CONTROL OF ENERGY CONVERSION IN A HYBRID WIND AND ULTRACAPACITOR ENERGY SYSTEM

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To my beloved parents,
My kind sisters and brothers
And not forgetting to all my friends
For their
Sacrifice, Love, and Encouragement

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ABSTRACT

In this thesis the design and implementation of a control strategy for interfacing a hybrid wind and ultracapacitor energy system is presented. The proposed system consists of a Permanent Magnet Synchronous Generator (PMSG)-based wind turbine and an ultracapacitor storage element. The PMSG-based wind turbine is connected to a DC (direct current) bus through an uncontrolled rectifier and a DC-DC boost converter; the ultracapacitor is interfaced to the DC-bus using a bidirectional DC-DC converter. In a wind energy system, because of the unpredictable nature of wind speed, a Maximum Power Point Tracking (MPPT) algorithm is essential for determining the optimal operating point of the wind turbine. This work proposes a new and simple MPPT algorithm based on hybridization of the Optimum Relation Based (ORB) and Particle Swarm Optimization (PSO) methods. The proposed MPPT is advantageous in being sensorless, converging quickly and requiring no prior knowledge of system parameters. In addition, a Linear Quadratic Regulator (LQR) strategy has been applied in designing the DC-DC converter controllers because of its systematic procedure and stability advantages and simplicity. Two controllers based on the LQR method have been designed and implemented. One controller forces input current of the boost converter to track the optimal reference current generated by the proposed MPPT algorithm. The other regulates the DC-bus voltage at a desired level. The regulation is accomplished by controlling the bidirectional converter interfacing the ultracapacitor and the DC-bus. The proposed energy system and its controllers have been simulated in MATLAB/Simulink and implemented using a TMS320F2812 eZdsp board. Simulation results indicate that the proposed PSO-ORB MPPT algorithm average efficiency is 99.4%, with harvested electrical energy 1.9% higher than the conventional OTC and ORB MPPT algorithms. The simulation results also demonstrate the effectiveness of the proposed LQR controllers in obtaining good tracking and their ability to quickly restore the system to its nominal operating point when it is exposed to a disturbance. The simulation results are highly comparable with the experimental results that have successfully verified the functionality of the proposed control techniques.

ABSTRAK

Dalam tesis ini reka bentuk dan pelaksanaan strategi kawalan untuk pengantaramukaan angin dan tenaga ultrakapasitor sistem hibrid dibentangkan. Sistem yang dicadangkan terdiri daripada Penjana Segerak Magnet Kekal (PMSG) - berdasarkan turbin angin dan unsur penyimpanan ultrakapasitor. Turbin angin berasaskan PMSG disambungkan kepada bas DC (arus terus) melalui penerus tak terkawal dan DC-DC penukar rangsangan; ultrakapasitor itu saling berkait bagi DC-bas menggunakan dwiarah DC-DC penukar. Dalam sistem tenaga angin, kerana sifat kelajuan angina yang tidak menentu, Pengesanan Titik Kuasa Maksimum (MPPT) algoritma adalah penting untuk menentukan titik operasi optimum turbin angin. Kerja ini mencadangkan algoritma MPPT baru dan mudah berdasarkan penghibridan Berdasarkan Perhubungan yang Optimum (ORB) dan kaedah Optimasi Kumpulan Zarah (PSO). MPPT yang dicadangkan adalah berfaedah dalam menjadi sensorles, menumpu dengan cepat dan tidak memerlukan pengetahuan terlebih dahulu untuk parameter sistem. Di samping itu, (LQR) strategi Linear Kuadratik Pengawal Selia telah digunakan dalam mereka bentuk penukar pengawal DC-DC kerana kelebihan prosedur yang sistematik dan kestabilannya dan kesederhanaan. Dua pengawal berdasarkan kaedah LQR dirancang dan dilaksanakan. Satu pengawal memaksa arus input daripada rangsangan penukar untuk mengesan rujukan semasa optimum dihasilkan oleh algoritma MPPT yang dicadangkan. Yang lain mengawal voltan DC-bas di tahap yang dikehendaki. Peraturan itu dicapai dengan mengawal penukar dwiarah antara muka ultrakapasitor dan DC-bas. Sistem tenaga yang dicadangkan dan pengawalnya telah disimulasi di dalam MATLAB/Simulink dan dilaksanakan menggunakan papan TMS320F2812 eZdsp. Keputusan simulasi menunjukkan bahawa PSO-ORB MPPT algoritma kecekapan purata dicadangkan adalah 99.4%, dengan tenaga elektrik yang dituai 1.9% lebih tinggi daripada konvensional OTC dan ORB MPPT algoritma. Keputusan simulasi juga menunjukkan keberkesanan pengawal LQR dicadangkan dalam mendapatkan pengesanan yang baik dan keupayaan mereka untuk segera memulihkan sistem untuk titik operasi nominal apabila ia terdedah kepada gangguan. Keputusan simulasi amat setanding dengan keputusan uji kaji yang telah berjaya mengesahkan fungsi teknik kawalan yang dicadangkan.

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LIST OF ABBREVIATIONS

ADC	-	Analog to digital convertor
ANN	-	Artificial neural network
CCS	-	Code composer studio
DC	-	Direct current
ESR	-	Equivalent series resistance
FLC	-	Fuzzy logic control
FNN	-	Feedforward neural network
HCS	-	Hill climbing search
LQR	-	Linear quadratic regulator
MPP	-	Maximum power point
MPPT	-	Maximum power point tracking
MPSO	-	Modified particle swarm optimization
OPP	-	One-power-point
ORB	-	Optimum-relation-based
OTC	-	Optimal torque control
P&O	-	Perturbation and observation
PC	-	Personal computer
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PMSG	-	Permanent magnet synchronous generator
PSF	-	Power signal feedback
PSO	-	Particle swarm optimization
PWM	-	Pulse width modulation
RPM	-	Rotation per minute
RTW	-	Real time workshop
SMC	-	Sliding mode control
TSR	-	Tip speed ratio
WECS	-	Wind energy conversion system
WRBFN	-	Wilcaxon radial basis function

LIST OF SYMBOLS

c_1, c_2	-	Acceleration coefficients
ρ^{wind}	-	Air density
Δd	-	Change in duty cycle
ΔD	-	Change in duty cycle
$\Delta\omega$	-	Change in generator speed
ΔP	-	Change in power
Δi_{ref}	-	Change in reference current
u	-	Control inputs vector
V_{cut-in}	-	Cut-in wind speed
$V_{cut-out}$	-	Cut-out wind speed
I_{dc}	-	dc current
$I_{dc-peak}$	-	dc current correspond to maximum power
V_{dc}	-	dc voltage
$V_{dc-peak}$	-	dc voltage correspond to maximum power
K_d	-	Derivative gain of PID controller
D, d	-	Duty cycle
P_e	-	Electrical power
G_{best}	-	Global best position
I_L	-	Inductor current
J	-	Inertia of wind turbine
w	-	Inertia weight
V_{in}	-	Input voltage
K_i	-	Integral gain of PID controller
$P_{m-\max}$	-	Maximum mechanical power
$C_{p\max}$	-	Maximum power coefficient
P_m	-	Mechanical power
T_m	-	Mechanical torque

I_{dc-opt}	-	Optimal dc current
$\mathbf{K}$	-	Optimal feedback gains vector
ω^*	-	Optimal generator speed
K_{T-opt}	-	Optimal parameter
λ_{opt}	-	Optimal speed ratio
T_{m-opt}	-	Optimal torque
K_{opt}	-	Optimum coefficient
I_o	-	Output current
v	-	Particles velocity
P_{best_i}	-	Personal best position
Φ	-	Perturbation size
β	-	Pitch angle
x	-	Position of PSO particles
C_p	-	Power coefficient
K_p	-	Proportional gain of PID controller
R	-	Radius of the turbine
V_{rated}	-	Rated wind speed
i_{ref}	-	Reference current
V_{ref}	-	Reference voltage
ω_m	-	Rotor speed
$\mathbf{x}$	-	States vector
f_s	-	Switching frequency
T_s	-	Switching period
λ	-	Tip speed ratio
ρ	-	Weighting element of inputs
q	-	Weighting element of states
$\mathbf{R}$	-	Weighting matrix of inputs
$\mathbf{Q}$	-	Weighting matrix of states
V_w	-	Wind speed

CHAPTER 1

INTRODUCTION

1.1 Background

Wind-energy systems have gained vast popularity as a renewable energy source in the past decade. This is because of the possibility of the depletion of conventional energy sources that have negative effects on the environment and also have high costs. Wind-energy is preferred because it is clean, pollution-free, inexhaustible, and secure. Therefore, a wind-energy generation system could become one of the significant candidates for a future alternative energy source.

However, based on the Betz limit [1], there is no wind turbine that could convert more than 59.3% of the kinetic energy of the wind into mechanical energy for turning a rotor. Unfortunately, modern wind turbines, in practice, generally fall only into the 35% to 45% efficiency range. Equations that express the fraction of power that the wind turbine obtains from wind include a power coefficient (C_p). For a wind turbine with a fixed blade pitch, this power coefficient is usually expressed as a function of the tip speed ratio (λ). λ is the ratio of the blade's tip speed (ω_m) to the actual wind speed (V_w). The $C_p(\lambda)$ curve has only one maximum point occurring at a certain optimum λ. In a varying wind speed environment, a maximum power point tracking (MPPT) algorithm must be included in the system. The MPPT algorithm is used for adjusting the rotational speed of the turbine in order to reach this optimal λ for all wind conditions.

Including the MPPT algorithm in the wind energy conversion system (WECS) allows for operation of the system at its maximum efficiency; however, the output voltage of the WECS becomes instantaneously variable in proportion to the turbine rotational speed. Because the WECS is directly connected the DC-bus, the DC-bus voltage itself will be variable. In order to maintain the DC-bus voltage at a constant value, a hybrid power system combining WECS and an energy storage system could be used. The storage system consists of a storage device and a power conditioning circuit. The storage device is used to filter the power fluctuation during wind energy generation and the power conditioning circuit is controlled to regulate the DC-bus voltage.

The hybrid power system proposed in this thesis is shown in Figure 1.1. It consists of a WECS and an ultracapacitor-based energy storage system. Both the wind generator and the ultracapacitor are interfaced to a common DC-bus by using conditioning circuits to supply a resistive load.

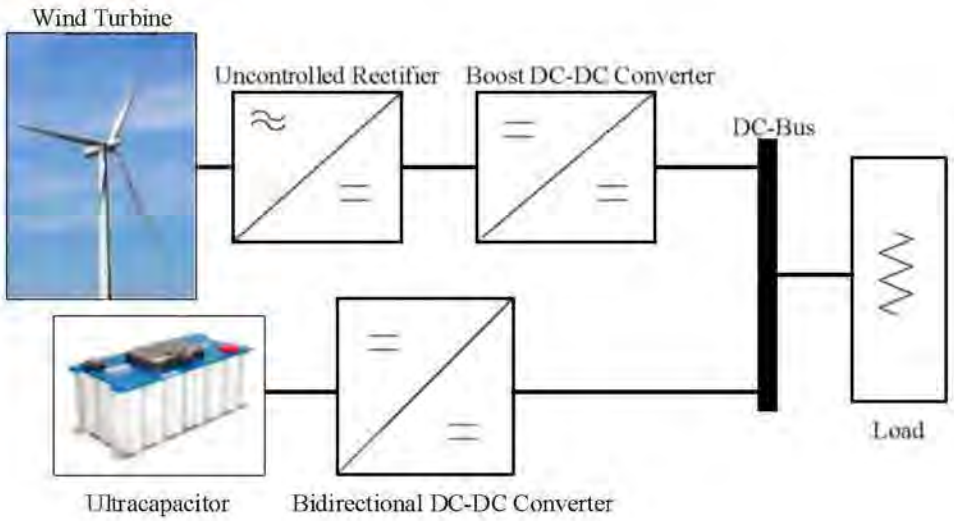

Figure 1.1 Schematic for the proposed hybrid energy conversion system

For small- to medium-scale wind turbines, the permanent magnet synchronous generator (PMSG)-based direct-drive fixed-pitch wind turbine is a preferred structure [2]. This structure is simple, with high reliability and efficiency, gearless construction, light weight, and with self-excitation features. The PMSG is controlled by a boost rectifier converter to maximize the output power from the wind

turbine. The combination of the PMSG and boost converter offers lower cost and is simple to implement and easy to control. For a PMSG, the generated torque is proportional to the machine's output current. Consequently, if the PMSG output current is controlled to track the generated reference current from the MPPT algorithm, maximization of the energy extracted from the wind turbine will be ensured.

According to the literature [3-5], ultracapacitors are able to provide fast dynamic response to load power changes. They are also capable of very fast charging and discharging. Therefore, they are suitable for filtering rapid fluctuations in wind power. Interfacing the ultracapacitor to the DC-bus requires a power electronic converter that allows reversible current conduction; accordingly, a bidirectional DC-DC converter is used in the circuit described in this thesis. By controlling the bidirectional converter switches, the DC-bus voltage is regulated and the fluctuating wind power is either delivered to or harvested from the ultracapacitor.

1.2 Problem Statement

The low efficiency of wind turbines, as well as the intermittent and unpredictable nature of wind, are major challenging issues of the wind-energy generation systems. For a WECS to operate efficiently, an MPPT algorithm is required. The MPPT algorithm should have the advantages of being sensorless, dependent, simple, and fast in tracking. Although the existing optimum-relation-based (ORB) MPPT algorithm is simple and fast in response to wind speed changes, it relies on the pre-existing knowledge of system parameters [6]. The perturbation and observation (P&O) technique, conversely, is a sensorless algorithm and does not require prior system knowledge. However, it is slow in response and has the probability of losing its tracking ability under rapid wind speed changes [7]. The response speed as well as the tracking efficiency can be improved significantly using the particle swarm optimization (PSO) MPPT algorithm considering its automated step size adaptability. Considering the benefits and drawbacks of each MPPT algorithm, a better or improved version of MPPT for wind energy systems should be

formulated. The new idea is to overcome the drawbacks of each MPPT algorithm, by combining the available MPPT algorithms. By hybridizing MPPT algorithms, the outcome could be attractive and promising.

As previously mentioned, because of continuous changes in wind speed, the operating points of WECS are expected to vary with time. Consequently, the power electronics converters involved in the WECS should have simple, robust, and stable controllers. Conventionally, proportional-integral (PI) controllers are designed to control these converters around a specific operating point. However, because of the continuous movement of the operating points and disturbances, adequate transient performance cannot be guaranteed using PI controllers [8]. Consequently, it is desirable, in this work and in general, to investigate the application of the linear quadratic regulator (LQR) control technique to designing the control system of the power electronic converters integrated into the hybrid wind/ultracapacitor energy conversion system.

1.3 Research Objectives

The objectives of this research are as follows:

(i.) To develop an effective solution to avoid system parameter dependency when obtaining the optimal curve in an ORB MPPT algorithm by incorporating a PSO algorithm

(ii.) To verify the effectiveness of the PSO-ORB MPPT algorithm through simulation by comparing it with a conventional ORB MPPT algorithm

(iii.) To formulate and implement LQR controllers for the power electronic converters interfacing the WECS and ultracapacitor storage device to a DC-bus

(iv.) To test the functionality of the developed hybrid wind/ultracapacitor energy conversion system incorporating the proposed MPPT algorithm and LQR controllers.

1.4 Research Scope

This research study has the following limitations and assumptions:

(i.) The wind turbine is a fixed- pitch variable speed type.
Depending on the speed control criterion, WECSs can be classified into two types: fixed speed and variable speed. Because of the regulation of rotor speed within a larger range, for better aerodynamic efficiency, the variable speed wind turbines are more widely used [8]. Controlling the pitch angle of the wind turbine blade is one possibility for extracting the maximum power from the wind. However, in small-scale wind turbines (less than 10 kW), this strategy becomes impractical because of their mechanical structure. For small power applications, the power converter is controlled for wind power optimization [9].

(ii.) The wind turbine is working in the MPPT region.
Assuming speed and power capture constraints are respected, the controller aims to limit the wind power captured when the wind speed is greater than the nominal speed and maximize the wind power harvested in the partial load region [8]. However, this work focuses only on the control of wind turbines in the partial load region (region 2), which generally enables MPPT by adjusting the electrical generator's output current. The working regions of wind turbines are further explained in section 3.2.

(iii.) The proposed hybrid system is stand-alone and it supplies a resistive load.

WECSs could be operated in stand-alone or grid-connected mode. For stand-alone operation the small-scale WECSs are used. The stand-alone WECS configuration can operate with either resistive or inductive loads. However, there is no effect of the L component on the generated DC power of the system [10]. Because the MPPT algorithm implanted in this study only depends on the DC power and seeking for the simplicity, this thesis focuses only stand-alone WECS supplying a resistive load. This configuration is similar to the one used in the studies [6] and [11]. The storage system is assumed to be sufficient for storing the excess power from the wind or delivering the shortage power into the load for all wind speeds.

1.5 Research Methodology

In order to achieve the objectives of the research, the following work methodologies have been followed:

(i.) A literature review of hybrid wind/ultracapacitor energy conversion system was carried out.

Advantages, working concepts, and electrical models of the system components were reviewed. The small-scale variable speed PMSG-based horizontal-axis wind turbine working in the MPPT region was selected. Then, the open-loop models of the boost and bidirectional converters were derived. The ultracapacitor model was also obtained.

(ii.) A critical and strategic literature review of MPPT methods was performed.

To propose a new MPPT algorithm, the common algorithms have been studied and summarized. Their strengths and drawbacks, based on several evaluation factors, were highlighted. Besides giving the overview of the existing MPPT algorithms, the objective of the review was to look for a gap in their coverage. Two of the best available algorithms were selected

to be combined and implemented as a new algorithm. The combination exploits the advantages of each method in order to overcome the drawbacks of the other.

(iii.) A new MPPT algorithm has been proposed.

A sensorless, simple, and efficient MPPT algorithm based on hybridization of the PSO and ORB MPPT algorithms was developed. Its performance was tested under different wind speed changes. The proposed MPPT algorithm has been compared with some conventional MPPT methods.

(iv.) The power converter controllers were designed.

In this step, the controllers for the DC-DC converters interfacing the hybrid wind/ultracapacitor energy system to the DC-bus were designed. The LQR method is positively characterized in literature as being robust, simple, and stable. Therefore, the LQR method was selected for designing the converter controllers for this research. The LQR controllers are formulated to minimize the cost function through changes in the duty-cycle in the converter models. A built-in function in MATLAB was used to solve the Riccati equation and calculate the state feedback gains.

(v.) Analysis and verification of the proposed control method effectiveness through computer simulations was performed.

To verify the performance of the designed controllers, a complete simulation model of the hybrid wind/ultracapacitor energy conversion system and its controllers was developed. The computer simulation package used was MATLAB/Simulink. In order to significantly reduce the simulation time, the average models of the rectifier-PMSG and DC-DC converters were used for simulation.

(vi.) The converters with their controllers for interfacing ultracapacitor energy storage to WECS were developed and built.

To validate the feasibility of the proposed control techniques, a hardware prototype was constructed. The tasks included selecting the appropriate

digital processor, designing the power circuit, gate drivers, feedback and signal conditioning circuits, and implementing the control algorithms. The selected digital processor was the TMS320F2812 eZdsp board.

(vii.) Verification, through hardware implementation, of the proposed control method's effectiveness and the converter performance was performed. Laboratory experiments were carried out on the hybrid proposed system under changes in wind speed, DC-bus reference voltage, and load. The experimental results confirmed the effectiveness of the power electronic converter controllers and MPPT algorithm.

1.6 Thesis Organisation

This thesis is organized into seven chapters. An outline of their contents is as follows:

(i.) In chapter 2, an extensive review of MPPT techniques used to track the MPP (maximum power point) of WECS is provided. The merits and drawbacks of each method are highlighted. In addition, this chapter presents several control techniques that are typically used for DC-DC converters.

(ii.) In chapter 3, the mathematical modelling of the different components of the system under study is described. Firstly, the wind turbine characteristics are presented. Then, the simplified model of the rectifier-PMSG is discussed. Thereafter, circuit topologies of the boost and bidirectional converters are depicted, state-space averaging technique theory is presented, and linearized and small signal models are developed. Finally, the electrical circuit for the ultracapacitor is provided.

(iii.) In chapter 4, the proposed PSO-ORB MPPT algorithm for tracking the MPPs of WECS is described. System simulation and performance

evaluation for different wind speed conditions are elaborated upon. The simulation results are compared to conventional ORB MPPT methods. The effects of hybridization are also analysed.

(iv.) In chapter 5, the application of the LQR method in optimizing the closed-loop performance for boost and bidirectional converters is discussed. Performance of the proposed controllers is compared with PI controllers. The LQR controllers design for a hybrid wind/ultracapacitor energy conversion system is explained, and the whole system is simulated in the MATLAB/Simulink simulation package.

(v.) Hardware design and implementation are presented in chapter 6. The laboratory experimental setup for the hybrid wind/ultracapacitor energy system is described. An explanation is given for the power converter circuits, gate drive circuit, feedback circuits, the TMS320F2812 eZdsp board and PMSG- based wind turbine emulator.

(vi.) In chapter 7, the simulation and experimental results of the proposed MPPT algorithm and LQR controllers are compared and discussed.

(vii.) In chapter 8, conclusions from the work undertaken are given and suggestions that may be considered as possible directions for future work are highlighted.

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