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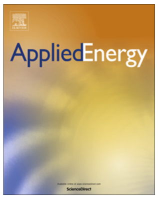

Regenerative air energy storage for remote wind–diesel micro-grid communities

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HIGHLIGHTS

- Regenerative Compressed Air Energy Storage (RAES) is described.
- A numerical model is developed for RAES.
- Cycle charging control strategies are developed for diesel generators based on energy storage efficiency.
- A thermal energy storage (TES) system is modelled to store waste heat from diesel generators to boost RAES efficiency.
- The models are demonstrated by optimizing a RAES system in a case study using real community load and wind data.

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ABSTRACT

Remote communities beyond the reach of conventional electricity grids primarily rely on diesel generators (DG) to supply electricity. The systems in these communities are costly to operate because of the high price of transporting diesel to remote areas, and the low overall efficiencies caused by part-load operation of the DG. There is increasing interest to use wind energy converters (WEC) to supplement DG, thereby lowering the fuel consumption and operating costs. In order to use WEC to reduce the economic and environmental burden that DG have on remote communities, an energy storage system can be incorporated to buffer both generation and demand. This can avoid curtailment of the WEC, operate the DG at optimal efficiency, and reduce the necessary maximum installed generator capacities.

Regenerative air energy storage (RAES) is a form of compressed air storage that is suitable for deployment in remote communities due to its ability to utilize waste heat from DG to boost the roundtrip efficiency of energy storage. This article presents a numerical model for a RAES system operating in a wind-diesel micro-grid. Simulations are run for varying WEC penetration levels and RAES energy capacities.

The results show that in systems with WEC penetration less than 75%, increasing WEC capacity is more economic than adding a RAES system. Above penetration rates of 75%, the use of RAES achieves increased diesel savings with only slightly longer payback than simple wind-diesel systems. In the remote Canadian community case study, the optimal RAES system is 0.5 MW and 1 MW h with a WEC penetration rate of approximately 75%. A larger RAES results in further fuel savings, and thus environmental benefit, with only marginal increase in simple payback period.

1. Introduction

Remote off-grid communities typically utilize diesel generators (DG) for electricity production [1,2]. The community electricity demand varies greatly, and consequently the DG operate at part-load with a corresponding decrease in efficiency. Whereas diesel fuel in urban areas is relatively cheap, transportation of fuel to remote communities increases the cost of electricity by up to a multiple of six to ten [3]. Besides the economic tolls incurred using DG, there are several environmental and social concerns, such as: communities are susceptible to electricity blackouts, pollution from exhaust gasses, and loud noise from DG [2]. In an effort to reduce the economic, environmental, and social costs, remote communities are investing in renewable electricity generators such as wind energy converters (WEC).

Diesel generators used in remote micro-grids must ramp power up and down in order to follow the variable community load. The transient and intermittent operation of DG requires them to regularly run at part-load, resulting in lower fuel efficiencies and higher

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Nomenclature

Acronyms

CAES	compressed air energy storage
DG	diesel generator
RAES	regenerative air energy storage
SOC	state of charge
TES	thermal energy storage
WEC	wind energy converter

Symbols

$C_{p,TES}$	specific heat capacity of the TES (kJ/kg/K)
E_{RAES}	stored electrical RAES energy (kW h)
F_{DG}	diesel generator fuel consumption (kW h)
$F_{D,start}$	diesel generator start-up fuel consumption (kW h)
HR	heat recovery effectiveness coefficient
M_w	water to air ratio
m_{TES}	mass of TES (kg)
$P_{RAES,chg}$	RAES charge power (kW)
$P_{RAES,dschg}$	RAES discharge power (kW)
$P_{RAES,max}$	RAES maximum power (kW)
$P_{RAES,min}$	RAES minimum power (kW)
P_{DG}	diesel generator power (kW)
$P_{DG,CC}$	cycle charging set-point (kW)
$P_{DG,max}$	diesel generator rated power (kW)
P_L	community electrical load (kW)
P_{WEC}	wind generated electrical power (kW)
$P_{WEC,curt}$	curtailed wind power (kW)
Q_{DG}	diesel generator waste heat (kW h)
$\dot{Q}_{Loss}$	rate of heat loss (kW)
$\dot{q}_L$	heat loss coefficient (kW/K)
Q_{TES}	TES heat (kW h)
q_w	specific heat in water (kW h/kg)
q_{w+a}	specific heat in water and compressed air (kW h/kg)
T	temperature (K)
T_{amb}	ambient temperature (K)
T_{comb}	compression temperature (K)
T_{TES}	TES temperature (K)
$T_{TES,max}$	maximum TES temperature (K)
t	time step duration (h)

Greek symbols

Δ	change
η_{DG}	diesel generator efficiency
$\eta_{RAES,chg}$	RAES charge efficiency
$\eta_{RAES,dschg}$	RAES discharge efficiency
$\eta_{RAES,SOC}$	RAES efficiency as a function of SOC
$\eta_{RAES,Power}$	RAES efficiency as a function of power

greenhouse-gas (GHG) emission intensities. The addition of variable output renewable electricity generators, such as WECs, further disrupts steady DG operation, thus further lowering DG efficiency and increasing emission intensity. Additionally, WEC output is often curtailed in microgrids with a high wind penetration rate [4]. Energy storage may be used to overcome this problem by buffering the variability of the community load and the output of renewable energy generators [4,5], thereby allowing the DG to operate in more stable conditions for optimal efficiency.

DG require a cooling jacket during operation to prevent overheating, typically using a water-glycol mixture. They also expel large volumes of high temperature gasses in the exhaust. Both forms of waste heat present an opportunity for the recovery of thermal energy. Typical DG waste heat temperatures range from 350 to 400 °C in the exhaust gasses, and 80 to 90 °C in the water jacket [6]. Using the modern heat recovery equipment, approximately 50% of the total waste heat can be recovered [7]. For example, a DG that is 33% efficient for an output electrical power of 100 kW results in 100 kW of recoverable waste heat and 100 kW of lost heat.

Regenerative air energy storage (RAES) is a technology in development which stores energy by compressing air and heating up water. RAES, also known as isothermal compressed air energy storage (CAES), improves upon conventional CAES by eliminating the need to burn fossil fuels in order to preheat compressed air prior to expansion. RAES systems in development use modified reciprocating compressors that are able to capture the thermal energy generated during the compression of air by injecting atomized water droplets into the cylinder for sensible heat gain [8]. The air and water are then separated and stored in tanks. During expansion, the process is reversed and the warm water droplets provide the thermal energy necessary to prevent the system from freezing. RAES technology under development is modular and can therefore be sited anywhere, unlike most conventional CAES which requires subterranean storage caverns [8]. RAES can achieve a high round trip efficiency of 70% compared to conventional CAES (29 to 54%) [9]. If waste heat is captured from a DG (or other source) the efficiency of RAES can be further increased. The power rating of the system is determined by the compressor/expander unit, and the storage capacity is determined by the air and water storage volumes and pressures. RAES is suitable for deployment in wind-diesel micro-grids due to its long cycle life, high roundtrip efficiency, and scalable power and energy sizing [8].

1.1. Energy storage for wind diesel micro-grids

In the recent literature, control strategies for wind-diesel and wind-diesel-storage hybrid micro-grids has focused on control for short term variations in order to maintain adequate power quality [10–15]. Bajpai and Dash review the recent literature relating to the system sizing, optimization, energy management, and modelling of hybrid renewable energy and diesel micro-grids, for which a brief summary follows [16]. The conventional method of system sizing is based on balancing the available resources with the demand. However, in areas where resource data is unavailable, non-conventional methods of sizing are investigated that use artificial intelligence. System optimization for renewable energy generation and storage is a trade-off between cost and reliability. The models for energy storage that are well defined in literature include hydrogen electrolysis and electrochemical battery technologies. Modelling the energy consumption of a DG is accomplished using the part-load efficiency curve, and simplified start-up/shutdown values. Energy management strategies should consider the electrical energy available from renewable sources, the state of charge of storage systems, diesel fuel prices, and the cost of utilization of energy storage (i.e. the costs resulting from the degradation of storage devices such as lead-acid batteries). Some of the challenges facing renewable energy micro-grids include high capital costs for energy generation and storage, low cycle lives among many energy storage technologies, general equipment and public safety, as well as grid stability and reliability.

1.2. Compressed air energy storage

There is recent literature suggesting CAES as a viable storage technology for wind-diesel micro-grids, but it all proposes the

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