DC Energy Storage Schemes for DVR Voltage Sag Mitigation System

H.P. Tiwari and Sunil Kumar Gupta

***Abstract*—The Dynamic Voltage Restorer (DVR) is series-connected power electronics based device. It provides technically advanced and economic solution to compensate voltage sag in both transmission and distribution systems. DVR output is determined according to the degree of disturbance in supply voltages. Sag compensation is achieved by injecting the required power into the line through DVR injection transformer. A variety of energy storage devices are used in DVR power circuit for supplying the input to inverter. In this paper, various energy storage devices which are generally used with the DVR power circuit are discussed in detail. Based on the comparative study suitable energy storage devices are suggested for a DVR system.**

Index Terms*—*DVR, Energy Storage Device, Voltage Disturbance.

I. Introduction

Power quality issues are divided into two categories voltage quality and frequency quality. Voltage quality issues are related with voltage sag, voltage swell, under voltage and over voltage while frequency quality issues are related with harmonics and transients. One of the most imperative power quality issues is voltage sag which is occur due to its usage of voltage sensitive devices. It has made industrials processes more susceptible to supply voltage sags [1]. Voltage sag and swell can be defined [2] as given in the following Table 1.

TABLE 1

Type of Disturbance	Voltage	Duration
Voltage Sag	0.1-0.9 p.u.	0.5-30 cycles
Voltage Swell	1.1-1.8 p.u	0.5-30 cycles

Voltage sags are caused by abrupt increases in loads such as short circuits or faults, motors starting, or electric heaters turning on or they are caused by abrupt increases in source impedance, typically caused by a loose connection [3]. Voltage sag mitigation devices are classified into three categories; (i) Traditional Solutions (ii) Uninterruptible Power Supplies (UPS) (iii) Dynamic Voltage Restorer (DVR). It comes under the category of custom power supply. The basic operating principle of the DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever voltage sag or voltage swell is detected [4]. It is used to protect sensitive user loads.

This paper is organized into VI sections. The DVR structure is presented in section II. Classification of energy storage devices is explained in section III. Detailed studies of energy storage devices are presented in section IV. Comparison of various energy storage technologies is discussed in section V and section VI presents the conclusion.

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II. DVR Structure

A basic structure for a DVR is shown in Fig.1.

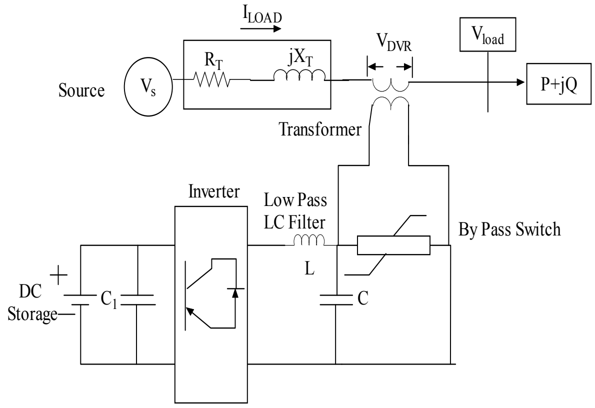

Fig.1. Basic Structure of Dynamic Voltage Restorer

The DVR device consists of five main sections; (i) Energy Storage Unit: It is responsible for energy storage in DC form. Flywheels, lead acid batteries, Superconducting Magnetic Energy Storage (SMES) and Super-Capacitors can be used as energy storage devices, the estimates of the typical energy efficiency of four energy storage technologies are: batteries – 75 %, Fly wheel – 80 %, Compressed air – 80%, SMES – 90% [5]. (ii) Inverter: It is used to convert DC power to AC power [6]. (iii) Passive Filters: It is clear that higher order harmonic components distort the compensated output voltage. Filter is used to convert the PWM inverted pulse waveform into a sinusoidal waveform. This is achieved by removing the unnecessary higher order harmonic components generated from the DC to AC conversion in the VSI. (iv) By-Pass Switch: This switch is used to protect the inverter from high currents. In case of a fault or a short circuit on downstream, the DVR changes into the bypass condition where the VSI inverter is protected against over current flowing through the power semiconductor switches [7]. (v) Voltage Injection Transformers: In a three-phase system, three Single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose [8].

III. ENERGY STORAGE UNITS

All the energy storage devices are classified into two categories direct energy storage and indirect energy storage as shown in Fig.2 [9].

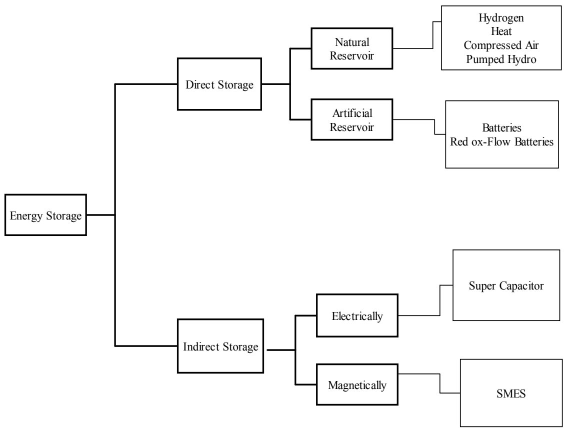

Fig.2. Classification of Energy Storage Devices

Electrical energy storage devices come under indirect energy storage categories. The stored energy is reconverted back to electrical energy, when a supply of electrical energy is required, it is difficult to store and reconvert large amount of energy. Various energy storage devices are presently used for voltage sag compensation in the DVR system. Electrical energy storage devices are super capacitor, superconducting magnetic energy storage (SMES) etc. Flywheel energy storage is used as a mechanical energy storage system. In the advance development fuel cell conservation technique is used in place of dc energy storage system.

Energy storage devices are divided into three categories:
(i) Small categories (<10MW): Flywheels batteries, capacitors, ultra capacitors (combined with DG devices) are comes in small categories.
(ii) Medium categories (10MW < energy < 100 MW): Large-scale batteries, lead-acid, NAS and Va Red ox are come in medium categories.
(iii) Large categories (≥ 100 MW). Pumped storage, compressed air energy storage (CAES) are comes in large categories.
Technical capability of energy storage devices is shown Fig.3.

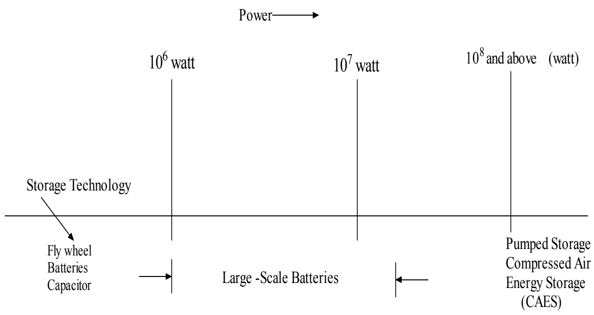

Fig.3. Technical Capability of Energy Storage devices [10]

Energy storages devices are two types' energy management devices and power quality storage devices [10]. Energy management devices such as ; pumped hydro, CAES, high temp batteries, flow batteries and H2 storage. Power quality storage devices such are super capacitors, SMES, flywheels and batteries.

Efficiency of storage devices is given by equation(1).

$$\eta = \frac{\text{Total output of electrical energy}}{\text{Total input of electrical energy}} \tag{1}$$

Generally η is varies from 30% to 95%.

Table.2. shows the applications of energy storage w.r.t to their storage capacity and discharging time period.

TABLE 2: APPLICATION OF ENERGY STORAGE

Application	Stored Capacity	Discharge Period
Power Grid Leveling	11 MJ-201 GJ	Few Sec. - Few Days
Power Quality	0.11-11 MJ	Few Sec.
Custom Devices	0.11-11 MJ	Few Cycle

It is shows that the power quality application shows discharging time period in few second and storage capacity 0.11-11MJ.

IV. DETAILED STUDIES OF ENERGY STORAGE DEVICES

(a) Pumped Hydro: Pumped hydro storage is a simple technology already in wide use. It has two large reservoirs, one is situated at the base level and the other is located at a different elevation. Water is pumped to the upper reservoir, where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines which generate electrical power as high as 100-1100 MW. This technique has various disadvantages like it includes high capital costs and long construction times as well as the geographic, geologic and environmental constraints associated with reservoir designing [11-13].

(b) Compressed Air Energy Storage (CAES): This type of storage use excess power to compress air and store this air in a cavern or former mine. Upon demand, stored air is released from the cavern, heated and stretched out through a combustion turbine to create electrical energy [13-14]

(c) Superconducting Magnetic Energy Storage (SMES): SMES is stores energy in the magnetic field developed due to the flow of direct current in a coil of superconducting material cooled below its critical temperature. Stored energy can be released by discharging the coil whenever required. To maintain the coil in its superconducting state, it is immersed in liquid helium pervasive in a vacuum-insulated cryostat [15]. Block diagram representation of SMES system is shown in Fig.4.

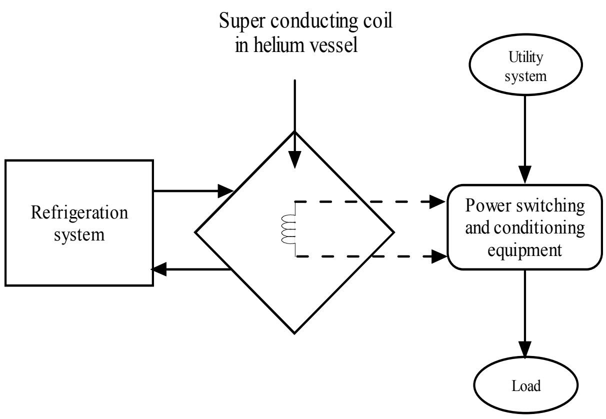

Fig.4. SMES Scheme

The energy stored in the coil is given by equation (2)

$$E = (0.5)\, LI^2 \qquad (2)$$

Where;
E is Energy stored in (W.s)
L is Inductance of coil (H)
I is DC current flow through coils (A)

(d) Flywheels: It is an inertial energy storage device that couples a motor generator with a rotating mass to store energy for short durations. Concept of rotational energy is used in the Flywheel energy storage. It stores the energy by using the rotor to a very high speed. The energy is converted back by slowing down the flywheel in it. Flywheels are charged and discharged via a combined motor/generator [13]. The combined set draws power provided by the grid to spin the rotor of the flywheel. During voltage sag condition or other power quality problems the motor/generator set provides power. The stored energy in the form of kinetic energy. In the rotor it is transformed to DC electric energy by the generator. The energy is delivered at a constant frequency and voltage through an inverter. Flywheel rotors are usually constructed of speeds up to 21,000 to over 48,000 rpm. It is used to achieve very high power densities. Flywheels provide 1-25 seconds of ride-through time, and back-up generators are typically online within 5-25 seconds stored energy is proportional to the flywheel's mass and the square of its rotational speed [19]. The energy stored in a flywheel given by the equation (3).

$$E = \tfrac{1}{2} I\omega 2 \qquad (3)$$

Where I is the moment of inertia of the flywheel and ω is its rotational velocity (radians/second).

The moment of inertia is given by equation

$$I = kMr\ 2 \qquad (4)$$

Where M is the mass of the flywheel, r is its radius and k is its inertial constant. k = 1 and k = ½ depends on the shape of the rotating object. The longer life, simpler maintenance, and slighter footprint of the flywheel systems are the advantage of flywheel [20].

(e) Batteries: Batteries are electrochemical devices which converts chemical energy into electrical energy during discharge time. It is classified as secondary storage devices. Their operating conditions depend upon charging and discharging cycle. The first commercially available battery was the flooded lead-acid battery while the valve-regulated lead-acid (VRLA) battery is the latest development. It has low-maintenance, spill- and leak-proof [13] and it is relatively compact. Batteries are constructed in a wide variety of capacities ranging from less than few watts to several megawatts.

(f) Capacitors: Capacitor has two oppositely charged electrodes, separator electrolyte and current collectors. Capacitors have been used to store energy and supply short pulses of high power (Galileo and Cassini). The most important advantage of capacitor is the capability to supply high current pulses repeatedly for hundreds of thousands of cycles. The batteries provide power only during the longer interruptions, reducing the cycling duty on the battery. Small super capacitors are commercially available to extend battery life in electronic equipment, but large super capacitors are still in development, the energy stored is related to the charge at each interface, q (Coulombs), and potential difference V (Volts), between the two electrodes. The energy E (Joules) is given by the equations [21].

$$E = 0.5\, q\, V \qquad (5)$$

$$E = 0.5\, CV^2 \qquad (6)$$

Table.3 represents the comparison between batteries and capacitors w.r.t. their energy density, power density, cycle life and discharge time.

TABLE 3. COMPARISON BETWEEN CAPACITOR AND BATTERY

Device	Energy Density Wh/L	Power Density W/L	Cycle Life Cycles	Discharge Time Seconds
Batteries	50-255	155	$1 - 10^3$	> 999
Capacitors	0.04 - 5	$10^5 - 10^8$	$10^5 - 10^6$	<1.01

(g) Fuel Cell: Fuel cells are renewable energy sources. It is an electrochemical conversion device. It transforms the chemical energy into continuous electrical energy. Fuel from the anode side and an oxidant from the cathode side combined in the presence of electrolyte and generate electricity. It consumes reactant, which must be replenished.

Fuel cells are stable and so many combinations of fuel and oxidant are possible. For example in hydrogen type cell hydrogen, hydrocarbons and alcohols are used as fuel and oxygen, air, chlorine are used as an oxidant.the regenerative fuel cell converts electrical energy into chemical potential energy by charging two liquid electrolyte solutions. It is reconverted back to electrical energy on discharge. It is a reversible electrochemical process in between two salt solutions. The fuel cell has discontinuous conduction performance advantage as well as cost of raw material in fuel cells is very low [27- 29].

V. Comparison of Various Energy Storage Technologies

Various storage technologies are compared with power rating versus discharging time as shown Fig.5. SMES and Low speed flywheel have a very short duration discharging time in few seconds. Lead acid batteries have discharging time in minutes. Flow batteries, NAS, CASE, and PHS have in discharging time in hours. Compression in between depth of discharging and time versus Efficiency is discussed in Fig.6. Lead acid batteries, flow batteries, CASE, PHS are having efficiency below 80%. Flywheel and SMES both have efficiency above 90%. Different Energy Storage system; Lead acid, VRB and Flywheel three energy storage systems are compared in Table 4. Comparison shows with respect to different Characteristic: energy density, power density, efficiency, service life, system packaging and charge control. Flywheel system is suggested for longer life and high efficiency devices. Table 5 shows a comparison between status of various storage technologies with respect to their efficiency, energy density, power density and sizes [16] - [18].

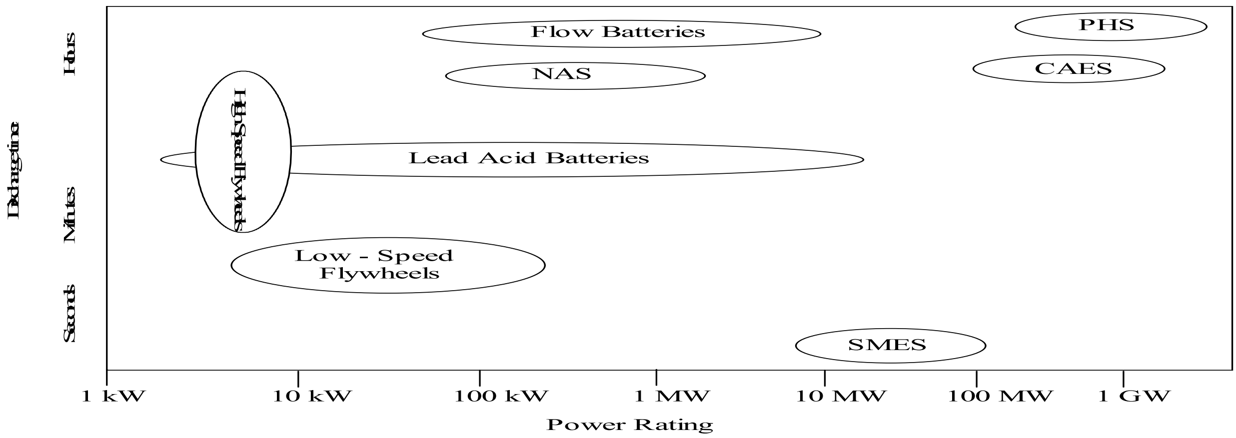

Fig.5. Power Rating versus Discharging Time [24]

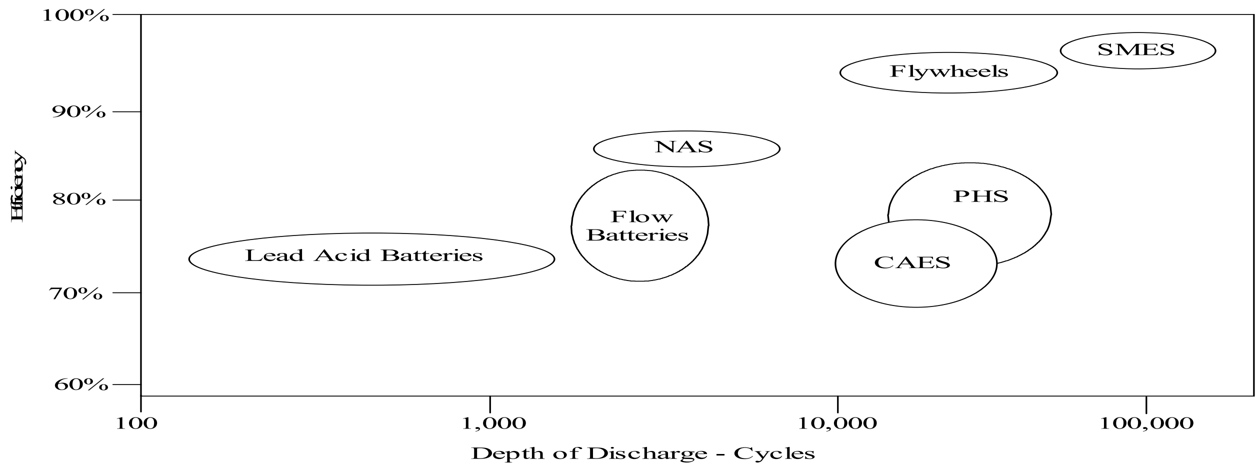

Fig.6. Depth of Discharging Time versus Efficiency [24]

TABLE 4: ENERGY STORAGE SYSTEM CHARACTERISTIC

Characteristic	Lead-acid	VRB	Flywheel
Storage Type	Chemical	Chemical	Mechanical
Energy Density Wh/lWh/kg	-	-	300
Power Density W/lW/kg	250	-	1500
Efficiency (%)Overall System	75-80	85	95
Service Life *(At Best)*	< 8 Years	5 - 10+ Years	20+ Years
System Packaging	Unitary	Modular	Modular
Charge Control	Separate	Integrated	Integrated

TABLE 5. SHOWS A COMPARISON BETWEEN VARIOUS STORAGE TECHNOLOGIES [9]

S. No.	Technology	Efficiency %	Energy Density [W-h/kg]	Power Density [kW/kg]	Sizes [MW-h]
1.	Pumped hydro	75	.27/100 m	Low	5000-20000
2.	Compressed gas	70	0	Low	250-2200
3.	SMES	90 +	0	high	20 MW
4.	Batteries	74-84	30-50	0.2-0.4	17- 40
5.	Flywheels	90 +	15-30	1-3	0.1-20 kwh
6.	Ultra capacitors	90 +	2-10	high	0.1-0.5 kwh
7.	Fuel cell	<70	300-600	1.06-2.50	250 mwh

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VI. CONCLUSIONS

In this paper, different storage devices are discussed and a comparison is made based on the percentage Efficiency, Energy density [W-h/kg], Power density [kW/kg], Sizes [MW-h]. On basis of comparison it is suggested that SMES, Flywheels and Ultra Capacitors seems to be better for storage requirements in DVR systems for achieving efficiency over 90%.

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