RENEWABLE ENERGIES CHARACTERIZATION AND THE DEVELOPMENT OF HYBRID RENEWABLE ENERGY HYDROGEN SYSTEMS

ABDUL MAJEED MUZATHIK

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DEDICATION

I dedicate this Ph.D dissertation to my mother Katheeja Ummah and to the memory of my father Abdul Majeed. I extend the dedication to my brother Muzzammil and other siblings, my wife Hussna, my children Aboothar, Hazoora and Muath, my relatives, friends and well-wishers for their endless support in each and every one of my endeavors.

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JANUARY 2011

Chairman : **Assoc. Prof. Wan Mohd Norsani bin Wan Nik, Ph.D.**
Member : **Assoc. Prof. Mohd Zamri Ibrahim, Ph.D.**
Assoc. Prof. Khalid bin Samo, Ph.D.

Faculty : **Maritime Studies and Marine Science**

There are many energy consuming applications which are beyond the realm of a distributed power network. The renewable energy is one of the alternative energy sources to overcome this problem. Hence, switching to alternative clean energy sources such as solar, wind, wave etc., could also provide solution to problems associated with traditional energy use such as, adverse effects on human health, regional and global environment, security issues and economics. However, using potentially clean energy resources on a large scale comes with technical challenges like regional availability, intermittence, and some inconvenience. A hybrid, renewable energy hydrogen system could be an elegant solution to these challenges.

This thesis presents the development, simulation and optimum design of a hybrid solar-wind-wave-hydrogen energy power generation system based on locally collected, midterm renewable energy and other relevant data. The meteorological data collected by concerned agencies were used in this research to develop a hybrid system which was statistically analyzed, interpreted and modeled. The average reference year for daily global solar radiation for Terengganu was one of the outputs, which is unique for this thesis.

Further, several new models have been generated and used for the development of new solar, wind and wave system designs suitable in the study area. The models are given below:

i. the monthly average daily global radiation on a horizontal surface from sunshine hour model was determined as $H/H_o = 0.2207 + 0.5249\ (n/N)$,

ii. the wind speed probability distribution model for the whole year was determined as $f(V) = \frac{1.81}{3.19}\left(\frac{V}{3.19}\right)^{0.81} \exp\left[-\left(\frac{V}{3.19}\right)^{1.81}\right]$,

iii. significant wave height from maximum wave height model was determined as $H_{\max} = 1.494 H_s + 0.01324$,

iv. wave peak period from wave mean period model was determined as T_{mean} = -269.9 * exp - ((T_p -9.609)/ 2.225)^2 + 271.9 * exp - ((T_p -9.615)/ 2.242)^2 + 3.254 * exp - ((T_p -6.903)/ 7.812)^2,

v. the significant wave height model for the whole year was determined as $f(H) = \frac{1.49}{0.69}\left(\frac{H}{0.69}\right)^{0.49} \exp -\left(\frac{H}{0.69}\right)^{1.49}$ and

vi. the extreme wave height prediction model was determined as $H_{TR} = 1.1866 + 0.3733\left[\ln(lT_R)\right]^{1/1.60}$.

From the statistical analysis of midterm, hourly solar, wind and wave data, it is seen that Kuala Terengganu region is favorably located for harnessing solar and wave power resources. A comprehensive hybrid renewable energy hydrogen test-bed system that includes solar photovoltaic (PV) system, wind turbines, wave energy convertor (WEC), a fuel cell stack, an electrolyzer, a hydrogen storage tank, an inverter, rectifiers, a computer base data collection system, and other associated components is an outcome of this thesis competed at the Universiti Malaysia Terengganu, Kuala Terengganu, Malaysia. Mathematical models for the main system components of the hybrid hydrogen system, namely, PV system, wind system, WEC system, fuel cell, electrolyzer and battery were developed using MATLAB and validated using the field data. A new model was developed to estimate the PV cell temperature, which is an important parameter for PV power output and determined as

$$T_{\mathrm{module}}\left({}^{o}C\right) = 0.943 \times T_{ambient} + 0.0195 \times Irradiance - 1.528 \times WindSpeed + 0.3529\ .$$

Due to hybrid systems having increased levels of complexity in comparison with single energy systems, optimum design development becomes more complicated. In order to efficiently and economically utilize the renewable energy resources, one optimal sizing method is necessary. In this project we have developed an optimal sizing method using MATLAB based on the genetic algorithm (GA), intending to obtain a global optimum configuration for a standalone, hybrid power generation system. The optimal sizing method was developed based on the loss of power supply probability (LPSP) and the annualized cost of system (ACS) concepts. The optimum configuration guarantees the lowest investment by using available, renewable energy sources with a hybrid hydrogen system and a battery bank.

The PV module capacity, wind turbine installation height, wind turbine capacity, wave energy converter capacity and battery capacity were used as decision variables in the optimization process. The developed optimization method was applied to analyze a hybrid solar-wind-wave-hydrogen energy system to supply power for a household in a remote area (Island), situated off the coast of South China Sea, at Terengganu, Malaysia. Technically a good optimal sizing configuration was found. Based on the system reliability and the annualized cost of the system, the best hybrid renewable energy hydrogen system configuration has been recommended to provide electricity for a household in the study area. The system consists of 15 kW of PV system, 1 kW wind turbine system at hub height of 10m and 3 kW wave power system, and 1000 Ah battery system with 6 kW electrolyzer, 2 kW fuel cell and a hydrogen storage capacity of (minimum) 463 Nm^3, which can meet the load requirement of a typical household with desired LPSP of 0%. The unit cost of energy of the hybrid system is US$ 0.605 /kWh. The study determined that a standalone hybrid solar-wind-wave energy hydrogen system is a feasible alternative to conventional electric supply, when access to the electric grid is not available.

Finally, the simulation tools, which have been developed using MATLAB in this research, are very flexible and can be used to find alternative and/or new, improved hybrid renewable energy system designs not only in the study area but also elsewhere using the locally available data.

Abstrak tesis yang dikemukakan kepada Senat Universiti Malaysia Terengganu sebagi memenuhi keperluan untuk ijazah Doktor Falsafah.

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Fakulti : **Pengajian Maritim dan Sains Marin**

Hari ini masih terdapat banyak lokasi yang tidak mempunyai rangkaian bekalan tenaga elektrik. Sistem tenaga diperbaharui merupakan salah satu sumber tenaga alternatif bagi mengatasi masalah ini. Oleh itu, penukaran kepada sumber kuasa alternatif mesra alam seperti tenaga suria, angin, ombak dan lain-lain juga dapat menyelesaikan masalah-masalah berkaitan dengan penggunaan tenaga tradisi seperti kesan terhadap kesihatan, kesan terhadap alam sekitar diperingkat setempat dan global, isu-isu keselamatan dan ekonomi. Walau bagaimanapun, dengan menggunakan sumber tenaga mesra alam yang berpotensi pada tahap skala yang tinggi, terdapat halangan teknikal seperti kedapatan, terputus-putus dan ketidakselesaan. Penggunaan sistem tenaga hidrogen hibrid diperbaharui dapat menyelesaikan cabaran-cabaran tersebut.

Tesis ini membentangkan perkembangan, simulasi dan rekabentuk optimum untuk menghasilkan tenaga hibrid suria-angin-ombak-hidrogen berdasarkan maklumat setempat yang dikumpul, tenaga diperbaharui antara-terma dan maklumat-maklumat lain yang bersesuaian. Data meteorologi yang direkod oleh agensi yang berkaitan dan dikumpulkan menerusi projek ini adalah bertujuan untuk membangunkan sistem hibrid menerusi analisis, interpretasi dan penghasilan model. Rujukan purata tahunan

radiasi global harian untuk negeri Terengganu adalah merupakan salah satu hasil yang unik dalam tesis ini.

Beberapa model baru juga telah dihasilkan untuk membangunkan sistem tenaga suria, angin dan ombak yang bersesuaian dengan kawasan kajian ini. Model-model tersebut adalah seperti berikut:

i. purata radiasi harian global untuk permukaan mendatar untuk sebulan dari "sunshine hour model" ditentukan dengan H/H_o= 0.2207 + 0.5249 *(n/N)*,

ii. model taburan kebarangkalian kelajuan angin untuk keseluruhan tahun telah ditentukan dengan $f(V)=\frac{1.81}{3.19}\left(\frac{V}{3.19}\right)^{0.81}\exp\left[-\left(\frac{V}{3.19}\right)^{1.81}\right]$,

iii. ketinggian signifikan ombak dari model ketinggian maksimum ombak ditentukan dengan $H_{\max} = 1.494H_s + 0.01324$,

iv. kitar puncak ombak dari model min ombak telah ditentukan dengan T_{mean} = - 269.9 * exp - $((T_p$ -9.609)/ 2.225)^2 + 271.9 * exp - $((T_p$ -9.615)/ 2.242)^2 + 3.254 * exp - $((T_p$ -6.903)/ 7.812)^2,

v. model ketinggian berkesan ombak untuk keseluruhan tahun telah ditentukan dengan $f(H)=\frac{1.49}{0.69}\left(\frac{H}{0.69}\right)^{0.49}\exp-\left(\frac{H}{0.69}\right)^{1.49}$, dan

vi. model ramalan ketinggian ombak ekstrem telah ditentukan dengan $H_{TR} = 1.1866 + 0.3733\left[\ln(lT_R)\right]^{1/1.60}$.

Dari analisa statistik data "midterm", suria untuk setiap jam, data ombak dan data angin, didapati bahawa kedudukan kawasan Kuala Terengganu adalah bersesuaian untuk menggunakan sumber kuasa suria dan ombak. Sistem platform ujian hibrid yang boleh diperbaharui yang komprehensif yang merangkumi sistem suria fotovoltaik (PV), turbin angin, penukaran tenaga ombak, sel bahan api , eletroliser, tangki simpanan hidrogen, penyongsang, penerus, sistem pengumpulan data berkomputer dan komponen-komponen berkaitan adalah merupakan hasil daripada kajian ini yang telah dijalankan di Universiti Malaysia Terengganu. Model matematik untuk komponen sistem utama bagi sistem hibrid hidrogen, seperti sistem PV, sistem angin, sistem ombak, sel bahan api, elektroliser dan bateri telah dibangunkan menggunakan MATLAB dan diuji dan disalurkan menggunakan data

lapangan. Model baru telah dibangunkan untuk menganggarkan suhu sel PV. Ia merupakan parameter utama untuk menghasilkan kuasa PV dan dapat dirumuskan seperti berikut

$$T_{\text{mod ule}}\left(^{o}C\right)=0.943\times T_{ambient}+0.0195\times Irradiance-1.528\times WindSpeed+0.3529\,.$$

Disebabkan sistem hibrid mempunyai tahap kompleks yang tinggi berbanding dengan sistem tenaga tunggal, pembangunan rekabentuk optimum menjadi lebih kompleks. Untuk menggunakan sumber tenaga diperbaharui dengan cekap dan ekonomi, ianya memerlukan satu cara pengsaizan yang optimum. Projek ini telah membangunkan kaedah pengsaizan optimum menggunakan MATLAB berdasarkan *algorithm generic* (GA). Bagi mendapatkan konfigurasi sistem optimum untuk sistem penjanaan kuasa hibrid dan kendiri, kaedah pengsaizan optimum telah dibangunkan berasaskan konsep "kebarangkalian kehilangan penghantaran kuasa" (LPSP) dan konsep sistem kos tahunan. Konfigurasi optimum menjamin pelaburan terendah dengan menggunakan sumber tenaga diperbaharui yang sediaada menggunakan sistem hibrid hidrogen dan sistem bateri.

Kapasiti modul PV, had tinggi pemasangan turbin angin, kapasiti turbin angin, kapasiti penukar tenaga angin dan kapasiti bateri digunakan sebagai pembolehubah keputusan dalam proses membuat keputusan yang optimum. Kaedah optimisasi yang dibangunkan telah digunakan untuk menganalisis sistem tenaga hibrid suria-angin-ombak-hidrogen untuk pembekalan kuasa dari rumah ke rumah yang terletak di kawasan terpencil (pulau), jauh dari pantai Laut China Selatan di Terengganu, Malaysia. Secara teknikal, konfigurasi pengsaizan optimal telah diperolehi. Berdasarkan ketahanan sistem dan kos tahunan sistem, konfigurasi sistem tenaga hibrid hidrogen diperbaharui yang terbaik telah dicadangkan untuk membekalkan tenaga elektrik kepada penduduk di kawasan kajian. Sistem ini terdiri dari PV berkuasa 15kW, tubin angin pada berketinggian 10m, sistem kuasa ombak 3kW dan sistem bateri 1000Ah serta 6kW elektroliser, 2kW sel bahan api dengan kapasiti penyimpanan minimum 463 Nm^3. Spesifikasi seperti ini dapat memenuhi keperluan tenaga kediaman yang biasa dengan LPSP 0%. Kos tenaga sistem hibrid adalah US 0.605/kWh. Kajian ini menunjukkan bahawa sistem hibrid hidrogen suria-angin-

ombak adalah alternatif praktikal bagi bekalan elektrik lazim, di mana laluan ke grid elektrik tidak diperolehi.

Akhir sekali, kaedah simulasi yang telah dibangunkan menggunakan MATLAB dalam kajian ini adalah amat fleksibel dan boleh digunakan untuk mencari dan merekabentuk sistem hibrid hidrogen diperbaharui atau untuk menambahbaik sistem ini bukan sahaja di kawasan kajian tetapi juga di mana sahaja dengan menggunakan data setempat yang sedia ada.