ENHANCING GRID SYSTEM PERFORMANCE BY INTEGRATING COMPRESSED AIR ENERGY STORAGE

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Dedicated to

My parents and kinfolk’s member for their boundless support and encouragement

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ABSTRACT

Wind energy is a boundless renewable energy which can be tapped continuously. It is clean and free energy making it incomparable with conventional fossil fuels. However, high stochastic nature of the wind the electric power generated affects the power quality of grid system. Compressed Air Energy Storage (CAES) is a mature energy storage technology in handling wind fluctuation problems such that the generated energy would be supplied to the grid without affecting the grid performance. Its large scale capacity storage, long storage period, fast ramp rates and low capital cost has made it as the best choice to be tagged to wind turbine in dispatching wind power. But, operating system of existing CAES is more to economic benefit, in which it will only discharge during high electricity cost and charge during low electricity cost. This thesis proposes a parallel connection of CAES with wind turbine where it can promise continuous supply to grid system with low power consumption during charging process. The first connection is to connect the wind turbine, drive train, compressors, tank, turbine and generator. While the other one is bypassing the direct connection of drive train**,** (wind turbine to compressor on a shaft and compressed air turbine to generator on another shaft). Derivation of mass flow rates leaving the tank is based on single stage expansion process. Analysis was carried out using MATLAB simulink to prove the effectiveness of the storage to react to the changes of wind speed, in which the results were focussed on the grid's voltage and active power. The results show that the proposed connection of wind CAES does not only able to smooth out wind power fluctuations but it also provides continuous power to supply the grid system compared to Battery Energy Storage. Moreover, its consumed lower power during charging process compared to existing CAES system.

ABSTRAK

Tenaga angin adalah tenaga yang tidak mempunyai had dimana ia boleh dialirkan secara berterusan. Ia bersih dan percuma oleh itu tidak dapat dibandingkan dengan tenaga minyak fosil konvensional. Tetapi, sifat tenaga angin yang berubah-ubah memberi kesan besar kepada kualiti kuasa elektrik di dalam sistem grid. Simpanan Tenaga Angin Termampat (CAES) adalah satu sistem simpanan tenaga yang cukup matang yang boleh menyelesaikan masalah angin yang berubah-ubah dimana tenaga yang dihasilkan akan dibekalkan ke grid tanpa member kesan terhadap prestasi grid. Saiznya yang besar, tempoh penyimpanan tenaga yang lama, kadar tindak balas yang cepat dan kos utama yang rendah telah menjadikannya pilihan yang baik untuk disambungkan dengan kincir angin untuk penghantaran kuasa angin. Walau bagaimanapun, sistem operasi CAES yang sedia ada adalah lebih kepada keuntungan ekonomi, dimana ia hanya akan dinyahcas ketika harga elektrik yang tinggi dan cas ketika harga elektrik rendah. Tesis ini memperkenalkan sambungan kincir angin dengan CAES secara selari dimana ia dapat menjanjikan sumber yang berterusan ke sistem grid dengan memerlukan kuasa yang rendah ketika proses mengecas. Sambungan pertama adalah meyambungkan kincir angin secara sambungan terus *drive train* atau sambungan kompresor, tangki, turbin dan janakuasa dengan kincir angin dengan satu gandar. Sementara itu, sambungan yang berikutnya adalah pintasan gandar (kincir ke kompressor di satu gandar, dan turbin udara mampat ke janakuasa di satu gandar lain). Pemerolehan kadar jisim yang meninggalkan tangki adalah berdasarkan sistem turbin satu tahap yang diperkenalkan dalam tesis ini. Analisis telah dijalankan menggunakan MATLAB Simulink untuk membuktikan keberkesanan penyimpanan tenaga untuk bertindak kepada perubahan kelajuan angin, dimana voltan dan kuasa menjadi keputusan utama dalam analisis ini. Keputusan menunjukkan, sambungan kincir angin dengan CAES yang diperkenalkan bukan sahaja mampu melicinkan kuasa angin yang berubah-ubah tetapi juga membekalkan kuasa yang berterusan ke sistem grid berbanding Tenaga Simpan Bateri. Tambahan pula, ia menggunakan kuasa yang lebih rendah berbanding sistem CAES sedia ada.

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LIST OF SYMBOLS

β_{ct}	-	Compression ratio for compressors
PbO_2	-	Lead dioxide
H^+	-	Ione hydrogen
e^-	-	Electron
ΔV	-	Average voltage decrement
P_m	-	Mechanical wind power
ρ	-	Air density
R	-	Rotor radius
V_w	-	Wind speed
C_P	-	Power coefficient
λ	-	Tip speed ratio
ω_R	-	Angular velocity
n	-	Rotational speed
T_{WT} , T_{shaft}	-	Wind turbine and shaft torque
J_{WT}	-	Inertia constant
K_{sh}	-	Shaft stiffness
θ	-	Position
G	-	Shear modulus
D	-	Shaft diameter
L	-	Shaft length
n_c , n_t	-	Polytrophic index for compressor and turbine
η_c , η_{HK} , η_t	-	Efficiency of compressors, heat

		exchanger and turbine
T	-	Temperature
p	-	Pressure
$P_{c,a}^{out}$	-	Power consumption by each compressor
$P_{t,out}$	-	Generated Mechanical power from turbine
m_c , m_t	-	Mass flow rate to compressors and turbine
c_p	-	Specific heat capacity
m	-	Mass
m_{in} , m_{out}	-	Mass flow rate entering and leaving the tank
R	-	Gas constant
v	-	Tank volume
T_s	-	Temperature inside tank
P_C , P_G	-	Power consume by compressors and power generated by turbine
p_b	-	Atmospheric pressure
γ , k	-	Ratio of specific heat capacities for ideal gas. Equivalent to
w_T	-	Work output of the turbine
c_p , c_v	-	Specific heat constant at constant pressure and volume
β_t	-	Compression ratio of turbine
P_{shaft}	-	Shaft power
P_{c_p}	-	Compressed air power inside the pipeline
g	-	Earth gravity
Q_{mfr}	-	Mass flow rate from drive shaft
H	-	Pressure head

i_d, i_q	-	dq stator current
v_d, v_q	-	dq stator voltage
λ_r	-	Rotor flux linkage
L_d, L_q	-	dq inductance
R_s	-	Resistance of stator winding
p_p	-	Number of pole pair
T_m, T_e	-	Mechanical and Electrical torque
$E_{Discharge}, E_{charge}$	-	Charge and Discharge energy from battery
K	-	Polarization constant
Q_{bat}	-	Maximum battery capacity
c_p, c_v	-	Specific heat constant at constant pressure and volume
i^*	-	Low frequency current dynamic
it	-	Extracted capacity
$Exp(s)$	-	Exponential zone dynamic
$Sel(s)$	-	Battery mode
i_d, i_q	-	dq stator current
M	-	Modulation index
V_{nom}	-	Phase to phase nominal voltage
V_{dc}	-	DC link voltage
i_d, i_q	-	dq stator current
kWh_{out}, kWh_{in}	-	Energy leaving and entering each system
t_c	-	Time taken to stop the compression process
Q	-	Reactive power

LIST OF ABBREVIATIONS.

AC	-	Alternative current
BES	-	Battery energy storage
CAES	-	Compressed air energy storage
CO_2	-	Carbon dioxide
DC	-	Direct current
DFIG	-	Doubly fed induction generator
Fb	-	Flow battery
FESS	-	Flywheel energy storage
GHG	-	Greenhouse gases
GW	-	Giga watt
HAWT	-	Horizontal axis wind turbine.
HPT	-	High pressure turbine
HX	-	Heat exchanger
H_2SO_4	-	Sulphuric sulphate
IEEE	-	Institute of Electrical and Electronic Engineering
IGBT	-	Insulated gate bipolar transistor
Li-ion	-	Lithium-ion batteries
LPT	-	Low pressure turbine
mfr	-	Mass flow rate
MPPT	-	Maximum power point tracking
MW	-	Mega watt
NaS	-	Sodium sulphur
NiCd	-	Nickel Cadmium
NO_X	-	Nitrogen dioxide

PB	-	Lead
PBO_2	-	Lead dioxide
PWM	-	Pulse width modulator
SCIG	-	Squirrel cage induction generator
SOC	-	State of charge
SO_2	-	Sulphuric Dioxide
SVC	-	Static var converter
VAWT	-	Vertical axis wind turbine
VSWT	-	Variable speed wind turbine

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CHAPTER 1

INTRODUCTION

1.1 Background of The Study

Throughout the years between 1996 until 2012, the wind power global capacity has shown exponential growth. By the end of 2012, the total wind power global capacity has reached a staggering 283 GW [1]. The European Wind Energy Association's expects wind energy to serve up to 15.7% of its 230 GW electricity demand by 2020 and 28.5% of 400GW demand by 2030. It is also expected that the generated wind energy in 2050 can provide half of Europe's power [2]. Since wind energy is free, the price for this energy will not increase thus it is widely used in many parts of the world. The production of electricity using wind energy can save several billion barrels of oil and avoid carbon emission and various types of greenhouse gasses. For example, running a 1 MW wind turbine for one year can reduce the following gasses from entering the atmosphere [3]:

- 1500 tons of carbon dioxide
- 6.5 tons of sulphur oxides
- 3.2 tons of nitrogen oxides
- 60 pounds of mercury

Basically, wind energy is captured by a set of rotating blades that transfers the mechanical and rotational energy to a shaft. The shaft then transfer this energy to a generator that converts it into electrical energy [4]. The main drawback of wind energy is its stochastic attribute that is dependent on spatial and temporal resolution.

It can only operate after a certain cut-in speed is reached and will stop operation if the wind speed exceeds the cut-out speed in order to protect the wind turbine system.

So far, several common approaches have been introduced in dealing with these fluctuation problems such as adjusting pitch angle and rotation speed of wind power generator, transferring generated wind power through DC link and inverting control system and applying energy storage, as highlighted in various reviews [5]. However, for this research, energy storage has been chosen as the most useful and effective methods to handle the fluctuation problem because it consists of an energy buffer that can effectively suppress during fast fluctuations. Energy storage with a proper controlled system is able to absorb small variation in wind power output and reduces negative impact on the existing power grid [6, 7].

Apart from that, with the presence of energy storage, the surplus wind energy can be stored and used at low wind speeds or high peak demand. At the same time, it can also be used to mitigate power fluctuation integrated into the grid during high wind speeds [8]. However, the conventional grid system has not been designed to accommodate energy storage systems. Therefore, careful planning needs to be done in order to ensure its compatibility with the grid. Furthermore, the storage system must be able to offset the amount of power when energy demand exceeds generation, which typically occurs during low wind speeds.

In stabilizing grid system with wind turbine application, energy storage can be categorized into bulk energy storage, distributed generation and power quality, as listed in Table 1.1 [9, 10]. Bulk energy storage acts to provide a large amount of intermittent electricity generation from renewable energy source. Its fast response in quickly discharging large amount of stored electricity during intermittent wind can mitigate some of the wind fluctuation problems (output smoothing, load levelling and spinning reserve) [11]. Distributed generation, also known as on-site generation disperses generation or decentralizes energy. Not only can it generate electricity from small energy source but it can also collect the energy from many sources. Thus, for wind application, it is able to deal with peak shaving and transmission deferral. Energy storage systems provide wide range of power quality protection due to their ability to react to the fast change in wind speed. With the presence of filters, energy storage (with standby mode), most transients can be avoided by limiting excess voltage. Thus energy storage systems are the most preferable solution for voltage sags, under voltages and interruptions power supply [12].

Table 1.1: Energy storage category

Category	**Energy storage technology**
Bulk energy storage	Pump hydro
	Compressed Air Energy Storage, (CAES)
	Lead-acid batteries
	Ni/Cd
Distributed generation	Lead-acid batteries
	Na/s, Li-ion, Zn/Br, V-redox, batteries
	Flywheel
	Hydrogen
Power quality	Lead-acid batteries
	Super Magnetic Energy Etorage (SMES)
	Flywheel
	Na/s, Li-ion, Zn/Br, V-redox, batteries
	Supercapacitiors

There are three main types of generators that can be installed along with wind turbines; i) Squirrel cage induction generator for fixed speed, ii) Doubly fed induction generator for variable speed and iii) Permanent Magnet Synchronous Generator (PMSG) for variable speed [13]. In [4, 7, and 8], PMSG is suggested to be connected to a variable speed wind turbine because of its higher efficiency, which leads to a better system performance. It also requires minimal maintenance cost and weighs less since it does not have external rotor current and gearbox. Gearbox is used to match the turbine's low rotational speed (high torque) with the generator's high speed (low torque). This is the main reason why PMSG does not require a gearbox to operate.

1.2 Research Objectives

This research is based on the following objectives

a) To propose a new approach in attaching CAES to a wind turbine to reduce the complexity of control system and to continuously powers the generator.
b) To smooth out wind power fluctuation in the grid system using CAES.
c) To validate the voltage and generated power at the grid system using different CAES configuration, battery energy storage and standalone wind system.

1.3 Research Scope

Selecting the right energy storage type helps to improve the grid system more efficiently. The technical benefit includes power consumed during the charging process, power generated during the discharge time, voltage, power and frequency regulation: hence increasing quality of supply at grid system. The economic benefits cover the installation, operation and maintenance cost of storage. Coupling with wind turbine helps to further reduce greenhouse gasses (SO_2, NO_x, and CO_2) emissions especially during charging process. Normally, it occurs during charging process where storage consumes power from the grid system to charge the energy storage. However, with wind turbine, power consumption to charge or discharge the storage is drawn from wind power itself.

This study focuses on bulk energy storage system for wind application. CAES is chosen to be combined with a wind turbine to smooth out wind power fluctuations. Typically bulk energy storage refers to a wind farm capacity of more than 10 MW with storage of more than 10-50 MW. However in this project, the system is scaled down to only a 2 MW wind turbine with a 2 MW discharge storage to illustrate CAES capability in smoothing out wind fluctuations. The 2 MW wind turbine is chosen in this research due to the fact that this is a typical value for a wind turbine system, as mentioned in [14]. The 2 MW wind power with 2 MW storage is modelled using MATLAB software to export the generated power to a 33 kV distributed grid via an AC/DC and DC/AC converter. Tan W.C et. al [15] stated that, 2 m/s to 6 m/s is the wind speed range in Ulu Pauh, Malaysia, thus this research considers the highest wind speed value of 6 m/s with mathematical variation of 3 m/s wind speed to generate 2 MW wind power at grid system.

A new approach parallel model of CAES is applied in this project to ensure that the tank (CAES storage) will never be empty and guarantee continuous supply to the grid system. To construct this parallel connection, the drive shaft connects the drive train and the generator is bypassed across the tank. The tank is connected between a shaft, a set of compressors and a turbine before entering the generator. To reduce the power consumed during air compression, a three-stage compression process is applied along with a single stage expansion. To further reduce the power consumption during air compression, a small mass flow rate (7.5 to 9) kg/s is set for the compression process. This (7.5 to 9) kg/s mass flow rate is half of the mass flow rate entering the expansion train in order to generate 2 MW mechanical power to run the generator. As mentioned in [16], mass flow rates required to run the compression train is twice the mass flow rate that runs the expansion train.

Battery energy storage and stand alone wind turbine are also modelled to validate the simulation results of wind CAES. The simulation results will cover the fluctuation characteristics of voltage, frequency and power generated to grid and the fluctuation of the AC/DC/AC link voltage.

1.4 Problem Statement

The power output of wind energy is directly proportional to the cube of wind speed and every single wind fluctuation affects the extracted wind power. This behaviour causes power fluctuation and voltage flicker in the grid system. Various types of control system and modelling are designed to tackle this fluctuation problem and to dispatch the wind energy in the most efficient way.

Kinetic energy of inertia control, pitch angle control, stall regulated control, and generator control and DC-link voltage control are the lists of power smoothing method with no energy storage. But these control systems are limited to a certain control ranges which totally dependent on wind speeds. In fact, even during high wind speeds, there is a possibility of wind energy to be wasted because; a normal device/component/equipment will not consider the surplus input source which is more than its rated value. This is designed in the system to enhance the life and longevity of the system itself. During high penetration wind speed, with an installed wind power of 9 MW, almost 27% of available wind energy is discarded [17]. While, in low wind speed, the non storage controllers is controlled to allow the wind turbine to operate at its optimum conditions [16].

The most effective way to deal with wind power fluctuation is using energy storage but unfortunately, its installation and maintenance cost is quite high. Different types of energy storage give diverse capability in solving wind power fluctuation problem. Thus, by choosing the suitable type of energy storage, high installation can be avoided. Based on bulk energy storage which listed in Table 1.1, CAES have low capital cost, large power rating, long life cycle and low Greenhouse Gasses (GHG) equivalent emissions compared to others [10, 18].

CAES is mature enough energy storage for wind applications. However, there are only two existing CAES system in this world, thus various research works related to this energy storage are focused on minimizing operational cost, considering their off–design performance, energy consumption and co-location the energy storage to decrease transmission requirement cost [19, 20].

The existing connection of wind CAES is mostly in series connection where the wind turbine connects to generator through CAES. No bypass option between the drive shaft to the generator. Normally, this series connection requires the tank to be filled up first before discharge or it can also be controlled to charge and discharge at the same time. Besides, this type of CAES usually charges during midnight where the low cost electricity and discharge during daylight where the electricity is high [21]. However, the electricity cost required to compress the air is still high due to the all available wind is compressed into the storage. Even though the air is compressed during low electricity cost, the power required to run the compressors to compress the available air is still high, which leads to the increment of electricity cost. At the same time, more heat is generated during compression process which leads to GHG emissions.

The new approach in combining wind turbine with CAES system can help to reduce power consumption during compression process, heat generation and work done to compress air because the parallel CAES is modelled to only compress the excess wind energy into storage. Correspondingly, for economic analysis, the installation cost and maintenance of CAES is less than Battery Energy Storage, (BES) [18].

1.5 Methodology

The CAES is mathematically modelled and tested in MATLAB Simulink software before it is combined with wind turbine and grid system. Meanwhile the existing model of battery is applied for result validation.

1.6 Contribution of the Research

The contributions of this thesis are listed as follows:

a) Detailed mathematical modelling of parallel CAES system which connects wind turbine, drive train, compressors and turbine in one shaft.

b) Derivation of mass flow rate leaving the tank for single stage expansion process application.
c) Validation of the CAES effectiveness in smoothing out power fluctuation and provide continuous power to the grid.

1.7 Thesis Organization

This thesis consists of six chapters which are outlined as follows:

Chapter 2 reviews the previous publications on wind turbine, energy storage and methods to overcome wind fluctuations problem. The charging and discharging process, advantages and disadvantages of the chosen storage are also mentioned in this chapter.

The research methodology will take place in Chapter 3 where the mathematical modelling of CAES complete with derivation to obtain the mass flow rate leaving the tank and the mass flow rate from the shaft. Wind turbine and drive train formation is described. BES, DC-DC control system and three phase inverter control system is also highlighted in this chapter.

Chapter 4 presents the simulation results for the proposed connection of wind CAES. Various test cases are carried out to verify the CAES models in different circumstances of wind speeds. Result validation using different configuration of CAES, BES and standalone wind are also analysed here.

Chapter 5 gives full conclusion throughout this study and several suggestions for future works in order to improve the current CAES work.

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