Characteristics and Applications of Superconducting Magnetic Energy Storage

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Abstract. Energy storage is always a significant issue in multiple fields, such as resources, technology, and environmental conservation. Among various energy storage methods, one technology has extremely high energy efficiency, achieving up to 100%. Superconducting magnetic energy storage (SMES) is a device that utilizes magnets made of superconducting materials. Outstanding power efficiency made this technology attractive in society. This study evaluates the SMES from multiple aspects according to published articles and data. The article introduces the benefits of this technology, including short discharge time, large power density, and long service life. On the other hand, challenges are proposed for future study. The high energy requirement of the cooling system and carbon emissions are some of the drawbacks of SMES. It’s found that SMES has been put in use in many fields, such as thermal power generation and power grid. SMES can reduce much waste of power in the energy system. The article analyses superconducting magnetic energy storage technology and gives directions for future study.

1. Introduction
Nowadays, resources use and storage have played important roles all over the world. Besides resources like water and fossil, electricity is more used widely in human society. In addition, with a growing population, the needs for energy rise quickly. Thus, high-effective energy storage technology would be so crucial to modern development. Superconducting magnetic energy storage (SMES) has good performance in transporting power with limited energy loss among many energy storage systems. Superconducting magnetic energy storage (SMES) is an energy storage technology that stores energy in the form of DC electricity that is the source of a DC magnetic field. The conductor for carrying the current operates at cryogenic temperatures where it is a superconductor and thus has virtually no resistive losses as it produces the magnetic field. The overall technology of cryogenics and superconductivity today is such that the components of a SMES device are defined and can be constructed. The integrated unit appears to be feasible for some utility applications at a competitive cost.
with other technologies. SMES is the only technology-based on superconductivity that applies to electric utilities and is commercially available today.

With such high efficiency, SMES requires particular circumstances to be installed. The device needs to function under low temperature, which made it cost a lot. In this situation, seeking cheap materials for cooling SMES becomes a popular topic. Various teams have worked on improving energy-saving technology and the wide application of SMES at a lower cost. It’s reported that there are some existing examples that SMES has put in use in many fields. For instance, the U.S Department of Energy has sponsored the improvement of SMES at the grid level. They try to develop SMES technology at the commercial sale level, storing power at appropriate costs [1]. Their study aims to develop a 1-2 MWh SMES system, which can offer the price of lead-acid batteries. Additionally, Bonneville Power Administration in Washington installed a 30MJ SMES unit, absorbing and releasing 10 MJ of power at a frequency of 0.35 Hz. In 2003, a 5 MW 7 MJ SMES was installed in Japan to balance the voltage dips in a crystal factory. These cases proved that SMES could provide us high-quality power and practicability.

Considering the high energy demand, the advantages and limitations of superconducting magnetic energy storage are discussed in the article. The advantages, limitations, and sustainability are discussed with the help of tables and figures. Diverse applications of SMES are assessed in the study and are analyzed. The improvement of SMES can be evaluated better with these pros and cons. Also, sustainable development is regarded in the research, which specifies improving water quality. Different applications are discussed in our study. Therefore, the evaluation of superconducting magnetic energy storage may be useful in various fields and applications.

2. Advantages
As an emerging energy storage technology, SMES has the characteristics of high efficiency, fast response, large power, high power density, long life with almost no loss. These advantages make SMES a potential solution for addressing the challenges in the future.

2.1 Energy Storage Efficiency
Due to the AC losses in the superconducting coil and eddy current losses in the cooling system, some energy is lost in the SMES system. But these two contributions can be reduced to a very low level if there is a suitable design of the superconducting conductor and the cooling system. As a result, SMES exhibits a very high energy storage efficiency in the region of 90% to 99% (typically more than 97%) [2]. That means it has little energy loss during the discharge and the charging, which can also be interpreted that SMES shows excellent energy conversion efficiency. The value is really excellent compared to other energy storage systems (batteries 70 to 90%, pumped hydro up to 70%). This high efficiency can be attributed to the lack of energy conversion from and to another form.

2.2 Discharge Time
Besides its high efficiency, SMES has very fast discharge times, only for milliseconds to 8 seconds for a full discharge. Discharging is possible in milliseconds if it is economical to have a Power Conversion System (PCS). That is really a rapid response compared to other technologies. Therefore, it can be utilized for power quality, such as the instantaneous voltage drop, flicker mitigation, and short duration UPS.

2.3 Power Rating
The typical rating of SMES is about 1-10MW now, but many researches are conducted on larger SMES systems in the range of 10-100MW. A tiny minority can even reach more than 100MW. Figure 1 compares the ranges of power and discharges time for different storage technologies. It is obvious that SMES has a higher level of power compared to some traditional technologies.
2.4 Power Density
SMES shows a relatively low energy density of about 0.5-5Wh/kg currently, but it has a large power density. The power per unit mass does not have a theoretical limit and can be extremely high (100 MW/kg). While Batteries present higher values in energy density but lower values in power density. These two technologies are also combined to compensate for their drawbacks. Figure 2 shows the power and energy per unit mass for SMES and two more mature technologies: capacitors and batteries. For SMES, the grey zone indicates the presently attained values. The black zone covers theoretically possible ranges, which require more research and development. The high power density of SMES makes it a promising candidate for pulse power sources in the military and civil fields, such as the electromagnetic launcher [4], magnetic forming (use of electromagnetic forces to form a metal) [5].
2.5 Life Span and Cycle Time
The lifetime of technology is mainly determined by the lifetime of the mechanical components. The life span of SMES is more than 20 years, which is also superior to most energy storage technologies because SMES has almost no loss characteristics through large numbers of discharge and charging cycles. That means SMES can afford more than 100,000 cycles throughout its life.

3. Application
SMES can be combined with multiple fields and give play to its advantages under the combination of different fields to make up for the shortcomings in these fields. Many power generation systems can convert other energy into electric energy. Then the electric energy flows to the grid along the cable for users to use, while SMES stores users' remaining unused electric energy. The electric energy is released to make up for the shortage of power generation for users to use during the low power generation period. This reduces the waste of excess power generated while still keeping the grid well-supplied.

3.1 Application of power generation field
3.1.1 Photovoltaic power generation
Photovoltaic power generation is a technology that converts light energy directly into electric energy by using the photovoltaic effect of the semiconductor interface. It is mainly composed of three parts: solar panel (module), controller, and inverter. A system of combination of Photovoltaic power generation (PVPGS) and SMES in Fig.1 show how they are combined. SMES can not only store energy but also play a benign role in PVPGS. In the last few years, our power system has had a number of different challenges, such as compensation of induced harmonics, reactive power, unbalance current, neutral current, unbalance voltage, voltage sags & swells, power fluctuations, and load fluctuations [7, 8]. And these challenges stem from the rapid growth in the use of static power converters, Switched-Mode Power Supply (SMPS), nonlinear loads, ever-growing and congested power lines, and renewable energy sources (RESs) with high permeability (e.g., the solar, the wind, etc.) [9, 10]. Especially among all kinds of RESs, PVPGS with no pollution, no geographical restrictions, and abundant reserves account for an increasing proportion of microgrids [11, 12]. Nevertheless, unfortunately, energy solar energy is highly random and obviously intermittent, resulting in large fluctuations in photovoltaic output power [13-15]. SMES can smoothly suppress the power fluctuation caused by load mutation, pulse load, and time-varying solar irradiance [16]. Byung-Kwan Kang and Sun-Ho Bae have done simulation tests on the combined SMES and PV system based on PSCAD/EMTDC [17]. They analyzed the impact of SMES on system stability, several important factors such as the capability of SMES, its grid connection supervision, power reserve, output power fluctuation of a photovoltaic system, and seasonal load requirements, etc.
3.1.2 Wind power generation.

In essence, wind power generation converts wind energy into mechanical energy, which is then converted into electricity to generate electricity. The principle of wind power generation is to use the wind to drive the windmill's blades to rotate. Then, the machine will rotate the speed to promote the generator to generate electricity through the speed increase. Modern wind power generation system (WPGS) mainly faces two main problems: the output power of wind power generation is greatly affected by wind speed, and the output power fluctuates randomly; When the power grid voltage drops, if the wind power generation equipment is simply cut off, the stability of the power grid will be seriously affected. There's an experiment of SMES in controlling the voltage of power systems integrated with wind farms at variable wind speeds. SMES, WPGS, and the research system were simulated using MATLAB/Simulink program and Simpowersystem Package [18]. And through this experiment, they draw the following conclusions to prove the following advantages of SMES in the application combined with WPGS: (1) When WPGS is installed with SMES, the voltage value remains constant regardless of wind speed changes, indicating that SMES and WPGS combined have the ability to stabilize the voltage. (2) SMES can reduce reactive power and reduce electric energy loss in the line [18]. Therefore, SMES plays an important role in stabilizing the wind power generation system. Meanwhile, Similar to PVPGS, when SMES is combined with WPGS, voltage and frequency fluctuations caused by external factors can be suppressed. In this combined system, the external factor should be the wind speed. Thus, Wind power systems with SMES in them can operate more stably [19].

Figure 3. A system combining PVPGS and SMES
3.1.3 Thermal power generation

Thermal power generation is actually the use of burning combustibles when the heat energy, through the power generation device into electricity generation. Thermal power generation systems are usually designed with Automatic Gain Control (AGC) that is an important function in the energy management system Energy Management System (EMS), it controls the output of the frequency modulation unit to meet the changing power demand of users and make the system in the economic operation state. The purpose of the AGC is to keep the system frequency and the actual power between different control areas at their respective specified nominal values when the system is subjected to load changes. If we connect the thermal power system with AGC and SMES, the role of AGC in the thermal power system will be enhanced [20]. The superiority of combining SMES with thermal energy generation was derived from an experiment by Sabita Chaine and M. Tripathy. The sensitivity and robustness of this experiment under different operating conditions demonstrate the effectiveness of tachyon energy storage devices such as SMES in suppressing power system oscillations with properly adjusted controllers [20].

3.2 Application of power grid

The growing demand for electricity around the world is putting enormous pressure on the environment and the economy. As a result, scientists in various countries have invented many renewable energy generation technologies to solve power supply pressure and environmental pollution problems. But economic challenges remain, such as the loss of grid lines and the dissipation of electricity before it is used during peak generation periods. These situations can lead to high costs of circuit repair and waste of precious resources such as electricity.

If there is an imbalance between the power load and the power supply or the frequency is unstable in an N-1 emergency, the power system may have Cascading outages. And these problems are exacerbated with the growth of RESs, which has some effects on microgrid (MG) performance, such as
the reduction of system inertia. So, the voltage and frequency fluctuations increase. Moreover, the RESs exchange electrical power to MGs through electronic power inverters, which cause higher power fluctuations than the traditional synchronous generators. Higher power fluctuations mean more pressure on the grid and a more erratic supply. Therefore, if the RESs have greater penetration, it is difficult to stabilize the frequency and voltage of the system [21].

Superconducting Magnetic Energy Storage (SMES) is one way to solve these problems. First, it is a form of energy storage that can store electricity that customers do not use during peak generation times and solve the pressure on the power supply during the generation downturn and during peak consumption hours. Secondly, it can be used in combination with various power generation systems and power grids to adjust the power grid, such as reducing the losses of the power grid, improving the stability of the grid, etc.

The superiority of SMES was verified in the experiments done by J.B.X. Devotta and M.G. Rabbani, and S. Elangovan [22]. The energy transfer between the power system and the SMES unit is based on the simultaneous control of the active and reactive power modulation of the SMES unit. An artificial neural network-based controller controls the active power, and a conventional regulator controls the reactive power. They were tested using a synchronous oscillation benchmark model. The results of this experiment demonstrated the ability of the SMES unit to effectively restore the stability of the power system. Moreover, another experiment done by Emad A Mohamed and Yasunori Mitani, tested by load frequency controller and SMES together, yielded that SMES has good robustness, stability, coordination, and responsiveness to the grid [21].

4. Sustainable Development Goals

4.1 Reducing poverty

China's new countryside is trying to apply superconducting magnetic energy storage to rural electric energy storage. China's new rural commune includes many rural families. The power source of rural families is often solar power generation. Due to the small daily power consumption, there may be a lot of power waste. Therefore, superconducting magnetic energy storage can be used to store the remaining electricity and transfer it to the national power grid, which can reduce the burden of local power generation. The advantages of using superconducting magnetic energy storage are: solar power generation is characterized by high power generation efficiency when the sunlight intensity is maximum. In this case, if the excess electric energy is directly input into the power grid, the electric energy loss is also the highest. Due to superconducting magnetic energy storage characteristics, the system can compensate for the load fluctuation and reduce the loss. In this way, when the surplus electric energy is input into the national grid when the sun is sufficient, the government can allocate funds to drive the development of poor areas. After the scale is formed, it will be a virtuous circle. When the sunlight is insufficient, the stored electricity can also be used for self-sufficiency to achieve the purpose of green and sustainable development.

4.2 Improving the aquatic environment

Taking hydropower as an example, the principle is that the dam intercepts the flowing water. On this basis, the stored water passes through the turbine to convert potential energy into electric energy to generate electricity. When the construction of a dam destroys the mobility of water, the reduction of downstream flow may lead to drought. The upstream impoundment of the dam may inundate agricultural land and some plants or cause flooding, all of which may destroy animal habitat and agricultural land[23]. Hydropower also changes the river structure, slowing down the water flow, depositing sand and gravel, and raising the riverbed, which constitutes an adverse living environment for some aquatic organisms and affects the water storage efficiency of the dam[24, 25]. The higher the riverbed, the less the water storage capacity.

Therefore, if we want to slow down or even solve these problems, we must take measures. The superconducting magnetic energy storage system can be used. Every time the dam carries out
hydropower generation, power is generated through the energy conversion effect of the turbine. When
the power generation exceeds the required power, the remaining power can be collected by the
superconducting energy storage system to store power. In this way, the utilization efficiency of power
generation is improved. When the utilization efficiency is improved, the water storage capacity of the
dam is reduced. That is, the power generation cost is reduced. Therefore, it can ensure a certain fluidity
of the basin and protect aquatic organisms and the basin's ecosystem.

To sum up, superconducting magnetic energy storage has a wide range of applications, and its use
has a positive impact not only on the ecological environment but also on society. If experts and scholars
in various fields worldwide continue to work together, it can increase the possibility of realizing the goal
of promoting the common sustainable development of mankind.

5. Challenges
Although the SMES system has considerable advantages, it still faces challenges on many fronts. The
following text shows the main challenges of SMES at present.

(1) The short storage duration is the most obvious one in its drawbacks. SMES can only be
implemented for short cyclic periods of several minutes to hours which is further shorter than the storage
duration of some batteries. SMES has a short energy storage duration because it shows a very high self-
 discharge ratio of 10-15% per day.

(2) SMES has a low energy density which is only about 0.5-5Wh/kg. The energy content of current
SMES systems is very small. Ways to increase the energy storage capacity of SMES are often to use
large energy storage units.

(3) A robust mechanical structure is usually required to withstand the very high Lorentz forces
generated by the magnet coils on the magnet coils without degrading the superconductivity.

(4) The substantial capital cost of SMES ranges from 1000 to 10000 dollars per kWh which is far
more than most other technologies.

(5) There are also challenges in the materials and configurations of a superconducting coil. For
instance, although the first generation of high-temperature superconductor, BSCCO (BiSrCaCuO), had
a high critical current, it was difficult to use in power applications at high magnetic fields. This is because
the critical current of magnetic tape decreases rapidly due to the magnetic field.

(6) The monitoring of the quench of the material needs to be more effective. In the event of the
quench of superconducting material in the system, it can be costly in terms of time and money to restore
the system to operate.

(7) The high energy requirements of cooling systems and the carbon emissions they generate mean
that SMES is not a fully environmental-friendly energy storage technology.

(8) The strong magnetic field is likely to threaten people's health. Exposure to high magnetic fields
often leads to abnormal heart rates, irregular changes in brain activity, damage to the immune system,
the appearance of skin diseases, etc.

6. Conclusion
In general, the demand for energy increases faster than we can imagine. Better energy storage can offer
a better supply of power. Superconducting magnetic energy storage did a great job in transferring power
efficiently. The technology can achieve maximum efficiency due to its fast discharge speed, great power
density, and long life span. Although SMES has low energy density currently, its great power density
balances the storage condition. Besides these advantages, SMES is also uniquely suited for multi-
domain applications because of its strong superiority. For example, it has good robustness, stability,
responsiveness, and coordination in power systems. It can be combined with multiple power generation
methods and can compensate for the shortcomings of multiple power generation methods. And the
application of SMES at the commercial sale level would be a future topic to study. It meets the UN
Sustainable Development Goals of improving the aquatic environment and reducing poverty. In addition,
the choices of convenient materials to cooling down SMES systems are big issues in this field. The
monitoring of quench needs to be improved for less loss. More research and development are needed to
better integrate with other technologies to compensate for its weakness and make it more competitive. The evaluation of superconducting magnetic energy storage technology provides a vision of future development.

References

[1] R.V. Holla, Energy storage methods-Superconducting magnetic energy storage-A Review, Journal of Undergraduate Research 5(1) (2015) 49-54.
[2] H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Progress in natural science 19(3) (2009) 291-312.
[3] www.electricitystorage.org.
[4] H.D. Fair, Electric launch science and technology in the United States, IEEE Transactions on magnetics 39(1) (2003) 11-17.
[5] T.E. Motoasca, H. Blok, M.D. Verweij, P.M. van den Berg, Electromagnetic forming by distributed forces in magnetic and nonmagnetic materials, IEEE transactions on magnetics 40(5) (2004) 3319-3330.
[6] P. Tixador, Superconducting magnetic energy storage: Status and perspective, IEEE/CSC&ESAS European superconductivity news forum, 2008.
[7] M.H. Bollen, R. Das, S. Djokic, P. Ciufo, J. Meyer, S.K. Rönnberg, F. Zavodam, Power quality concerns in implementing smart distribution-grid applications, IEEE Transactions on Smart Grid 8(1) (2016) 391-399.
[8] S. Rönnberg, M. Bollen, Power quality issues in the electric power system of the future, The electricity journal 29(10) (2016) 49-61.
[9] T. Penthiya, A.K. Panda, S.K. Sarangi, M. Mangaraj, ANN controlled 4-leg VSC based DSTATCOM for power quality enhancement, 2015 Annual IEEE India Conference (INDICON), IEEE, 2015, pp. 1-6.
[10] W.U. Tareen, S. Mekhilef, M. Seyedmahmoudian, B. Horan, Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system, Renewable and Sustainable Energy Reviews 70 (2017) 635-655.
[11] J.T. Bialasiewicz, Renewable Energy Systems With Photovoltaic Power Generators: Operation and Modeling, IEEE Transactions on Industrial Electronics 55(7) (2008) 2752-2758.
[12] A. Gholami, M. Ameri, M. Zandi, R.G. Ghoachani, S. Esfahani, S. Pierfederici, Photovoltaic potential assessment and dust impacts on photovoltaic systems in Iran, IEEE Journal of Photovoltaics 10(3) (2020) 824-837.
[13] J.J. Justo, F. Mwasilu, J. Lee, J.-W. Jung, AC-microgrids versus DC-microgrids with distributed energy resources: A review, Renewable and sustainable energy reviews 24 (2013) 387-405.
[14] K.W. Kow, Y.W. Wong, R.K. Rajkumar, R.K. Rajkumar, A review on performance of artificial intelligence and conventional method in mitigating PV grid-tied related power quality events, Renewable and Sustainable Energy Reviews 56 (2016) 334-346.
[15] W. Ma, W. Wang, X. Wu, R. Hu, F. Tang, W. Zhang, X. Han, L. Ding, Optimal allocation of hybrid energy storage systems for smoothing photovoltaic power fluctuations considering the active power curtailment of photovoltaic, IEEE Access 7 (2019) 74787-74799.
[16] J.X. Jin, J. Wang, R.H. Yang, T.L. Zhang, S. Mu, Y.J. Fan, Y.Q. Xing, A superconducting magnetic energy storage with dual functions of active filtering and power fluctuation suppression for photovoltaic microgrid, Journal of Energy Storage 38 (2021) 102508.
[17] B.-K. Kang, S.-T. Kim, S.-H. Bae, J.-W. Park, Effect of a SMES in power distribution network with PV system and PBEVs, IEEE transactions on applied superconductivity 23(3) (2012) 5700104-5700104.
[18] S.M. Said, M.M. Aly, B. Hartmann, Application of SMES for voltage control of power systems with high wind power penetration, 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), IEEE, 2018, pp. 461-466.
[19] S. Said, M. Aly, B. Hartmann, A robust SMES control for enhancing stability of distribution systems
[10] F. Ozdogan, F. Ozdogan, M. Ozer, Application of superconducting magnetic energy storage unit for damping of subsynchronous oscillations in power systems, Energy conversion and management 40(1) (1999) 23-37.

[20] S. Chaine, M. Tripathy, Design of an optimal SMES for automatic generation control of two-area thermal power system using Cuckoo search algorithm, Journal of Electrical Systems and Information Technology 2(1) (2015) 1-13.

[21] E.A. Mohamed, Y. Mitani, Load frequency control enhancement of islanded micro-grid considering high wind power penetration using superconducting magnetic energy storage and optimal controller, Wind Engineering 43(6) (2019) 609-624.

[22] J. Devotta, M. Rabbani, S. Elangovan, Application of superconducting magnetic energy storage unit for damping of subsynchronous oscillations in power systems, Energy conversion and management 40(1) (1999) 23-37.

[23] B.R. Deemer, J.A. Harrison, S. Li, J.J. Beaulieu, T. DelSontro, N. Barros, J.F. Bezerra-Neto, S.M. Powers, M.A. Dos Santos, J.A. Vonk, Greenhouse gas emissions from reservoir water surfaces: a new global synthesis, BioScience 66(11) (2016) 949-964.

[24] R.J. Schmitt, N. Kittner, G.M. Kondolf, D.M. Kammen, Deploy diverse renewables to save tropical rivers, Nature Publishing Group, 2019.

[25] M.L. Thieme, D. Khrystenko, S. Qin, R.E. Golden Kroner, B. Lehner, S. Pack, K. Tockner, C. Zarfl, N. Shahbol, M.B. Mascia, Dams and protected areas: Quantifying the spatial and temporal extent of global dam construction within protected areas, Conservation Letters 13(4) (2020) e12719.