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An energy-constrained state priority list model using deferrable electrolyzers as a load management mechanism

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HIGHLIGHTS

- This paper propose an state priority list model to control DE units.
- The characteristic function of energy state is used to prioritize DE units.
- The model maintains the diversity of operating status of DE charging process.
- The model optimally determines the operating status of DE units to meet target.

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ABSTRACT

To reduce the consumption of fossil fuel and greenhouse gas (GHG) emissions, incentive-based policies are used to encourage end-users to utilize more clean energy. Hydrogen energy is an ideal clean energy that can be integrated into the next generation power grid. Deferrable electrolyzers (DEs), as a typical electricity-to-hydrogen conversion devices and capable of modulating power consumption, can convert excessive power to store electricity as hydrogen. Therefore it can be used as a method for load management. The main contribution of this paper is to propose an energy-constrained state priority list (ECSPL) model, for analyzing the charging response of aggregated loads consisting of DE units. The typical hysteresis control of DEs as a load management mechanism is first discussed. A characteristic parameter, i.e. the energy state of DE charging load, is used to group and prioritize the DE units. The proposed ECSPL model optimally determines the operating status of DE charging and standby process, and it maintains the user-desired DE charging trajectory considering customer-constraints. The proposed model maintains the diversity of operating status of DE charging and standby process to prevent unexpected synchronization phenomenon for operating status. To evaluate the performance of the proposed method, an estimated baseline of the aggregated DE charging loads is obtained based on natural hysteresis control. The ECSPL control method of DE units for intra-hour load balancing is then evaluated. The effects of different energy-constraints, deadbands of sampled end-use state comparison, error associated with the charging-trajectory measurements are modeled to evaluate the performance of controlled DE group. The ECSPL model is described and demonstrated by the modeling results of investigated DE units.

1. Introduction

Widespread interconnection of power systems can effectively facilitate renewable energy integration because with sufficient reserve capacity supported by flexible energy management, they may offset the fluctuations caused by wind and solar power sources [1]. But excessive increase of short-term variability from such intermittent renewable energy resources may limit conventional generator's ability to regulate quickly. Thus the future electricity grid needs to keep controllability on various resources in order to lower the whole system's operation cost and manage unexpected fluctuations from renewable energy sources [2]. With the development of advanced metering instrument (AMI), many demand-side distributed energy resources (DERs) have been proposed for providing ancillary services to meet the "resilient dispatch" requirements, such as continuous regulation, energy

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Nomenclature

Notation	Description
E_c	amount of required charging energy of deferrable electrolyzer
E	charging trajectory under hysteresis control scheme over the charging horizon
T_{ES}	user's desired charging-horizon
E_{ES}	time-varying setpoint energy level
η	one-way energy conversion efficiency
P_{R_ES}	required rated power for charging processes for individual deferrable electrolyzer to meet required charging energy E_c
P_R	rated power for charging processes for individual deferrable electrolyzer
e	error of charging trajectory measurements
σ_e	standard deviation of error of charging-trajectory measurements
ε	sampled energy state comparison
$\varepsilon_-, \varepsilon_+$	index of state transition boundaries
$\nu_{ON}, \varepsilon_{OFF}$	additional index to describe energy constraints
δ_{ES}	deadband width of sampled energy state comparison
n	hysteresis control logic variable
P_{DE}	aggregated power response of deferrable electrolyzer units
P^*_{DE}	target power of deferrable electrolyzer units
a, b, M, c, d, N	indexes of controlled units in SPL method
θ_s	temperature setpoint
δ_{HP}	thermostat deadband width
Δt	sampling time interval
θ_0	initial temperature
P_u	aggregated uncontrolled charging power outputs
$P_{baseline}$	hourly load profile as the day-ahead averaged from P_u
P_c^{ACE}	area control error signal
P_c^{LF}	load following signal
GHG	greenhouse gas
DEs	deferrable electrolyzers
ECSPL	energy-constrained state priority list
AMI	advanced metering instrument
VPP	virtual power plant
EPP	efficient power plant
PHEV	plug in hybrid electric vehicle
DERs	distributed energy resources
PDF	probability density function
TCAs	thermostatically controlled appliances
PEMFC	polymer electrolyte membrane fuel cell
ACRP	additional control region partition
ASOC	additional state of charge to describe controlled regulation capacity
RRMSE	related root mean square errors

imbalance management, instantaneous contingency or replacement reserves for renewable integration [3,4]. Spinning reserve optimization for reduction of system pollution was also discussed in [5,6].

As one option of demand-side DERs, it is recognized that the production of 'green' hydrogen is the first step in the process of realizing the migration from fossil fuels to hydrogen energy. It is also known that the associated stages of hydrogen storage, gas transportation and reconversion (to heat, shaft power or electricity) are essential and at present costly. It is important, therefore, that both the electrolysis and hydrogen utilization stages are carried out at high efficiency in order to maximize the value of the available wind and other zero-carbon power. Overall energetic and economic analyses of the full chain of technologies required to achieve complete implementation all these components into a next-generation grid lie beyond the scope of this paper. In a broad context, several authors have analyzed various hydrogen generation and use chains including transportation and stationary applications [7–11]. Crocket et al. [12] and Korpas [9] identified overall conversion efficiencies for the electrolyzer-based load management approach. The US DOE has set unit cost targets for electrolyzer technologies [13], and unit cost estimates for high volume production rates of hydrogen technologies have also been estimated [14,15]. The approaches taken in these studies aimed to assess the energy savings and carbon benefits of facilitating the hydrogen production via electrolysis within the capacity limits of the existing transmission and distribution system.

Technologically, the controlled DEs are an excellent pathway to support wind integration into a power system. For example, in [7] the yield from wind-hydrogen on the variable wind day (at 50% wind penetration) was 165 tonnes (5495 MW h LHV), which is equivalent to 18% of the electricity demand on that day. Obviously the hydrogen yields and DE utilization factors are limited by the inherently low annual capacity factors of renewable power sources [8]. There are a couple of objectives considered: (1) A much greater yield will be required if hydrogen is to make a significant contribution to industrial, domestic and transport energy requirements and (2) this justifies the widespread implementation of DE as a tool for achieving a cleaner energy system. Currently, there are two approaches to achieve the above objectives: (1) to increase the rate of hydrogen production and the utilization of electrolyzers by integrating other zero-carbon power sources of high capacity factor and (2) to enhance the regularity and controllability of DE charging process with a certain given operating constraints (comfort-constraints), which will improve the performance to off set renewable intermittency of DE charging load.

For example, the charging process of DE to produce hydrogen can be treated as a load management mechanism to off set the fluctuations of wind power in an autonomous power system [16,17]. The load factor of the fossil fuel power plant load profile can be maximized through DE charging load shifting function over one day. Wind power curtailment can be minimized because of more offsetting wind fluctuations via regulating DE charging load [18]. There are two benefits when considering controlling DE charging process: (1) increase system spinning capacity and (2) provide clean hydrogen from wind/solar power to achieve zero/low-carbon footprint.

For enhancing regularity and controllability of DE charging load, it is very important to model the detailed load charging process of electric-to-hydrogen to reflect the energy storage operating limits. When integrating more DE units, one can set up an effective control strategy based on the detailed charging process to access more realistic grid operation effects, for enhancing system spinning reserve capacity. As discussed in [19,20], one effective way to integrate electrolyzer load to power system operation and optimization is the virtual power plant (VPP) model, or the so-called efficient power plant (EPP), such as residential thermostatically controlled loads [21–23]. Similar method is also used in control strategy of plug in hybrid electric vehicle (PHEV) charging load [24,25]. It is feasible that in the electrolyzers-based EPP model the DEs be treated as distributed generators in a power system to participate resource regulation and operation optimization if a reasonable control strategy is implemented. Once the operating-constrained electrolyzer load models are obtained, the economics