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PEAK DESIGN OF A CONVERTER-MACHINE SYSTEM ON A LOAD CONTOURSMEARED TO A CAES SYSTEM

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ABSTRACT

This paper deals with the design of a converter machine system considering a set of operating points (speed, torque) composing a routine cycle. From the 1-D analytical modelling of the Permanent Magnet Synchronous Machine (PMSM) and the power electronic converter, a design methodology minimizing the power losses-to-volume ratio is established where the flux weakening control structure is considered within the system sizing. Based on a deterministic approach developed for PMSM sizing only, we propose a methodology to include the converter losses in the machine design process. Hence, we demonstrate how the computing time can be significantly reduced limiting the calculation of the flux weakening mode to a few critical power points. This method is applied to a liquid piston mechanism as part of a Compressed Air Energy Storage (CAES) system. We then validate the converter-machine design method from a 2-D analysis applied to the most significant points. Finally, the PMSM design from both methodologies with and without considering the converter losses are compared. Results highlight how the converter affects the machine sizing and the distribution of power losses to reduce the total losses of the system.

INTRODUCTION

In recent years, the challenges of air pollution, fossil oil crisis, and greenhouse gas emissions have aroused unprecedented amount of attentions on Electric vehicles (EVs) from the governments, academia and industries all over the world. After intensively developing over the last decades, the worldwide promotion and application of EVs have reached a considerable scale. However, the dynamic performance, cost, durability of an EV are still closely related to the design, integration, and control of its energy storage system (ESS). It is generally known that the battery-only ESS with high cost and short cycle life has become one of the biggest obstacles hindering further penetrations of the EVs. Lithium-ion battery only ESS with high energy density and relatively good power density dominate the most recent group of EVs in development, however, its degradation can be accelerated when there is high peak discharging/charging power demand during the operation process. Alternatively, super capacitors (SCs) can tolerate much more charging/discharging cycles and exhibit superior ability to cope with high peak power, due to their specific energy storage mechanism, but the low energy density hampers their large scale application on EVs. A hybrid energy storage system (HESS) introduced also SCs which can bridge the gap between them is considered as one of the most promising solutions to solve the forgoing problems entrenched in battery-only/SC-only energy. The configuration of a HESS vary with different connections of the battery, super capacitor and DC/DC converter. The employed HESS in this work is the most studied configuration that using a bidirectional DC/DC converter to connect the super capacitor with the battery in parallel, in which case, the voltage of super capacitor can be adjusted in a wider range. Existing research has demonstrated that HESS can dramatically improve braking energy recuperation efficiency, eliminate the need for battery over-sizing, and reduce the weight and cost of the entire system. However, the application of HESS has introduced complicated sizing and energy management problems.

Finding the specific number of super capacitor banks and battery cells that can minimize the cost, mass, energy consumption and battery degradation of the HESS is the so called HESS sizing problem. A sample-based global Dividing Rectangles (DIRECT) optimization algorithm is implemented to solve a formulated multi-objective sizing problem of the HESS. While the non-dominated sorting genetic algorithm II (NSGA-II) is applied to obtain the Pareto frontier of battery degradation and total cost in designing a semi-active HESS. Proposed to solve the sizing problems of different HESSs with convex optimization algorithm.

The energy management strategy (EMS) of HESS aims to allocate the energy request between different energy sources for achieving desired performances, both the rule based and optimization based approaches are comprehensively investigated in previous work. A time efficient utility function based control of a semi-active HESS was proposed and carried out in by formulating a weighted multi-objective optimization problem, then the formulated problem is solved based on the Karush-Kuhn-Tucker (KKT) conditions proposed an energy management strategy for a HESS based on fuzzy logic supervisory wavelet-transform frequency decoupling approach, which aims to maintain the state of the energy (SOE) of the super capacitor at an optimal value, to increase the power density of the ESS and to prolong the battery lifetime. An explicit model predictive control system for a HESS was proposed and implemented to make the HESS operating within specific constraints while distributing current changes with different ranges and frequencies respectivelybetween the super capacitor and battery developed a real-time predictive power management control strategy based on neural network and particle swarm optimization algorithm to minimize the integral cost including battery degradation and energy consumption. A variable charging/discharging threshold method and an adaptive intelligence technique based on historical data was proposed to

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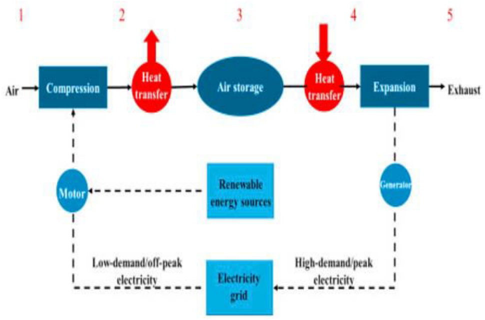
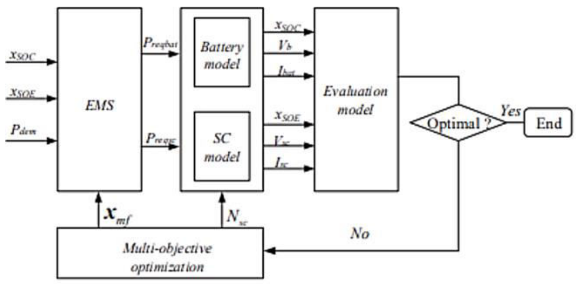
improve the power management efficiency and smooth the load of a HESS. Two real-time energy management strategies based on KKT conditions and neural network were investigated and validated with experimental work to improve the battery state of health performance of a HESS effectively.

The continuous previous efforts have improved the overall performances of HESS considerably. However, most of the aforementioned work researched only on either the sizing or the energy management problem, in which case, the global optimal performance cannot be achieved since the design and control problems of HESS are mostly coupled in fact. Only sub-optimal solution is available when try to optimize the sizing and control parameters separately due to the reduced searching space. Some of the existing approaches in literature are off-line which are quite useful as the reference in designing real-time EMS but not appropriate for real implementation. Besides, most of the real-time implementable EMSs are mostly manually devised in the existing efforts which are not able to achieve the optimal performances.



Considering the drawbacks of the state-of-the-art methods, this work will investigate the HESS sizing and realtime control problem as a coupled problem. In particular, the HESS of an electric race car is investigated as a case study. Although win the race is the only ultimate goal on a circuit, we should try to minimize the cost for a racing team and the environmental impact caused by the waste battery as much as possible during a race or for the offline training, which can match the spirit of the electric racing better. Our goal of this work is to introduce the HESS with proper sizing parameters and optimized real-time EMS to improve the cycle life of the battery without scarifying the mileage of the electric race car too much. A multi-objective optimal sizing and control framework incorporating the battery model, super capacitor model, evaluation model and a devised vectorized fuzzy inference system is proposed in this work. With this framework, the Pareto optimal solutions of the formulated multi-objective optimal sizing and control problem can be obtained, besides, both the optimal sizing and the static parameters of a fuzzy logic control (FLC) based EMS can be achieved simultaneously for all the solutions on the Pareto frontier which then can be implemented for real-time application.



Framework of the Bi-Level optimal design and control

The working scheme of the Bi-level optimal design and control is illustrated as follows. Firstly, the multi-objective algorithm will generate the sizing parameter matrix and the corresponding static tuning parameter

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matrix of the energy management system, in this work, the mentioned matrices are respectively the number of super capacitor banks and the parameters of the membership functions (MFs) in different pages of the optimization parameters. Secondly, the FLC based EMS constructed with the new membership functions will control the generated new HESS to output the demand power from the battery and super capacitor respectively. Then, the maximum number of laps can be obtained when both the battery and super capacitor arrives at the minimum state of charge values set in the constraints, while the capacity loss of the battery is evaluated with the average current of the battery during the whole scenario. There are quite a lot of existing literature to model the capacity loss of the lithiumion battery. The capacity loss model is mostly validated by discharging the battery with constant current C rate, and we havent find any work that can predict the battery capacity loss dynamically with validated experimental work. Thus, we choose to estimate the capacity loss of the battery with average load as many previous work did. When the Pareto-frontier of the two evaluation indexes is obtained, the above iteration will terminate, otherwise, it will continue.

Carbon dioxide emission, one of the major causes for global warming, has been recognised as a pressing issue and needs to be tackled in this generation. To address this issue, reducing use of fossil fuels is unavoidable, which calls for power generation from renewable energy sources to meet the electricity demand. It has been evidenced by the rapidly increased penetration of renewable energy to the power network in recent years. In 2014, power from renewable energies represented approximately 58.5% of the net additions to the global power generation capacity, with considerable growths in all regions. By the end of 2014, renewables, mainly wind, solar PV and hydro power, accounted for an estimated 27.7% of the world's power generation capacity, enough to supply 22.8% of global electricity. However, due to the inherent intermittence of the most renewable energy sources, there is a great challenge in the power generation and load balance to maintain the stability and reliability of the power network. While various solutions are sought, energy storage has been recognised as one of the feasible technologies to address these issues, which facilitates the power balancing by decoupling the generation and consumption in the time and space domains through multiple charging and discharging cycles.

Based on the form of energy stored in the system, major energy storage technologies include mechanical (pumped hydro, compressed air, and flywheel), electrochemical (batteries), electrical (capacitors), chemical (hydrogen with fuel cells), and thermal energy storage. Technical characteristics of the selected energy storage technologies are listed. Mechanical storage systems, has long lifetime, low energy capital cost, and much larger power/energy rating than other energy storage technologies listed. Therefore, they are suitable for time shifting, load shaving, load leveling, and seasonal energy storage. As one of the two large-scale commercialized energy storage technologies, large-scale commercialized Compressed Air Energy Storage (CAES) plants which are able to provide rated power capacity over 100 MW by single generation unit, have demonstrate to be reliable in the large-scale energy management.

METHODOLOGY

Dynamic Battery Model

The most existing battery models for the simulation of battery behavior basically include the experimental, electrochemical and electrical ones. In order to obtain the optimal sizing parameters and energy management strategy for the HESS considering the characteristics of the battery in practical conditions, it is necessary to implement a proper dynamic battery model that can describe the battery dynamic behavior precisely. In this work, a modified Shepherd model is employed to depict the dynamic characteristics of the battery during charging and discharging process. The dynamic battery model are presented with the assumption that the internal resistance is constant and the thermal behavior of the battery is neglected.

Discharge:

$$V_{batt} = E_0 - K\frac{Q_{\max}}{Q_{\max} - it}it - K\frac{Q_{\max}}{Q_{\max} - it}i - Ri + Ae^{(-B \cdot it)}$$

Charge:

$$V_{batt} = E_0 - K\frac{Q_{\max}}{Q_{\max} - it}it - K\frac{Q_{\max}}{it - 0.1Q_{\max}}i - Ri + Ae^{(-B \cdot it)}$$

Depending on the scale of a CAES system, it can be roughly divided into large-scale CAES (> 100 MW), micro-scale CAES (tens of kW) and small-scale CAES ranged in between. Large-scale CAES systems are normally built for grid applications in load shifting, peak shaving, and frequency/voltage control. Small-scale CAESs are more suitable for integration with renewable energy for back-up, load following and uninterruptible power supply. An application of small-scale CAES system for load following was presented in which an approach of investigating and controlling was also used to minimise the specific compression work. Micro-scale CAES is capable to be used in a multi-purpose system. A good example of a micro-scale CAES combines energy storage, air cycle heating and cooling was analysed. Proper types of expansion machines suit different CAES system scales and operations. High performance of these systems is only achieved when appropriate compressors and expanders are selected. As a matter of fact, overall performance of a CAES system is significantly affected by the efficiencies of air compression and expansion processes, because they are the "interfaces" to transfer different energies where significant exergy loss normally occurs. In a cycle from the charge to the discharge, more stages of the compression and expansion processes are used, more sensitive are the compressor's and expander's efficiencies to the overall round trip efficiency. It was demonstrated that the isentropic efficiencies of compressors and expanders/turbines are the two most influential parameters impacting the overall CAES performance.

CONCLUSION

This paper has presented a PMSM design methodology from a load profile composed of a set of operating points. The aims were to consider and include both the converter losses and the flux weakening mode control within the PMSM sizing optimization, based on an analytical and deterministic approach. The paper has demonstrated how the local current optimization can be decoupled from PMSM sizing optimization by reducing the calculations to a few critical points. Results applied to an offshore storage system highlighted that the contribution of the converter losses in the energy balance is significant. The consideration of the converter losses in the PMSM design influences the PMSM internal layout and enables a redistribution of the power losses: this minimizes the total power losses but keeps the same external sizing since the total PMSM losses are still the same. In view of the power involved in this application, the method will extend in future works to wound rotor synchronous machines with and without salient poles to compare the performances of wound rotor with permanent magnet over the profile cycle presented in this paper.

Constant	Value
ρ_c	2.10^8 Ωm
B_r	1.2 T
f_{sw}	2 kHz
k_e	$6.5.10^{-3}$ $Ws^2/T^2/m^3$
k_f	0.4
k_h	15 $Ws/T^2/m^3$
k_L	1.2
k_t	0.5
k_{sw}	0.35 mJ/A
R_{c0_d}	0.8 mΩ
R_{c0_i}	1.1 mΩ
V_{c0_d}	1.75 V
V_{c0_i}	2 V

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