DESIGN AND OPERATION OF SOLAR-HYDROGEN-STORAGE INTEGRATED ELECTRIC VEHICLE CHARGING STATION IN SMART CITY

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Abstract

This paper proposes the novel design and operation of solar-hydrogen-storage (SHS) integrated electric vehicle (EV) charging station in future smart cities, with two key functionalities: 1. super-fast and off-grid charging; 2. multi-energy charging system using solar, hydrogen and energy storage. The integrated system design and modelling of SHS-EV charging station include hydrogen fuel cell generator to conduct off-grid and high-density power generation, a local solar power generation facility, a power-to-gas electrolysis for hydrogen production from power grid and solar power, and hydrogen and battery storage facilities to conduct local energy balancing. The operation model of SHS-EV charging station is established through a nonlinear optimization problem with complex objective function. Objective function of SHS-EV charging station is to minimize the operation costs including hydrogen fuel and electricity purchase costs. The system constraints are the technical limits of individual energy devices, as well as the system-level balancing of energy supply with the EV charging demand. The simulation results show that the proposed SHS-EV charging station can meet the EV charging demand by super-fast and off-grid charging from multi-energy sources. The SHS-EV charging station can also provide CO_2 free power generation at point of charging. By using particle swarm optimization (PSO) to solve the SHS-EV charging system optimization model in MATLAB, the operation costs of SHS-EV charging station are greatly reduced.

1 Introduction

With the continuous development of global economy, human beings have experienced the gradual increase of energy crisis and air pollution. Therefore, low-carbon and renewable energy have received a great attention to tackle the energy shortage as well as environmental issues. Many countries already have proposed carbon emission standards aiming to reduce energy consumption, increase the efficiency of electricity generation, reduce greenhouse gas emissions and encourage the development of clean energy. Although the conventional fossil energy generation technologies are mature with large capacity and high operation stability, the energy utilization efficiency is limited with lack of flexibility to balance supply and demand. The overall carbon and pollutant emissions will lead to the global warming and environmental pollutions which restrict its further development. Clean energy is divided into renewable and non-renewable. Renewable energy includes wind energy, water energy, solar energy, geothermal energy, tidal energy, etc. Non-renewable clean energy includes nuclear, biomass, hydrogen, etc. Renewable energy has the advantages of competitive power generation costs as well as low-carbon emissions, however the uncertainty and intermittency of renewable energy sources will lead to the randomness and volatility of energy supply and usage. Hydrogen as a decarbonised fuel will provide a reliable and low-carbon energy option to combine with renewable energy for long-term operation.

Currently, it is estimated that the global fleet of EVs stands at 7.5million mainly comprising of small/light vehicles while the deliveries of medium and heavy commercial vehicles are rapidly increasing. China accounts for the largest share of EVs at 45% while Europe has emerged as one of the fastest growing markets with sales growth of 44% in 2019 [1]. Types of EVs depending on battery classification include Battery EVs (BEVs) and Fuel Cell EVs (FCEVs). The main difference in the two types is that FCEVs do not require external charging systems while BEVs are fully dependent on external power from the grid for purposes of charging the storage unit [2]. The relatively slow growth of the global EV market is attributed to high cost of production. However, it is estimated that over 100 million EVs will be in use globally by 2035. Further, EV production is set to reach 548 million by 2040 [1].

With the growing popularity of EVs, several approaches are undertaken to address the issue of charging infrastructure. One of such approaches involves the development of a larger charging infrastructure comprising of residential and non-residential types of charging stations. The charging stations are further classified under slow charging (level 1 and level 2) and fast charging stations (level 3 and DC). As explained by Xi et al. [3], level-one charging stations make use of standard wall outlet that typically provides a connection of 110V/15A. For this type of connection, the typical charging time to fully charged battery is 12 to 18 hours. Level-two charging stations on the other hand have a larger appliance circuit mainly rated at 220V. A larger capacity of 400 to 500V is used in fast charging stations thus enabling a typical EV battery to be charged in less than one hour. In the UK, fast charging stations have increased significantly over the years.

2 Methodology

2.1 EV charging infrastructure

As shown in Figure 1, This paper proposes a prototype design of the solar-hydrogen-storage (SHS) integrated electric vehicle (EV) charging station. The integrated system design and modelling of SHS-EV charging station include hydrogen fuel cell generator to conduct off-grid and high-density power generation, a local solar power generation facility, a power-to-gas electrolysis for hydrogen production from power grid and solar power, and hydrogen and battery storage facilities to conduct local energy balancing. The SHS-EV charging station can buy and sell electricity from the power grid which is incentivised by the daily electricity price variation.

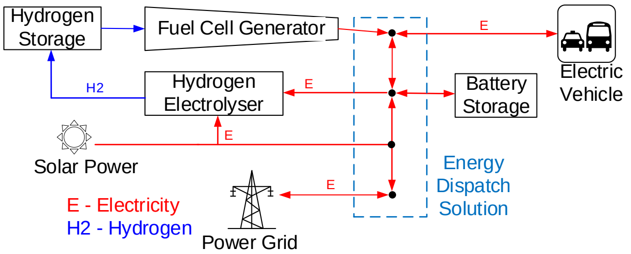

Fig.1: Prototype design of SHS-EV charging station

2.2 Hydrogen System Model.

The electrolyser, fuel cell generator (FC) and hydrogen storage tank are modelled as individual units through certain energy connections as a whole hydrogen generation and storage system. The energy production and consumption of each unit is represented by the equivalent electric power equations [4].

The equivalent electric power of hydrogen output in t period of hydrogen production by electrolyser is as follows:

$$P^t_{H_2,i} = P^t_{E2H}\alpha_{E2H} \quad \mathrm{i} \in \mathrm{N}_{\mathrm{HSS}}$$

The power generation of hydrogen fuel cell is as follows:

$$P^t_{H2P,i} = P^t_{H-FC}\beta_{E2P}, \quad \mathrm{i} \in \mathrm{N}_{\mathrm{HSS}}$$

The equivalent state of charge (SOC) of hydrogen storage capacity of hydrogen storage tank in t period is as follows:

$$E^t_{H_2,i} = E^{t-1}_{H_2,i} - (P^t_{H-FC,i} + P^t_{SH,i} + P^t_{H_2,i})\Delta t, \quad \mathrm{i} \in \mathrm{N}_{\mathrm{HSS}}$$

Where: P^t_{E2H} and P^t_{H-FC} are the power consumption of electrolysis and fuel cell respectively; α_{E2H} and β_{E2P} are the conversion efficiency of electrolyser and fuel cell respectively; $E^{t-1}_{H_2,i}$, $P^t_{SH,i}$ andΔt are the residual hydrogen storage equivalent electricity in t-*1* period, the equivalent power of hydrogen load and unit time period respectively; $\mathrm{N}_{\mathrm{HSS}}$ is the set of hydrogen system nodes.

2.3 Photovoltaic Power Model

A simplified photovoltaic power generation model is adopted to assume the output power is only affected by light intensity and ambient temperature [5]:

$$P_{pv} = P_{STC}G_{AC}\frac{[1+k(T_c-T_r]}{G_{STC}}$$

Where: P_{pv} is photovoltaic cell output power; G_{AC} is light intensity; P_{STC} is the maximum test power under standard test conditions (sunlight incident intensity of 1000W/m^2, ambient temperature of 25°C); G_{STC} is the illumination intensity under standard test conditions, and its value is 1000W/m. K is the power temperature coefficient; T_c is the operating temperature of the panel; T_r is the reference temperature.

2.4 Battery Storage Model

This paper used the battery as the energy storage component. Battery plays an important role in balancing power fluctuation and improving power quality in SHS-EV charging station. The available capacity SBat,l,t of the battery is [5]:

$$S_{Bat,a,t} = S_{Bat,a,t1}\left(1 - \sigma_{Bat,a}\right) + (P^{cha}_{Bat,a,t} * \eta^{cha}_{Bat,a} + \frac{P^{dis}_{Bat,a,t}}{\eta^{dis}_{Bat,a}})\Delta t$$

Where: $S_{Bat,a,t}$, $S_{Bat,a,t1}$ are the residual capacity of battery pack *a* in time *t* and *t1*, respectively; $\sigma_{Bat,a}$ is the self discharge rate of battery group *a*; $P^{cha}_{Bat,a,t}$, $P^{dis}_{Bat,a,t}$ are the charging power and discharge power of battery pack *a* in time *t*, and the power during discharge is negative; $\eta^{cha}_{Bat,a}$, $\eta^{dis}_{Bat,a}$ are the charging efficiency and discharge efficiency of battery pack *a* in period *t*.

2.5 Electricity Purchase and Sale Model

$$C_S = \sum_{t=1}^{24}(c^t_{grid}\sum_{i=1}^{Npv} P^t_{G,i} + c_{SH}\sum_{j=1}^{N_{HSS}} P^t_{SH,j})$$

Where: c_{grid}^{t} and c_{SH} are the price of selling or purchasing electricity to/from the power grid and the price of hydrogen generated from per unit of electricity in *t* period respectively [4].

2.6 Investment Costs

$$C_{IC} = C_{IC,PV} + C_{IC,BS} + C_{IC,HSS}$$

$$\mathrm{C_{IC,PV}} = \frac{\mathrm{P_{PV}}(1+\mathrm{r_{PV}})^{\mathrm{yPV}}}{365\left[(1+\mathrm{r_{PV}})^{\mathrm{yPV}}-1\right]}\mathrm{c_{IC,PV}}\sum_{\mathrm{i=1}}^{\mathrm{N_{PV}}}\mathrm{P_{PV,CAP,i}}$$

$$\mathrm{C_{IC,BS}} = \frac{\mathrm{P_{BS}}(1+\mathrm{r_{BS}})^{\mathrm{yBS}}}{365\left[(1+\mathrm{r_{BS}})^{\mathrm{yBS}}-1\right]}\mathrm{c_{IC,BS}}\sum_{\mathrm{k=1}}^{\mathrm{N_{BS}}}\mathrm{P_{BS,CAP,k}}$$

$$\mathrm{C_{IC,HSS}} = \frac{\mathrm{P_{HSS}}(1+\mathrm{r_{HSS}})^{\mathrm{yHSS}}}{365\left[(1+\mathrm{r_{HSS}})^{\mathrm{yHSS}}-1\right]}\mathrm{c_{IC,HSS}}\sum_{\mathrm{j=1}}^{\mathrm{N_{HSS}}}\mathrm{P_{HSS,CAP,j}}$$

Where: *y* and *r* are the design life and discount rate of equipment respectively(y=10, r=10%); $C_{IC,PV}$, $C_{IC,BS}$, $C_{IC,HSS}$ are the unit capacity investment cost of PV, battery and hydrogen system respectively; $P_{PV,CAP,i}$, $P_{BS,CAP,k}$, $P_{HSS,CAP,j}$ are the installation capacity of PV and energy storage system (both battery and hydrogen) of the I, K, J node respectively; $c_{IC,PV}$, $c_{IC,BS}$, $c_{IC,HSS}$ are the average daily investment cost of PV, battery and hydrogen system after discount respectively [4].

2.7 Constraints Condition

2.7.1 Photovoltaic Power Output Constraints: Due to the randomness and volatility of solar energy, the photoelectric output is coordinated according to the predicted power [6].

$$P_{Pv,k,t} = P_{Pv,k,t}^{for},\ 0 \le P_{Pv,k,t} \le P_{Pv,k}^{n}$$

Where $P_{Pv,k,t}^{for}$, $P_{Pv,k}^{n}$ are the predicted power and rated power of the k photovoltaic cells at time t.

2.7.2 Battery Storage Output Constraints: Battery as an energy storage unit does not generate electric energy, so the battery capacity remains unchanged throughout the coordination period [6].

$$S_{Bat,a,T} = S_{Bat,a,0}$$

Where $S_{Bat,a,T}$ and $S_{Bat,a,0}$ are the ending capacity and initial capacity of the battery pack *a* in the coordination period.

2.7.3 Hydrogen Storage Output Constraints:

$$E_{H_2,i}^{min} \le E_{H_2,i}^{t} \le E_{H_2,i,CAP},\, i \quad \in \mathrm{N_{HSS}}$$

Where $E_{H_2,i,CAP}$, $E_{H_2,i}^{min}$ are the capacity and lower limit of hydrogen storage tank respectively, and the lower limit is 20% [4].

2.7.4 The Power Output of each Energy Sources

$$\begin{cases} 0 \le P_t^{pv} \le P_{t,pv}^{out} \\ P_{min}^{in,electrolyser} \le P_t^{in,electrolyser} \le P_{max}^{in,electrolyser} \\ P_{min}^{FC} \le P_t^{FC} \le P_{max}^{FC} \end{cases}$$

Where P_t^{pv} is the power consumed of PV at time slot t, and $P_{min}^{in,electrolyser}$ and $P_{max}^{in,electrolyser}$ are the upper and lower limits of $P_t^{in,electrolyzer}$, P_{min}^{FC} and P_{max}^{FC} are the upper and lower limits of fuel cell generation [7].

2.8 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is used to solve the system optimization model. In the basic PSO algorithm, the formula of particle position x_{ij}^{t+1} and velocity v_{ij}^{t+1} [8].

$$v_{ij}^{t+1} = \omega v_{ij}^{t} + c_1 r_1\left(P_{ij}^{t} - v_{ij}^{t}\right) + c_2 r_2\left(P_{gj}^{t} - v_{ij}^{t}\right)$$
$$x_{ij}^{t+1} = x_{ij}^{t} + v_{ij}^{t+1}$$

Where: *t* is the number of iterations; ω is the inertia weight factor; c_1 and c_2 are the learning factors; P_{ij}^{t} is the position of individual optimal value of particles; P_{gj}^{t} is the position of global optimal value; x_{ij}^{t} is the position of particles in t iterations.

3 Results and Discussion

The case study for SHS-EV charging station is conducted with EV charging data in Shanghai. The energy devices of hydrogen, photovoltaic and battery storage are modelled according to the Methodology section. The main technical and economic parameters of the SHS-EV charging station are shown in Table 1. The case study takes 24 hours as the scheduling period with hourly energy dispatch solution in a summer reference day.

Table 1 The parameters of SHS-EV charging station.

Parameters	Value
PV installed capacity(kW)	500
PV installed cost (kW/$)	530.52
Battery capacity (kW)	500
Battery installed cost (kW/$)	462.13
Battery initial state of charge (%)	40
Rated charge and discharge power of battery (kW)	500
Minimum battery state of charge (%)	25
Maximum battery state of charge (%)	100
Battery charge and discharge efficiency (%)	85
Rated capacity of hydrogen tank (m^3)	1000
Initial capacity of gas tank（%）	30

Hydrogen tank cost (m^3/$)	38.51
Tank storage efficiency (%)	95
Electric to gas efficiency (%)	75
Electricity-to-gas coefficient (kWh/m^3)	0.2
Gas-to-electric efficiency (%)	65
Gas-to-electricity coefficient (m^3/kWh)	0.295
Renewable energy feed-in tariff (kWh/$)	0.05

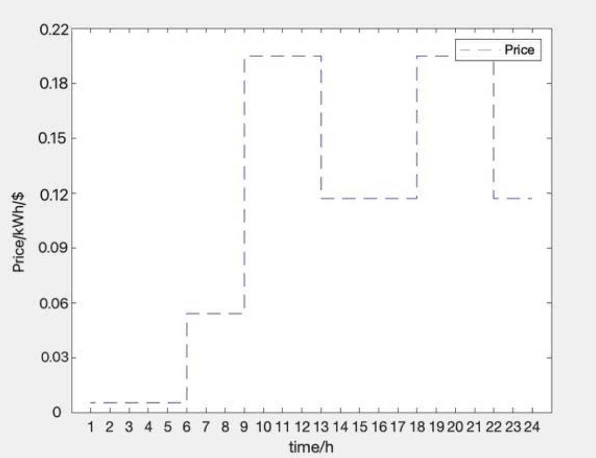

Fig. 2: Daily electricity price.

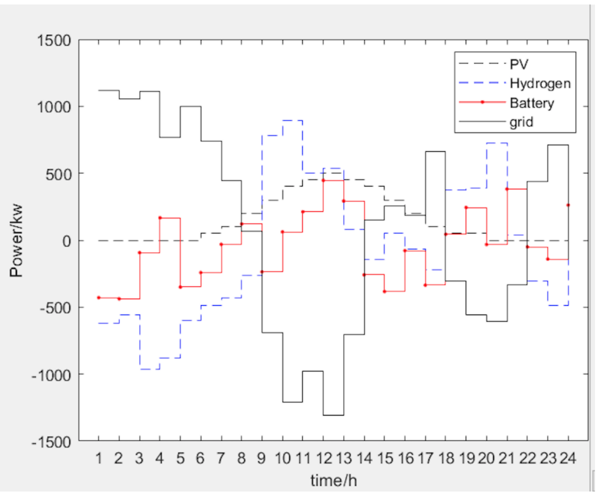

Fig. 3: Optimal energy dispatch solution.

When the electricity price becomes lowest during the night, the hydrogen production costs from the electricity will be lower than other time. From the figure 2 and figure 3, during the period 1 am to 6 am, the output of photovoltaic energy is eliminated. At this time, 1000kW of hydrogen can be stored for power generation. Such amount of hydrogen will be used during the periods of 9 am – 1pm and 6 pm – 10 pm when the grid electricity price is high. By integrating hydrogen system, the power grid can also achieve peak load regulation at a compensation price less than the feed-in price of other energy sources. The charging station also carrys out a certain amount of hydrogen production and storage for auxiliary peak load regulation, to ensure that the fuel cell generator has a certain peak load regulation ability when the EV charging load is high and photovoltaic energy is insufficient. Also, SHS-EV charging station is designed to sell the electricity to the grid when the electricity price is high, because it is cost-efficient for the grid to buy the electricity from charging station. This is represented as a negative value of grid output in figure 3, when the electricity price is higher than other time in figure 2.

From 6 am to 6 pm, photovoltaic energy is the main output energy source for the charging station. Except during the peak charging period, hydrogen fuel cell generator, battery storage and photovoltaic energy work together to generate electricity for the EV charging. In the off-peak charging period, hydrogen storage energy and battery storage energy are in a negative state, indicating that both kinds of energy sources are stored their energy during this period. During the period of 6pm to 11pm, photovoltaic energy is unavailable, the energy output is from hydrogen storage energy and battery storage energy, as well as from the grid.

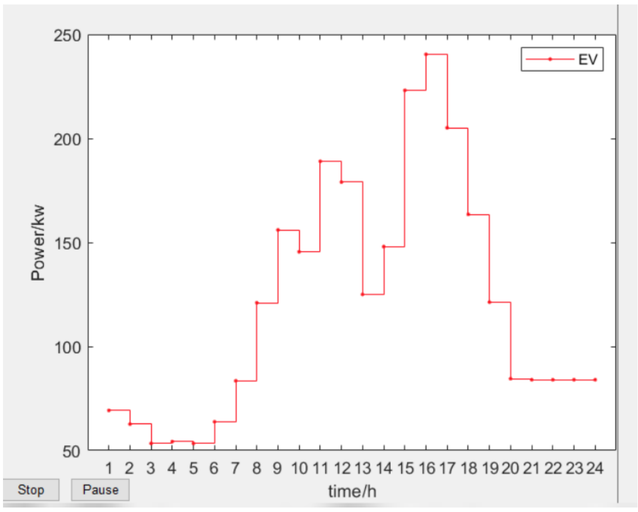

Fig. 4: EV equivalent charging load curve.

Figure 4 demonstrates the EV equivalent charging load for SHS-EV charging station, which is calculated from a classic EV charging load by incorporating a fast charging pattern to assume an EV can be fully charged in 10 minutes. This EV charging load curve has double peaks which are during the day from 9am to 1pm, and in the evening from 6pm to 10pm. These two peaks represent the centralized charging period of EVs, which liaises with the highest electricity price periods in Shanghai by comparing figure 2 and figure 4.

It can be seen from the figure 5 that the reserve energy of battery and hydrogen storage systems become low in the period of high electricity price, especially in the period of 8 pm – 10 pm, the capacity of battery energy storage is less than 30%, and the hydrogen energy storage is less than 20%. During the period of 11 am to 1 pm, the electricity is mainly provided by the photovoltaic energy, and the consumption of hydrogen storage energy and battery storage energy become low during this period. During the period of low electricity price, such as 1 am to

8 am, and in conjunction of the low EV charging load at night, both hydrogen and battery storage systems are charging towards a 100% capacity.

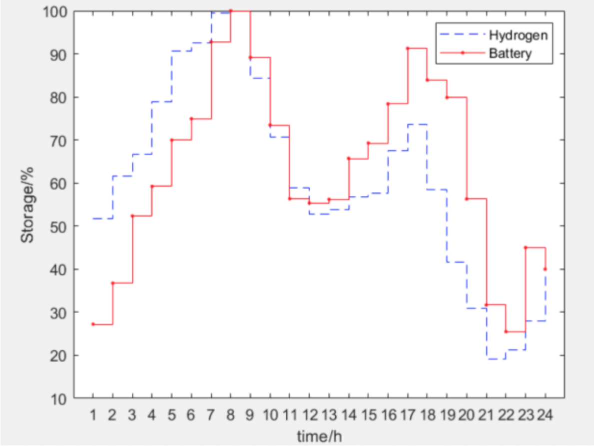

Fig. 5: Hydrogen and battery energy storage for 24 hours.

The costs to run this SHS-EV charging station in one day will be $1,478.2 if only buy the electricity from power grid. By the integration of SHS energy sources in this charging station, it will only cost $1113.88 to produce electricity for the EV charging, with a cost saving of $364.32 in a day. To charge an EV (Tesla Model 3) will cost $7.39 in 10 mins (due to the new policy in Shanghai that the commercial charging costs cannot exceed $0.12 per kWh). The peak EV charging load needs ae maximum number of 5 chargers to meet the EV charging requirement. In the three hours of peak charging time every day, 90 cars can be charged, while the rest of the time, an average of 8 cars can be charged in every hour. This charging station will earn $1906.62 revenue every day, so that the daily profit of a SHS-EV charging station is $792.74. The total capital investment cost for the SHS-EV charging station is calculated at $534,835. Therefore, the SHS-EV charging station will recover its capital investment and start gain profit after four years of service.

4 Conclusions

In this paper, the novel design and operation of SHS-EV charging station is proposed by integrating multi-energy sources of photovoltaic power, battery storage, and hydrogen generation and storage system. The modelling of energy devices as well as the system operation of SHS-EV charging station are established. Particle swarm optimization (PSO) algorithm is used to solve the charging system optimization model to minimize the SHS-EV charging station operation costs. The power outputs of each SHS energy devices are optimally distributed in respond to the variations of electricity price and EV charging load. The optimal energy dispatch solution of system costs and energy storage levels are realized. The energy reserves for EV charging as well as providing peak electricity to the power grid are always guaranteed at the expected level. The utilization rate of the hydrogen storage system is high, and the reliability of the system operation is increased by considering multi-energy sources. The feasibility study of SHS-EV charging station is verified in terms of investment costs, daily operation profit and payoff period. The results show that compared with the traditional EV charging system using grid electricity, the cost of this SHS-EV charging station is greatly reduced.

5 Acknowledgements

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