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Supercapacitors Energy Storage System for Power Quality Improvement: An Overview

Power quality problem causes a misoperation or failure of end user equipments. Distribution network, sensitive industrial loads and critical commercial operations suffer from outages and service interruptions which can cost financial losses to both utility and consumers. In India the use of electronic loads is increasing very fast and the gap between demand and the supply have made the reliability and power quality a critical issue. Further there is continuous thrust on optimal utilization of the non-conventional energy sources along with the central power station. In this paper a critical review have been presented chronologically various work to improve quality of power with the help of energy storage device i.e. Supercapacitors energy storage systems for ASD, elevators, UPS, and power distribution system, ride through capability, real power injection and reactive power injection for stabilization of the system.

Keywords: Power Distribution System, Supercapacitors Energy Storage System, Distributed Generation, Reliability, Power Quality, Equivalent Series Resistance and Equivalent Parallel Resistance.

1. Introduction

The first complete electric power system was built by the Thomas Edison in September 1882 in the New York city ;through the steam driven dc generator supplying at 110 Volt. Due to dc system and low voltage level; the losses in transmission line (I^2R) puts the limitation for the long distance transmission of the power. After development of the transformer and ac transmission system by L.Gaulard and J.D. Gibbs led to ac electric power system. In the year 1889, the first ac transmission line in North America was put in to operation in Oregon between Willamette falls and Portland. So the literature reveals that the power system was inherently of dispersed generation nature or decentralized generation i.e. distributed generation (DG) is no new concept [1].

Nowadays the power system is in a process of undergoing from regulated market to deregulated, centralized to more localized system that are situated to near the load; the reason behind the increased concern for environment, to utilize renewable energy technologies, flexibility , lower initial investment costs, lower time of project completion, electricity market liberalization, developments in DG technology, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity [2,3] .Further with the fast increase in electronic loads has made the quality of power supply a critical issue .Since the power distribution system must be able to supply the power reliably while maintaining the power quality through out the year; so there is strong need of energy storage capability with the central power utility and also the non conventional energy resource .

The reason behind overview of supercapacitors energy storage system is that supercapacitors are less weighty than that of battery of the same energy storage capacity, a

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fast access to the stored energy, Charging very fast than battery, Charge/discharge cycle is 10^6 time, storage capacity independent of number of charging/discharging cycles, energy density for Supercapacitor is 10 to 100 times larger than of traditional capacitors(typical 20-70 MJ/m^3), capacities up to 5F/cm^2, life cycles 25-30 years, high efficiency (95%),power density 10 times greater than batteries, Charge and discharge time very less, rated capacitance value ranging from 0.043-2700F,nominal voltage ranging from 2.3 to 400 V,rated current ranging from 3-600 A, operating temperature ranging -40°C to 85°C,Maintenance free, very low leakage current, also non polar [4, 5, 6, 7].

2. Power Quality Issues

a) Voltage flicker

DG may cause voltage flicker as a result of starting a machine or sudden change in the DG output which results in a significant voltage change on the feeder. In case of non dispatchable source, the output fluctuates.

The voltage flicker can be reduced by controlled voltage starting of Induction generators, tighter synchronization; Inverters are controlled to limit inrush currents and the change in output levels so that it must follow the IEEE standards 519-1992[8, 9, 10].

b) Voltage sags

The most common power quality problem is voltage sag; the DG may or may not help. However, the ability of DG to reduce sags is very dependent on the type of generation technology and interconnection location, during voltage sag, DG might act to counter sag. Large rotating machines can help support the voltage magnitudes and phase relationships. Although not a normal feature, Inverter-based distributed generators can be controlled to supply reactive power for voltage support during sag [8, 9, 10].

c) Sustained Interruptions

To improve the power system reliability and to provide backup power, incase of power interruption, or to cover for contingencies when part of delivery system is out of service. Unfortunately, with an uncontrolled-inverter and lack of storage capacity might not be capable of operating in stand-alone mode. When the DG is interconnected in parallel with the utility distribution system, some operating conflicts might arise that affect the system reliability. An example is the interference with utility relaying and reducing the devices reach. Therefore; DG has the potential to increase the number of interruptions in some cases [8, 9, 10].

d) Voltage regulation

Alternators are capable of providing active and reactive power and, hence, can be used to regulate the voltage in the distribution system to which they are interconnected. Initially it seems that DG should be able to improve the voltage regulation on the feeder. Some technologies are unsuitable for regulating voltages like simple induction machines, most utility interactive inverters that produce no reactive power. Also, the most utilities do not want the DG to attempt to regulate the voltage because that would interfere with utility voltage regulation equipment and increase the chances of supporting an island. Generators controls are much faster than conventional tap-changing transformer and switched capacitor banks larger DG greater than 30% of the feeder capacity that is set to regulate voltage will often require special communications and control to work properly with the utility voltage regulating equipments [8, 9, 10].

e) Harmonics

There are harmonics concerns with both rotating machines and inverters, although concern with inverters is less with modern technologies; based on IGBTs that use PWM technology and are capable of generating output that satisfy the IEEE standards(512-1992) for harmonics. Harmonics from rotating machines are not always negligible, particularly in grid parallel operation. The utility power system acts as a short circuit to zero-sequence triplen harmonics in the voltage, which can result in surprisingly high currents.

For grounded wye-wye or delta–wye service transformers, only synchronous machine with 2/3 pitch can be paralleled without special provisions to limit neutral current. For service transformer connections with a delta connected winding on the DG side, nearly any type of three-phase alternator can be paralleled without this harmonic problem [8, 9, 10, 11].

3. Super Capacitor Energy Storage (SCES)

Supercapacitor is a double layer capacitor; the energy is stored by charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is function of the available electrode and electrolyte surface, the size of the ions, and the level of the electrolyte decomposition voltage. Supercapacitors are constituted of two electrodes, a separator and an electrolyte. The two electrodes, made of activated carbon provide a high surface area part, defining so energy density of the component. On the electrodes, current collectors with a high conducting part assure the interface between the electrodes and the connections of the supercapacitor. The two electrodes are separated by a membrane, which allows the mobility of charged ions and forbids no electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other [5, 12].

Usually supercapacitors are divided into two types: double-layer capacitors and electrochemical capacitors. The former depends on the mechanism of double layers, which is result of the separation of charges at interface between the electrode surface of active carbon or carbon fiber and electrolytic solution. Its capacitance is proportional to the specific surface areas of electrode material. The latter depends on fast faraday redox reaction. The electrochemical capacitors include metal oxide supercapacitors and conductive polymer supercapacitors. They all make use of the high reversible redox reaction occurring on electrodes surface or inside them to produce the capacitance concerning with electrode potential. Capacitance of them depends mainly on the utilization of active material of electrode.

The working voltage of electrochemical capacitor is usually lower than 3 V. Based on high working voltage of electrolytic capacitor, the hybrid super-capacitor combines the anode of electrolytic capacitor with the cathode of electrochemical capacitor, so it has the best features with the high specific capacitance and high energy density of electrochemical capacitor. The capacitors can work at high voltage without connecting many cells in series. The most important parameters of a super capacitor include the capacitance(C), ESR and EPR (which is also called leakage resistance).Further some of available supercapacitor in market are shown in table.1 and cost trend is also shown in table. 2 [13, 14, 15].

Table.1 Available Supercapacitors in Market [16, 17, 18, 19, 20]

Sl.No.	Manufacturer	Specifications of Supercapacitors
1	Power Star China Make (single Unit)	50 F/2.7V, 300F/2.7V, 600F/2.7 V, ESR less than 1mΩ.
2	Panasonic Make (Single Unit)	0.022-70F, 2.1-5.5V, ESR 200 mΩ-350 Ω
3	Maxwell Make (Module)	63F/125V, 150A ESR 18 mΩ 94F/75 V, 50 A, ESR 15 mΩ
4	Vinatech Make	10-600F/2.3V, ESR 400 -20 mΩ, 3-350F/2.7, ESR 90-8 mΩ

5	Nesscap Make (module)	15V/33F, ESR 27 mΩ 340V/ 51F, ESR 19 mΩ

Table.2 Supercapacitor Cost Trend [21]

Sl.No.	Year	Cost /Farad ($)	Cost/kJ($)
1	1996	0.75	281.55
2	1998	0.40	151.23
3	2000	0.01	32
4	2002	0.023	7.51
5	2006	0.010	2.85
6	2010	0.005	1.28

4. Various Approaches for Power Quality Improvement by SCES

In 1996 Kazimierczuk and Cravens did the feasibility study for application of SCES in Aircraft Distributed Power Systems. In the experiment, under various operating conditions the **voltage regulation was improved for approximately 35 sec**, also provided emergency power at fix loads **as per military Standard MIL-STD-00704E(AS) [4].**

Barrade did the simulations & implemented experimentally to improve profile of **transportation station, elevators and backup power for UPS** and found the suitable [12].

Barrade and Rufer did the simulations & developed a **Val-Vert prototype system** based on SCES for voltage drop compensation for weak trolley busses sub-station distribution system and finds; voltage can be maintained with in standard limits. [22]

In 2001, Sels, Dragu, Craenenbroeck, and Belmans made a comprehensive study and predicted that flywheels and traditional batteries are best when there is need for emergency power for a very long time, while Supercapacitors can be used for **short duration** to improve the power quality. [6]

In 2002, Palma, Enjeti, and Aeloiza, made analytically a comprehensive work **to provide ride through** for ASD system with SCES & developed the compensator topology experimentally found that is capable of compensating voltage sags from zero to 99% for short voltage interruptions and maintained the dc link voltage constant during the transient period. Further, the simulations show the effectiveness of the proposed compensator and experimental results validated these results [7].

In 2004, Rufer, David and Barrade developed a prototype substation for **weak transportation network** to compensate voltage based on SCES and found it as alternative, promising and innovative results, also may prove economically competitive as the cost of Supercapacitors reduces [23].

In 2005 Zang did work on SCES to develop **PI control technique** for AC/DC-DC/AC power circuits for energy conversion in case of short duration and found that the reliability of the power supply and power quality are improved [24].

In 2006 Lu and Zhang did the simulations and experimental work for active-reactive power compensation based on SCES in distribution system in **the island mode, switching transients mode, grid connected mode** and found that the SCES system releases the stored energy to load and improved the reliability of power supply and power quality [25].

In 2006 Degobert, Kreuawan and Guillaud, worked; then simulation experimental result showed that by SCES system **undispatchable** power can be made dispatchable, fast fluctuations can be reduced in **stand alone** as well as **in grid connected mode** for hybrid system composed of a photovoltaic and micro turbine [26].

In 2006 Zhongdong, Minxiao, Yunlong and Zheran did Simulations and experimental work for Adjustable Speed Drive System based on SCES of 15 KVA the results shows that during **short term outage** ASD are able to keep normal operation and the effects caused by power quality problems are considerably eliminated. [27]

In 2006 Cheng, Mierlo, Bossche and Lataire, developed control principle using **dynamic voltage restorer** for the power quality improvement in distributed power generation based on SCES, and found that DVR can be applied to compensate the voltage fluctuations in the AC grid due to inconstant power injections from distributed power generation systems for short time duration (400msec) and stand alone mode. [28]

In 2006 Chong Han; Huang, A.Q.; Ding Li; Mamath, H.; Ingram, M.; Atcitty, S.; **modeled and designed transmission ultracapacitors with modular voltage source converter with SCES** for to provide ride through capacity, enhance power quality and improve utility reliability of the system. [29]

In 2007 Abbey and Joos **complemented wind energy with the SCES system to reinforce the dc bus** during transients, thereby enhanced low voltage ride through (LVRT) capability [30].

In 2008 Srithorn, P.; Sumner, M.; Liangzhong Yao; Parashar, R.; incorporated SCES with **STATCOM to deliver the real power to the grid for improving the stability margin** of the power system [31].

In 2008 Srithorn, P.; Sumner, M.; Liangzhong Yao; Parashar, R.; incorporated SCES with STATCOM **to deliver the real power and reactive power to system to improve the system stability** margin [32].

In 2008 Xiao Li; Changsheng Hu; Changjin Liu; Dehong Xu; incorporated SCES to aggregately control **for smoothing medium frequency wind power fluctuations and maintaining** Wind farm terminal voltage [33].

In 2009 Kuldeep Sahay, Bharti Dwivedi; did the **simulation using SCES for Energy Stabilization of distribution system** [34].

5. Importance of Proper Design of SCES and Future Scope of Work

The utmost requirement of proper design and implementation of SCES is maintaining the reliability of the power distribution system in the grid connected mode, the switching transient mode, the island mode. This is also important in various analyses such as sustained interruptions, voltage flicker, voltage sags, harmonics, voltage regulation, voltage stability. There are other different aspects related to power distribution system where the storage study is essential, some are listed as follows.

1. Calculation of load schedule,
2. Optimal use of non-conventional energy sources,
3. Dispatchability of Power,
4. Ride trough capability of Supply
5. Reduced insulation,
6. Transformer connections and ground faults,
7. Design of system elements: transformer, feeders,

The review presented in this paper explains the efforts made with various features of the Storage technologies, various approaches to improve the power quality of the ASD system, Aircraft system, Transportation system, Elevators, UPS and Design of Converter control system; based on SCES. There are still vast scopes of work, particularly in the power deficient countries like India, where scheduled and unscheduled power outages takes place, also the power quality of the supply is poor; some are as follows.

1. The optimal placement of SCES.
2. The optimal utilization of the non-conventional Sources along with SCES.

3. Reactive power planning with SCES.
4. Dynamic stability improvement.
5. Transient stability improvement.
6. Transmission capacity improvement.

6. Conclusions

Through a critical survey of the literature for the energy storage system especially for the Supercapacitors energy storage system for improvement of power quality of the different systems; an overview has been presented. Various aspects of the problem, such as to provide ride through, stabilization of power system, to make undispatchable power into dispatchable, to improve power quality of weak transportation system, of aircraft distribution system UPS, elevator and PDS adopting PI control technique, dynamic voltage restorer in the island mode, switching transients mode, grid connected mode, in stand alone for the short term outage. Therefore it would prove a good energy storage option and power quality maintenance purpose with power conditioning system as the cost falls down being the life and its efficiency is very high.

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