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Application and prospect of phase change energy storage in power system

Yingchun Qian [a], Dajun Si [a], Yueheng Zhao [a], Kai Hu [a], Yun Liao [b*], Shuyun Wang [b]

[a] *Yunnan Power Grid Company Limited, Kunming 650217,China*
[b] *Huazhong University of Science and Technology,WuHan 430074,China*

Abstract.

Energy storage technology is an important way to realize the efficient use of energy in power system，phase change energy storage as a new and efficient energy storage technology has a wide range of applications in power system. Phase change energy storage can improve new energy utilization, reduce the electricity of abandoned wind power and solar energy. This paper introduces the development，classification，characteristics and advantage of phase change energy storage materials and emphasizes the application of phase change energy storage in power system, At last, the factors influencing the development and application of phase change energy storage technology are analyzed.

Keywords: Phase change energy storage, phase change materials, power system

1. Introduction

Due to a mounting shortage of fossil fuels, international conventions propose: improving power supply structure and developing new energy power generation are the goals of our country's energy development. In recent years, new energy technology has made a lot of progress and the proportion of installed capacity in the power grid is increasing [1]. However, the weaknesses of new energy: intermittence and randomness, have a serious impact on the power quality from the grid. Thus, the maximum grid-connected capacity of new energy accounts for only 15%-25% of the total capacity of the power grid [2, 3]. What's worse, when the regulating capacity of the system is poor, it may lead to some unhealthy phenomena, such as wind power curtailment. In the first quarter of 2016, the wind power curtailment was 19,200,000,000 kW h and the average wind power curtailment rate was 26%. The provinces: Gansu, Jilin, Ningxia, and Xinjiang are the most seriously influenced places. The wind power curtailment rate of these provinces are: 48%, 53%, 35% and 49% respectively[4]. In order to increase the maximum grid-connected capacity of renewable energy and ensure the safe and stable operation of the system, energy storage equipment should be equipped in the renewable energy generation system. Such behavior can track the load alternation, improve the flexibility and regulating peak capacity, and finally reduce the curtailment.

In intelligent grid, energy storage becomes an important supporting technology for large-scale centralized and distributed new energy generation access[5-7]. *Research on energy storage white paper 2017* points out, until the end of 2016, the accumulative loading capacity of global energy storage program is 167.24GW. And the loading capacity of the pumped storage power station accounts the most. It is 161.23GW and the percentage is 96%. But the further development of the pumped storage power station is limited by the geographical and ecological environment. Thus, the research on new storage technology is very important. In 2016, the National Development and Reform Commission (NDRC), the State Energy Bureau etc. issued *Guidance on the promotion of electric energy substitution* and *Electricity development 13th Five-Year plan.* They clearly point out: for the northern residents, the traditional

* Manuscript received May 6, 2019; revised March 17, 2020.
* Corresponding author. Tel.: 17776526201; *E-mail address*:1132172267@qq.com
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resource will be replaced by electricity in the following four fields: heating, production, transportation and electricity supply and consumption. In a word, phase change energy storage plays an irreplaceable role in the process of propulsion power substitution.

On the basis of a large number of literature, this paper reviews the classification of energy storage technology, the development process, classification, characteristics and advantages of phase change energy storage materials, the application of phase change energy storage in the power system. Finally, it analyzes the factors which influence the development and application of phase change energy storage and put forward the future research direction.

2. Research on Energy Storage Technology

2.1. Classifications of common energy storage technologies

The common energy storage technologies in power system mainly include four types: physical energy storage, electromagnetic energy storage, chemical energy storage and thermal energy storage. The methods of physical energy storage include: flywheel energy storage, pumped storage and compressed air energy storage. The methods of electromagnetic energy storage include superconducting and super capacitor storage energy. Moreover, the methods of chemical energy storage include battery energy storage(such as: lead-acid, lithium ion) and hydrogen storage energy. Finally, the methods of thermal energy storage include thermochemical storage, sensible heat storage and phase change energy storage[8-11], which is shown in Fig. 1.

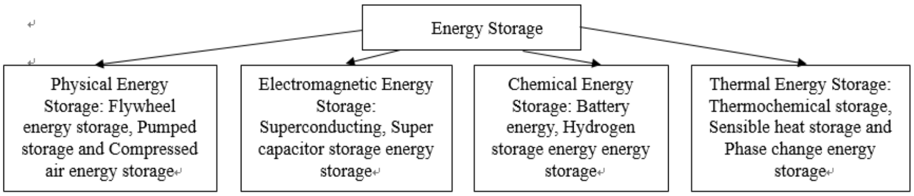

Fig. 1. The classification of energy storage technology

This paper also lists the characteristics of common energy storage technology[12-14], which is shown in Table 1.

Table 1. Characteristics of common energy storage technologies

Types	**Efficiency**	**Storage**	**Times**	**Influence**	**length**	**Weakness**
Pumped storage	70%-85%	big	thousands	greatly	minute	limited by hydrological conditions and site restrictions
Compressed air storage	40%-50%	big	thousands	greatly	minute	low response speed, high geographical requirements and low efficiency
Flywheel storage	85%-95%	big	unlimited	limited	second	large noise, high cost and low energy density
Super capacitor storage	85%-95%	medium	thousands	greatly	second	high cost, low energy storage density and small storage capacity
Superconducting	85%-95%	big	unlimited	limited	second	high cost, difficult construction and maintenance
Battery storage	80%-90%	medium	hundreds	greatly	second	short life expectancy and two times pollution
Hydrogen storage	40-50%	big	thousands	limited	second-mi nute	low efficiency, high cost and immature technology
Heatl storage	30-70%	big	thousands	limited	minute	low response speed, immature technology

2.2. Previous research of PCES

2.2.1. Development process of PCMs

In recent years, PCES receives great attention on basic research and technology application[15]. People focus on the composition and structure and develop some composite PCMs. Such as microcapsule PCMs, porous matrix composite PCMs, setted PCMs and nanocomposite PCMs etc[16]., through the following technology: physical adsorption, microcapsule encapsulation, polymer coating, nano technology etc. The composite PCMs improves the performance of single PCMs, improves the energy storage efficiency and energy storage capacity of PCES, and extends the application scope of PCES, and promotes the continuous development of PCES in the storage of renewable energy and waste heat recyclization.

2.2.2. Classification of PCMs

PCMs can be classified from three aspects: phase change temperature, phase change composition and phase change morphology, which is shown in Fig. 2.

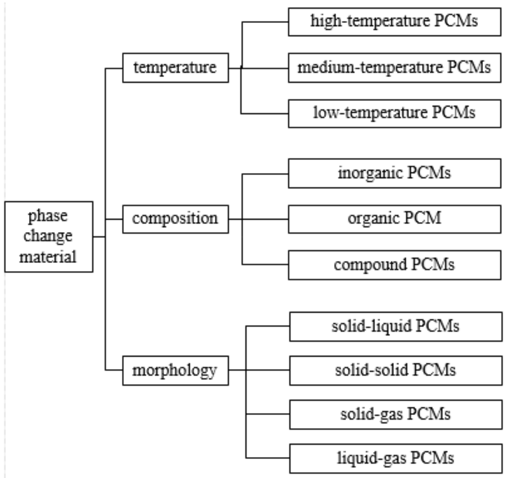

Fig. 2. Classification of PCMs

1) According to the phase change temperature[17], PCMs can be divided into high-temperature PCMs (above 250℃), medium-temperature PCMs (100℃ ~250℃) and low-temperature PCMs (below 100℃). Among them, the temperature of high-temperature PCMs hardly changes when the phase change occurs. It can satisfy the demand for the stable operation of power system[18], which is suitable for the small power generation, the solar power, the industrial waste heat recyclization and so on[19].

2) According to the phase change composition[20], PCMs can be divided into inorganic PCMs, organic PCMs and compound PCMs. Inorganic PCMs contains water, crystalline hydrate, molten salt and other inorganic substances; Organic PCMs includes paraffin, acetic acid and other organic compounds; Compound PCMs is a mixture of inorganic and organic PCMs. The heat storage and heat release during the phase change process of water vapor has been used in many aspects, such as the heat transmission of molten salt, the steam generation, and the steam turbine generating[21-23].

3) According to the phase change morphology, PCMs can be divided into solid-liquid PCMs, solid-solid PCMs, solid-gas PCMs and liquid-gas PCMs. And solid-liquid PCMs and solid-solid PCMs are widely used at present. Solid - solid PCMs has a small volume change during phase change, thus, the advantage of it is no leakage problem, little corrosion and long service life.

In a summary, the advantages of PCMs are: occupying a small area; no secondary pollution, recyclization. Therefore, the phase-change energy storage equipment has great application prospects in the distribution network which contains distributed generation. For example, the electrothermal phase change energy storage furnace, which is developed by Nanjing Jinhe Energy Materials Co., Ltd., adopts large capacity microstructural composite phase change heat storage technology in the world for the first time. Compared to the traditional heat storage method, the unit volume heat storage of the phase change storage mode is higher. Thus, the cost of investment is lower and the space is effectively saved. So, it is suitable for large-scale thermal storage and heating application of electric energy.

2.2.3. The characteristics of PCES

Due to the large unit heat storage and the constant temperature of exothermic process which is recognized in the application of power system[24], PCES has become the focus of recent research. The common basic features of PCMs are compared and showed out in Table 2[25-27].

Table 2. Comparison of the basic characteristics of PCMs

performance	molten salts PCMs	paraffin PCMs	molten salts-ceramic matrix composite PCMs	high density composite PCMs
energy storage（kg/m^3）	high	slightly high	fairly high	fairly high
latent heat（kJ/kg）	slightly high	high	slightly high	high
temperature（℃）	high	low	high	low、medium
coefficient of heat conduction	big	small	big	slightly big
cost	low	low	slightly high	fairly high

Due to the characteristics of the power system itself, it is required that PCMs should have high energy storage density, latent heat, temperature, heat conduction coefficient and low cost. From the above table, it is clear that the physical characteristics of the molten salts-ceramic matrix composite PCMs is most suitable. With the continuous development of the technology, it has broad prospects in the application of power system.

As a kind of thermal energy storage, PCES has unique advantages compared with battery energy storage (such as liquid battery) and sensible heat storage[28-29]. The advantages are shown in Table 3.

Table 3. Comparison of phase change energy storage and battery energy storage energy

	flow battery	sensible heat storage system	phase change storage system
cost（RMB/kW·h）	5000	210	800
pros	multiple uses	lowest cost vast temperature variations	lower cost high density and efficiency
cons	highest cost low density	only storage heat low density and efficiency	only storage heat small temperature variations

From Table 3, it can be seen that the cost of phase change energy storage is lower, with high energy density and efficiency, smaller area needed in construction, and high application value in distributed power system.

PCMs has certain advantages in thermos-physical properties, kinetic properties, chemical properties and economic benefits. Besides, PCES has other advantages:

Firstly, the temperature allocation of the unit thermal storage can be flexibly adjusted according to the user's demand for heat or the working condition.

Secondly, multiple energy storage units can be flexibly connected in series and parallel. The heat storage of this cascade can reach over 100MWh, which meets all kinds of thermal capacity required by users. The whole device is designed with modular design and strong compatibility and support for future expansion which can avoid duplication of investment.

Thirdly, it can be combined with other energy storage technologies to improve the energy storage efficiency and energy storage capacity of other energy storage methods. It will do good to achieve multi-energy complementation, such as compressed air storage with heat storage.

3. Application of PCES in power system

In recent years, the application of PCES in various fields attracts wide attention, and it is more mature in the field of building energy saving[30-32]. In the electric system PCES also plays an important role in improving the capacity of new energy, regulating the peak of the power grid and improving the performance of electric system. It is embodied in two aspects of the power supply and the user.

3.1. Application of PCES in power supply side

1) Deeply transform flexibility of thermal power. Flexible transformation of thermal power units includes improving the depth peaking shaving of units, climbing capability, speed of starting and stopping and so on. Using the characteristics of PCES and combining cogeneration units, it breaks the rigid constraint " pricing electricity based on heat amount", and realizes the thermoelectric decoupling. Thus, It can effectively improve the variable load rate of thermal power unit, the precision of load regulation and the performance of primary frequency modulation. In a summary, the unit has a wider load regulating range and the flexibility of the power system is enhanced[33-35].

At present, China Guodian Zhuanghe power generation CO., Ltd.; Huaneng International Dandong power plant; Huaneng Yingkou power plant etc. carry out the flexible transformation of the fire motor group in the country at first. Under the AGC control mode, the minimum load is remarkably controlled to about 30%.

2) Compressed air energy storage with heat storage. The principle is shown in Fig. 3: Under adiabatic compressed air energy storage and STATCOM which has different phase change energy storage temperature, PCMs can make the air be heated / refrigerated in phases. So the compression process of the air is close to adiabatic and produces a large amount of high temperature compression heat. The compressed heat energy is stored in the heat storage device and heats the compressed air during the energy release process. Moreover, the turbine is driven to work. After a series of PCMs, the temperature difference between the air and the heat storage material is lowered. Thus the heat loss in the heat exchange process is reduced. Compared with the traditional compressed air energy storage, the storage capacity of compressed air with heat storage is greatly improved. Its storage efficiency can reach about 75%[36-37]. In 2013, Germany's Adele-Stassfurt project invested 12 million euros to build a demonstration system with 90MW output power and 360MW·h storage capacity.

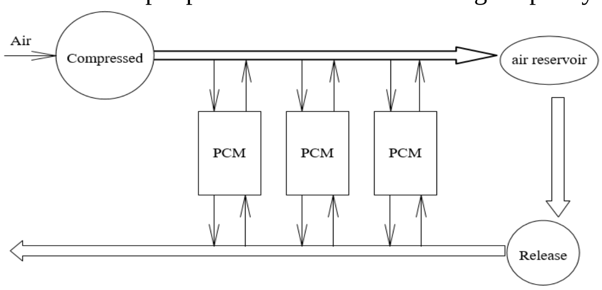

Fig. 3. principle of adiabatic compressed air energy storage intermediate PCMs

3) Solar power and storage. The solar power and thermal power station is usually composed of three subsystems: heat gathering, heat storage and power generation. Direct energy transfermation is realized through heat conduction. The heat storage elements of the thermal storage section can be characterized by sensible heat storage, phase change heat storage and chemical heat storage. At present, photothermal

power generation mainly uses the sensible heat of molten molten salt to store heat. During the process, molten salt absorbs and releases heat at 350~550℃. In 2008, the Andasol in Spain with parabolic trough solar thermal power plant was put into operation. At present, in the United States, Spain and Italy, many solar generation plants of molten salt heat storage have been commercialized to run[38]. The 28.3MW photothermal power generation project has been built in China. The central control Delingha 10MW power station has generated more than one year. The total installed capacity is about 500MW. It is expected to install 5GW light and thermal power generation by 2020.

However, there are some problems in the use of molten salt heat storage, such as high viscosity, easy decomposition of the liquid carbonate, strong corrosion of the chlorine salt to the container, the small heat of dissolution of nitrate and the low thermal conductivity. What’s worse, because the solidification temperature of molten salt is higher, it is necessary to maintain a certain temperature during the shutdown and it is necessary to preheat the pipe before reopening which causes unnecessary electrical loss[39]. Compared with the sensible heat storage of molten salt, the latent heat storage heat of phase change materials has a wider applicable temperature range and higher energy storage density. The system configuration is relatively simple, the speed of charging and releasing is faster and the cost is lower.

4) Power grid peak adjustment. PCES can not only have the effect of "shifting peak and filling valley" like other energy storage technologies, but also can greatly improve the capacity of the power grid to peak the peak and eliminate the wind power by configuring PCES in cogeneration power unit to decouple its "thermal power" rigid constraints and achieving the flexible operation of the thermoelectric unit[40].

3.2. The application of PCES on the user side

1) Valley’s electric phase change heat storage heating[41]. At present, in North China, the following ways are generally used in winter heating in cold areas, such as, municipal heating, gas fired boiler, direct electric heating, ground source heat pump, air source heat pump, etc. Compared with the above heating technology, the valley’s electricity phase-change regenerative heating system has the advantages of low power consumption, low dependence on infrastructures, high reliability and easy maintenance.

In August, 2017, Nanjing Jinhe Energy Materials Co., Ltd. developed an "electrothermal phase change energy storage furnace" in the world for the first time. It uses large capacity microstructural composite phase change heat storage technology, which directly converts the valley electricity into heat energy, stores in the phase change heat storage body, which can meets the needs of providing hot water, hot air.

2) Phase change cold storage technology. Phase change cool storage technology can be divided into three types: ice storage technology, gas hydrate cool storage technology, latent heat type thermal fluid storage technology[42]. In the low load period, the electric refrigeration unit is used to refrigerate, and the cooling amount is stored by the latent heat of PCMs. It is released in the peak period of load to meet the cooling capacity of the air conditioning or production process, so as to achieve the purpose of "shifting peak and filling the valley" and balance the load of the power grid. At the same time, the refrigeration unit and the corresponding supporting facilities are reduced, thus, the operation cost is saved. Ice storage technology uses water ice phase change to store and release heat, and its energy storage density reaches 335kJ/kg, which is 7-8 times of water storage[43].

3) Deep cold storage technology. Cryogenic power storage technology is a technology that directly uses heat storage (cooling) to large-scale power management. Using liquid air as energy storage medium and low liquefaction point under atmospheric pressure, it solves the problem of low energy density and high pressure storage of compressed air energy storage in general heat storage technology. It is also the result of combining PCES and compressed air energy storage. Low temperature liquefaction and storage are quite mature technology. Therefore, the cryogenic electricity storage technology provides a variety of static and dynamic services for the power grid, such as peak cutting, load tracking, emergency reserve capacity and so on[36]. In 2011, the world's first cryogenic energy storage demonstration system (400kW/3MW. H) was built and operated to verify the feasibility of cryogenic storage technology[38].

4) Industrial waste heat recovery. At present, the recovery and utilization of industrial waste heat is an important challenge in the operation of power system[44]. The inherent heat capacity and latent heat of

PCMs can store a lot of heat energy, which is one order higher than the magnitude of sensible heat storage. In addition, the heat output of PCES is stable and the temperature of PCMs is basically unchanged, which ensures the stable operation of the thermal storage system. The heat stored can be used in many aspects such as dehumidification, refrigeration, heating, and power generation.

5) Auxiliary time-sharing electricity price. Time sharing price management is similar to peak filling and valley filling. In the electricity market where TOU price is implemented, PCES can effectively assist users in realizing TOU price management. Storing heat at low electricity price and releasing heat at high electricity price, namely, "low storage and high release", PCES reduces the overall electricity consumption cost.

6) Mobile heating. A phase-change energy storage mobile heating vehicle is developed by utilizing the characteristics of phase change energy storage equipment, such as small occupied area and high energy storage density. Mobile heating is a new type of waste heat utilization and intensive heating mode, which breaks the mode of pipeline transportation. It is mainly composed of heat storage element, control unit, heat release / heat storage pipe, vehicle and so on. It uses high performance PCMs as the core. It can reclaim and store the waste heat of power industry and transport it to the user side with a mobile heating car and provides hot water and heating[45]. At present, mobile heating vehicles have been put into use in some cities such as Shandong, Jiangsu, Hebei and Tianjin.

4. Factors Which Affect the Development and Application of PCES

Compared with other energy storage methods, PCES starts late and the technology is immature, which is mainly embodied in the research of PCMs, and different types of PCMs have different shortcomings, which are manifested in the following aspects:

1) Solid-liquid PCMs: the price is cheap, but the existence of supercooling and phase separation can lead to the poor storage of energy[46]. The energy storage density is difficult to maintain, and it will decline with the continuous circulation. It is easy to produce leakage problems, pollute the environment, corrode, package container price and so on.

2) Solid-solid PCMs: the main disadvantage is low latent heat and high price.

3) Inorganic PCMs: generally corrosive, subcooled and phase separated.

4) Organic PCMs: low thermal conductivity and partial organic PCMs also have the disadvantage of unstable performance.

Although many compound PCMs are developed and make up the shortage of single PCMs in recent years, such as microcapsule PCMs, porous composites PCMs, shape setted PCMs and nano composite PCMs, there still exist some disadvantages such as, complex technology and high cost.

Because PCES still has many shortcomings, its application in the power system is still in its infancy. It is not able to access the power system on a large scale before solving the technical and cost problems. However, as a new type of energy storage, the characteristics and advantages of PCES are very obvious. Under the trend of global low-carbon economy and new energy revolution, PCES has a wide application prospect. The future research focuses on the aspects such as, the development of new PCMs, the improvement of compatibility and cost reduction of PCMs, the optimization control of storage / heat release process, the effective combination of PCES and other energy storage methods, the coordinated and optimized operation of the modern power system with the PCES and so on.

5. Conclusion

PCES is a storable, adjustable, friendly power system with peak load capacity, and has great potential for development. In this paper, the development, classification, characteristics and advantages of PCMs are introduced in a large number of documents. The application of PCES in the power system is emphasized, and the factors that affect the development and application of PCES are analyzed. After summarizing and analyzing, we can see that with the improvement and perfection of PCMs, the application of PCES in power system will be more and more extensive. PCES will play an important role in improving the level of new energy consumption and reducing the loss of wind and light. It can not only improve the economy of power system operation, but also meet the demand of energy saving and emission reduction, which is in line with the development trend of today's society. Therefore, it is very necessary and urgent to study PCES.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yingchun Qian and Dajun Si concuted the research; Yueheng Zhao and Kai Hu Searched Literature; Yun Liao and Shuyun Wang wrote the paper; All authors had approved the final version.

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