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Optimal coordination of variable renewable resources and electric vehicles as distributed storage for energy sustainability[☆]

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ABSTRACT

This paper evaluates the coordination between electric vehicle (EV) fleets, as distributed storage devices, and variable renewable sources for mitigating energy imbalances and offering significant potentials for energy sustainability in an electricity infrastructure. The paper investigates the impact of such integrations for enhancing the environmental sustainability, social sustainability, and economic operation of electric power systems. The goal is to keep the energy sector on track for addressing the 2 degree Celsius (2DC) target per Copenhagen climate agreement.[1] The paper identifies strategies for large-scale integration of variable generation resources without compromising the electricity infrastructure security. The power system uncertainties pertaining to hourly load and wind energy forecast errors, and random outages of generation and transmission components are taken into consideration in Monte Carlo scenarios. The stochastic optimization of day-ahead hourly scheduling of electricity is formulated as a mixed integer linear programming problem. The merits of the proposed optimization model are demonstrated by applying four numerical case studies. The conclusion is that the applications of renewable energy resources and the intelligent assimilation of EV fleets (both as a provider and a consumer of energy) offer major potentials for alleviating power system peak demands, minimizing power grid operation costs and hourly wind energy curtailments, and limiting the environmental impacts of fossil fuel-based thermal generating units in the stochastic operation of an electricity infrastructure.

1. Introduction

Economic, social, and environmental challenges will have to be balanced as the electric utility industry progresses toward a more sustainable and modern grid, while meeting its principal obligations of delivering affordable, reliable, and safe electricity to its consumers. According to the International Energy Agency (IEA) [1], the electricity industry is not on track to limit the long-term escalation in the average global temperature to 2 degrees Celsius (2DC) per the Copenhagen Accord. As such electric utilities face formidable challenges for satisfying energy triangle obligations pertaining to environmental sustainability, energy security, and economic competitiveness. As the world looks to combat climate changes, a shift from carbon-based fuels to non-carbon based fuels is inevitable. At the same time, distributed generating units are employed progressively at load centers for promoting energy efficiency, alleviating the dependence on foreign fossil fuel, and boosting the security of transmission-constrained power systems. In this regard, sustainability is shifted from a nice-to-do to a must-to-do paradigm in the electric utility industry which requires pioneering technologies for addressing energy challenges [2].

It is possible to considerably reduce carbon footprints in electric power systems through large-scale integrations of renewable resources. Given proper scales, clean and renewable energy has the potential to support the balance of the energy triangle. According to IEA, the increased share of power generation from renewables, as well as natural gas in tandem with limited use of least efficient

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[1] In 2010, governments agreed that there is an urgent need to reduce emissions so that global temperature escalations are limited to below 2 degrees Celsius.

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Nomenclature

Indices:

b, j, o: Index of bus
d: Index of demand
i: Index of thermal units
l: Index of transmission line
s: Index of a scenario
t: Hour index ($t = 1$–24)
v: Index of EV fleet
w: Index of wind turbine

Variables:

$C^s_{v,t}$: Operation cost of fleet v at time t in scenario s ($)
$E^s_{v,t}$: Available energy in batteries of fleet v at time t in scenario s (MWh)
$E^{net,s}_{v,t}$: Net discharged energy of EV fleet v at time t in scenario s (MWh)
$F_{c,\,i}$: Production cost function of a thermal unit i
$F^{ET}_{e,i}$: Emission function of unit i
$F^r_{c,i}$: Availability cost function of a thermal unit i ($/h)
$I_{i,t}$: Commitment state of unit i at time t
$I^s_{c,v,t}$: Commitment state of EV fleet v in charging mode at time t in scenario s
$I^s_{dc,v,t}$: Commitment state of EV fleet v in discharging mode at time t in scenario s
$I^s_{i,v,t}$: Commitment state of EV fleet v in idle mode at time t in scenario s
$MP^s_{1,t,b}, MP^s_{2,t,b}$: Non-negative slack variables for real power mismatch at bus b at hour t in scenario s
$P^s_{i,t}$: Generation dispatch of a unit i at time t in scenario s (MW)
$P_{d,w,t}$: Power generation curtailed of wind turbine w at t (MW)
$PL^s_{l,t}$: Real power flow on line l at hour t in scenario s (MW)
$P^s_{c,v,t}, P^s_{dc,v,t}$: Charge/discharge power dispatch of EV fleet v at time t in scenario s (MW)
$P^s_{v,t}$: Generation dispatch of EV fleet v at time t in scenario s (MW)
$P^s_{m,v,t}$: Charge/discharge power dispatch of EV fleet v at segment m at time t in scenario s (MW)
$SD_{i,t}$: Shutdown cost of a unit i at time t ($)
$SU_{i,t}$: Startup cost of a unit i at time t ($)
W^s_t: Objective function of sub-problem
X^{off}_{it}: OFF time of unit i at time t (h)
X^{on}_{it}: ON time of unit i at time t (h)
$y_{i,t}$: Startup indicator of unit i at time t
$z_{i,t}$: Shutdown indicator of unit i at time t
$\Delta^{\max}_{it}$: Maximum acceptable power adjustment of a unit i at time t (MW)
$\theta^s_{j,t}$: Bus voltage angle at time t in scenario s (rad)

Parameters:

$B^s_{b,t}$: Set of units that are connected to bus b at time t in scenario s
$b_{m,v}$: Slope of segment m in linearized charge/discharge curve of EV fleet v
D_b: Set of loads that are connected to bus b
$E^{\min}_v, E^{\max}_v$: Min/Max energy stored in batteries of EV fleet v (MWh)
$EMS^{ET}_{\max}$: Emission limit (lb)
$L_{f,b}, L_{t,b}$: Set of lines starting from/ending at bus b
$N_{v,t}$: Status of grid connection of fleet v at time t
NE^s_v: Ratio of the number of EVs in fleet v in scenario s to the number of EVs in base case
NG: Total number of units
NL: Total number of lines
NB: Total number of buses
NT: Total number of periods under study
NV: Total number of EV fleets
$P^{\min}_{c,v}, P^{\max}_{c,v}$: Min/max charging capacity of EV fleet v (MW)
$P_{D,t}$: Total system demand at time t (MW)
$P^{d,s}_{D,t}$: Demand served at time t in scenario s (MW)
$P^{\min}_{dc,v}, P^{\max}_{dc,v}$: Min/max discharging capacity of EV fleet v (MW)
$P_{i,\min}$: Lower limit of real power generation of unit i (MW)
$P_{i,\max}$: Upper limit of real power generation of unit i (MW)
$P^{\max}_{m,v}$: Maximum power output at segment m in charging/discharging cost curve of EV fleet v (MW)
p^b: Probability of base case
p^s: Probability of scenario s
$PL^{\max}_l$: Maximum capacity of line l (MW)
$SD^{ET}_{e,it}$: Shutdown emission of unit i at time t (lb)
$SU^{ET}_{e,it}$: Startup emission of unit i at time t (lb)
T^{off}_i: Minimum down time of unit i (h)
T^{on}_i: Minimum up time of unit i (h)
UR_i: Ramp-up rate of unit i (MW/h)
DR_i: Ramp-down rate of unit i (MW/h)
$UX^s_{i,t}$: Outage status of generation unit i at time t in scenario s (if available 1, and 0 otherwise)
$UY^s_{l,t}$: Outage status of the line l at time t, in scenario s (if available 1, and 0 otherwise)
X_{jo}: Inductance of a line between buses j and o (p.u.)
η_v: Cycle charging efficiency of EV fleet
$\lambda,\ \pi,\ \rho,\ \mu$: Lagrangian multipliers

coal-fired plants, would curb emissions by 640 Gt in 2020 and help restrain local air pollutions. According to the World Wind Energy Association (WWEA) [3], the total installed global wind energy capacity increased from 18 to 175 GW between 2000 and 2010. However, while traditionally large thermal power plants can be operated as base power supply, and many can ramp up and down to address electricity demand fluctuations, the variability of renewable sources can disturb the balance of electricity generation and demand.

The large integration of wind energy (greater than 30% of energy) into the electricity infrastructure necessitates the redesign of conventional power systems and the modification of their operating practices [4]. Although an increase in the number and the geographic distribution of wind turbines can alleviate the temporal variability of wind energy and reduce wind speed forecasting errors, the lack of seasonal correlation of wind energy and electricity demand could result in energy balance disparities [5,6]. Several methods can be adopted to address this challenge which include the integration of flexible thermal plants (e.g. natural gas turbines), expansion and assimilation of transmission grid, demand response practices, and the utilization of energy storage ranging from batteries, ultra-capacitors, compressed-air storage, flywheels to hydroelectric storage reservoirs [7,8].

Batteries, with the possibility of fast charging and discharging, can play a significant role among storage alternatives. The surplus wind energy can be stored in batteries and discharged at a later time when needed. Thus, a battery storage system can capture the wind energy surplus during off peak periods when the demand