. The rotational speed of the generator follows very well the immediate changes of the wind speed in order to bring OP around its optimal value where WECS is at its high level of efficiency. This is verified by the variation of the power efficiency and tip speed ration around their nominal values despite of the changes rapid of the wind speed $\left(C_p^{opt} = 0,47, \lambda_{opt} = 7\right)$. The electrical power follow very well the wind speed change and it's in concordance with the theoretical power (the theoretical power is a cubic function of the wind speed). As showed, the parameters simulated of WECS exhibit the fluctuations for two reasons: the low mass of the WT and the dynamic rapid of the system brought by the MPPT-FLC. Compared to the traditional HCS strategy, the MPPT-FLC strategy allows WT to respond rapidly to wind speed changes in order to extract a maximum energy.

In term of power coefficient, the proposed strategy capture 2.28% more energy than the HCS strategy, the result of comparison is given in Table 2.

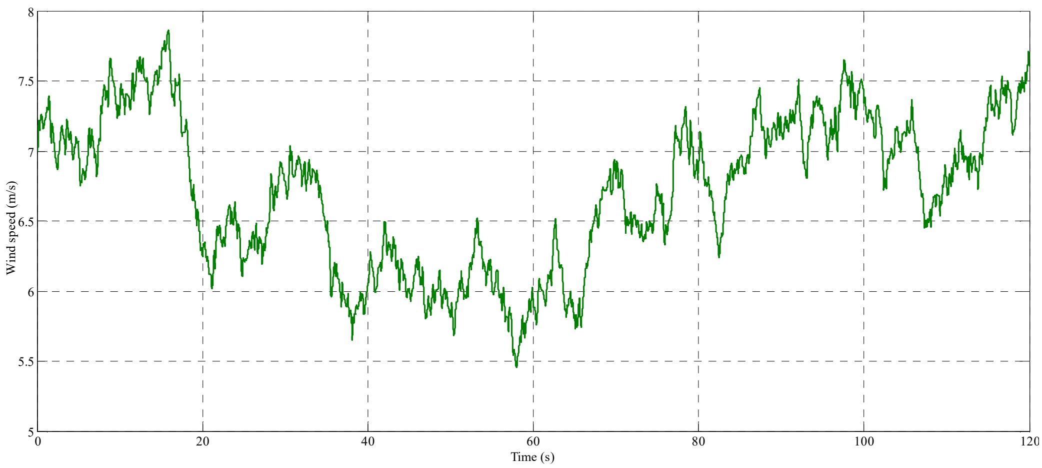

Fig. 3. Wind speed profile

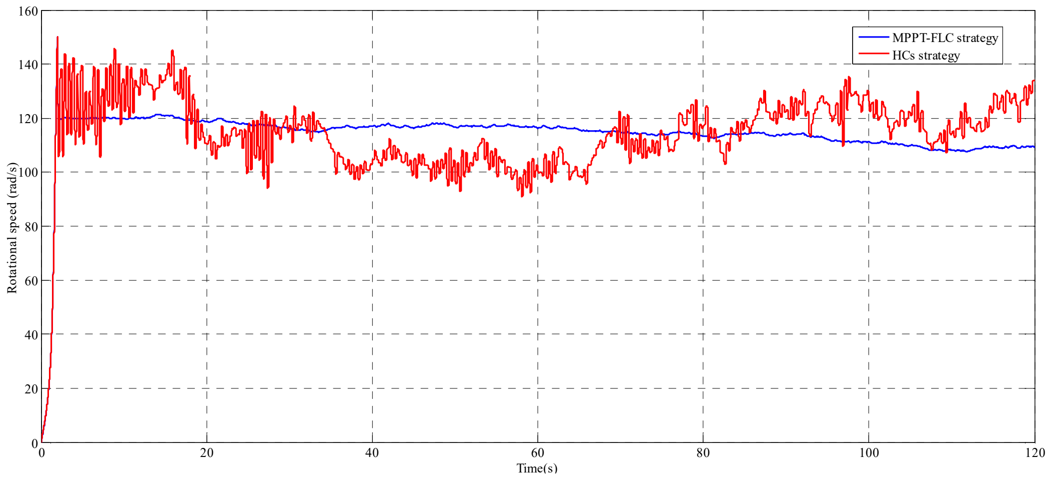

Fig. 4. Rotational speed of the generator

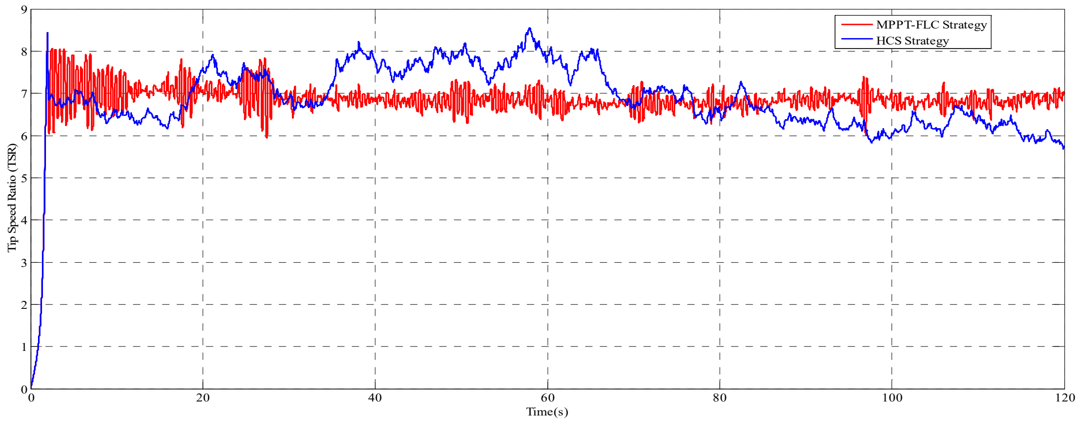

Fig. 5. Tip Speed ratio (TSR)

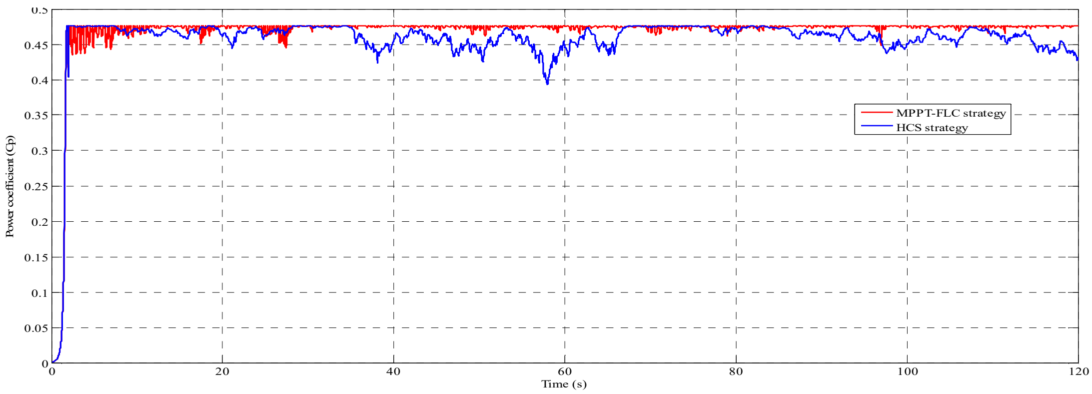

Fig. 6. Power coefficient

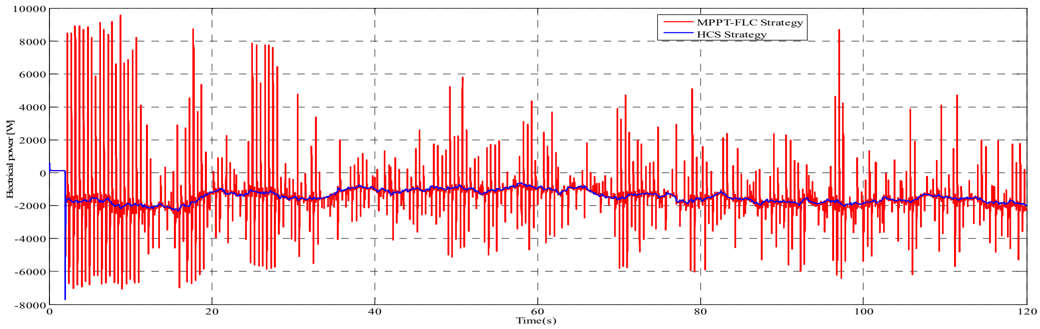

Fig. 7. Electric power produced

Table 2: Result of comparison between MPPT based on FLC and HCS strategy

Mean power coefficient (%)		Increasing power percentage (%)
MPPT strategy proposed	46,65	2,28
HCS strategy	45,61	-

Table 3: Parameters for a 6 KW WECS

parameters	value	Parameters	Value
R	2,5	c_0	0,0061
G	6,25	c_1	-0,0013
J_{eq}	3,99	c_2	0,0081
R_s	1,265	c_3	$-9{,}7477.10^{-4}$
R_r	1,43	c_4	$-6{,}5416.10^{-5}$
L_s	0,1452	c_5	$1{,}3957.10^{-5}$
L_r	0,1452	c_6	$-4{,}54.10^{-7}$
L_m	0,1397	p	2
ω_s	100 π	ρ	1,25
k_Ω	0,001	k_P	0,001
k_Ω^{ref}	40		

5. Conclusion

This work presents a MPPT strategy for maximizing the produced energy of a WT based on SCIG. The strategy is based on monitoring, searching and tracking the optimal power point by FLC concept. This MPPT strategy makes the optimization and control WECS simple and more flexible. Its main advantage is that independent of the wind speed measurement and the characteristic of the system, and may be used for all kinds of system. The simulation results have shown that the proposed strategy improves very well the efficiency of WECS.

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