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Performance characteristics and parametric optimizations of a weak dissipative pumped thermal electricity storage system

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ABSTRACT

Based on the weak dissipative assumption, a more universal thermodynamic model of the pumped thermal electricity storage (PTES) system is established, where the main irreversibilities are considered and several key operating parameters are introduced. Analytic expressions for some key performance parameters, e.g., the round trip efficiency (RTE), heat pumping rate, and power output, etc. of the PTES system are derived. The upper boundaries of the RTE at the maximum power output and the maximum RTE for some given parameters are determined. The optimally operating regions of several parameters operating at different modes are determined. Notably, a generalized thermodynamic model of weak dissipative electrical energy storage (EES) systems is proposed, and consequently, the results obtained from the PTES system may be applied directly to reveal the performance characteristics of these EES systems.

1. Introduction

Large-scale electrical energy storage (EES) technologies, which are regarded as an important approach to solve the mismatch of electricity supply and demand in time, enhance the flexibility and stability of the grid, improve energy utilization efficiency, reduce environmental impacts related to the use of traditional fossil fuels, and overcome the inherent instability and intermittence of the renewable energy sources, have attracted great interest of engineers and researchers in recent years [1–6].

The pumped hydro storage (PHS) is the dominating large-scale EES technology currently because of its fast response, low self-discharge rate, long lifetime, and high round trip efficiency (RTE) [1–4,6,7]. Besides, the compressed air energy storage (CAES) technology, especially the advanced adiabatic compressed air energy storage (AA-CAES) technology, whose performance is competitive compared with the PHS technology, is considered as an EES technology with great promise and becomes a hot research topic [8–13]. However, the application of PHS and CAES technologies is constrained due to the heavy dependences on special geological and geographical formations. Specifically, one PHS system requires water reservoirs with volumes on the order of 10^7 m^3 and one CAES system requires robust caverns which can withstand pressure up to 100 bar as the containers. Consequently, various EES technologies, e.g., flywheels, super capacitors, flow batteries, Superconducting Magnetic Energy Storage, etc., resulting from the motivation of establishing the site-independent EES systems [1–4], have been proposed. Unfortunately, among all these alternative EES technologies, few are currently able to provide the grid-scale capacity (typically greater than hundreds of MWh), high enough power output, and long enough discharging time duration simultaneously. As a result, the pumped thermal electricity storage (PTES) technology, the concept of which was first proposed in 1920s [14], has attracted the attention of many researchers once again even though there are no demonstration systems have been constructed. Various models of the PTES system have been put forward by adopting different types of thermodynamic cycles, e.g., Carnot cycle [15–17], Brayton cycle [18–26], Rankine cycle [27–33], and differently working substances, e.g., water/steam [31,32], CO_2 [26–30,33], and their performance characteristics have been analyzed.

By adopting endoreversible cycle models and Newton's heat transfer law, the concise thermodynamic models of the Carnot PTES system, Carnot pumped cryogenic electricity storage (PCES) system, and Brayton PTES system were recently proposed [15–17,22]. Guo et al. [17,22] investigated the performances of the Carnot PTES, Carnot PCES, and Brayton PTES systems and revealed the effects of the internal and external irreversible losses. However, the performance

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Nomenclature

A	surface area (m^2)
a	ration of irreversible parameters
B	ration of temperatures/parameters of potential reservoirs
D	piston frontal area (m^2)
g	acceleration of gravity (ms^{-2})
k_L	heat/energy leakage coefficient ($W K^{-1}$)
k	cycle number of the Carnot engine
l	cycle number of the Carnot heat pump
m,N	mass (kg)
P	power output (W)
P_{In}	power input (W)
P^*	dimensionless power output
q_L	external heat leakage loss rate (W)
Q	heat (J)
R	heat pumping rate (W)
R^*	dimensionless heat pumping rate
S	entropy ($J K^{-1}$)
s	piston shifts (m)
t	time (s)
T	temperature (K)
U	energy (J)
u_L	external energy leakage loss rate (W)
W_{In}	work input (J)
W_{Out}	work output (J)
w_{In}	work input per cycle (J)
w_{Out}	work output per cycle (J)
X	parameters of potential reservoirs
x	dimensionless time
y	dimensionless time

Greek letters

δ	Stefan-Boltzmann constant ($W m^{-2} K^{-4}$)
η	efficiency of Carnot engine
η_T	RTE
λ	Lagrangian multiplier
μ	chemical potential (J/kg)
ρ	effective emissivity
σ	Stefan-Boltzmann constant ($Wm^{-2} K^{-4}$)
τ_{Cha}	whole time of charging phase (s)
τ_{Dis}	whole time of discharging phase (s)
ψ	COP of Carnot heat pump

Subscripts

e	heat engine/energy generator
H	TES reservoir/high-potential reservoir
m	maximum
O	ambient/low-potential reservoir
p	heat pump/energy pump
$P(Pm)$	MPO state
$\eta(\eta m)$	maximum efficiency state
$\eta_T m$	maximum RTE state
$\eta_T Pm$	maximum RTE at MPO state
$\psi(\psi m)$	maximum COP state

Abbreviations

CAES	compressed air energy storage
COP	coefficient of performance
ECES	electrochemical energy storage
EES	electrical energy storage
MPO	maximum power output
PHS	pumped hydro storage
PTES	pumped thermal electricity storage
PCES	pumped cryogenic electricity storage
RTE	round trip efficiency
TES	thermal energy storage

characteristics of the endoreversible thermodynamic cycles are closely dependent on the law of heat transfer between the working substance and the thermal energy storage (TES) reservoir [34–37], namely, different heat transfer laws result in different performance characteristics.

After scrutinizing the results obtained from different thermodynamic cycle models [38–45], Esposito et al. adopted the weak dissipative assumption to establish a novel thermodynamic model of Carnot heat engines [46], in which the law of heat transfer between the working substance and the TES reservoir was not specified. They obtained the upper and lower boundaries of the efficiency of the weak dissipative Carnot heat engines at the maximum power output (MPO). In addition, the Curzon-Ahlborn (CA) efficiency $\eta_{CA} = 1-\sqrt{T_L/T_H}$ [34] can be obtained under the condition of the symmetric dissipation. With the help of the weak dissipative assumption, several researchers investigated the performance characteristics of several typical thermodynamic cycles [47–53] and obtained some significant results.

In this paper, by using the weak dissipative assumption, a more generalized model of the PTES system without specifying the heat transfer law between the working substance and the TES reservoir is proposed, in which the main irreversibilities are take into account, whereas the complicated engineering details are neglected. With the help of the proposed model, the analytical expressions of several important performance parameters are derived and the performance characteristics of the PTES system can be investigated in detail. The rest of the present paper is arranged as follows. In Section 2, the model of a weak dissipative Carnot PTES system with irreversible losses is briefly

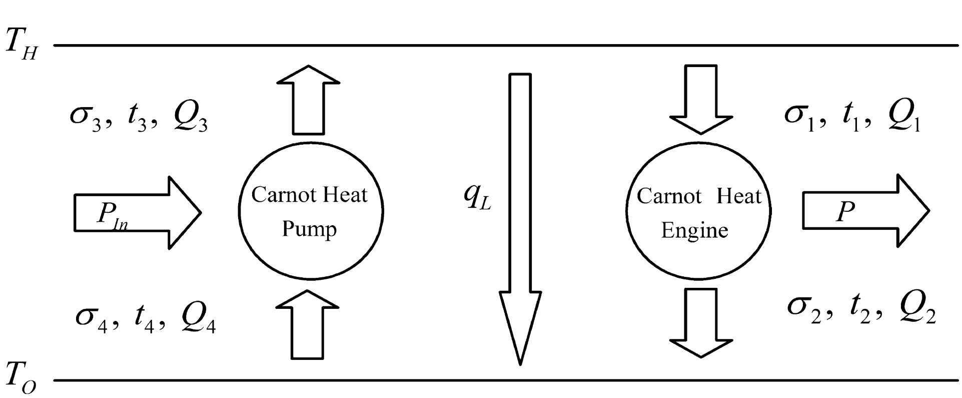

Fig. 1. The schematic diagram of a weak dissipative Carnot PTES system.