ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 8, August 2013

HYBRID DSTATCOM BASED ON SUPERCAPACITORS & BATTERIES FOR PERFORMANCE IMPROVEMENT OF DISTRIBUTION NETWORK

Dr.Kuldeep Sahay

Professor, Dept. of EE, Institute of Engineering & Technology, Lucknow, Uttar Pradesh, India

ABSTRACT: Internationally the demand of energy is going up day by day, which is causing the gap between demand and the generation to be high. Further Single-phase loads on a three-phase supply system result in an unbalance in the system voltage and supply current leading to Voltage sags/swells in the network. DSTATCOM is a custom power device that is used to regulate the voltage sags/swells in the distribution system for maintaining the rated voltage level at the terminal of load/sensitive loads. The DSTATCOM can inject three-phase voltages at point of common coupling whose magnitude and phase angle can be regulated with PI controller, while the supercapacitors are used to meet the instantaneous power demand since they can store and quickly release significant amounts of energy, while the batteries are used to supply average power demand. This research paper explores combination of batteries and supercapacitors storage system in DSTATCOM for control of load terminal voltage and regulation of SCESS/BESS voltage/energy storage capability, the enhancement in the power quality and reliability.

Keywords: Hybrid Distribution Static Compensators (H-DSTATCOM), Supercapacitors Energy Storage System (SCESS), Battery Energy Storage System, Voltage Sags, Voltage Swells.

I.INTRODUCTION

DSTATCOM are used in the distribution system for improvement of power quality issues. The voltage sags/swells have become the main cause of equipment malfunctioning, tripping in the industries due unbalance between the power supply and demand. DSTATCOM, however, are limited in their ability to improve system performance due to limited capability of delivering quick/instantaneous real power. From the last decade, there have been considerable developments and improvements in energy storage technologies for example, SMES, Flywheel, Fuel Cells and in the battery technologies .On the contrary, these technologies have some limitations, SMES require a lot of space, high shielding for its magnetic effect and complex auxiliary system, fuel cells quite slow initial response and limited number of charge/discharge cycle [1, 2, 3, 4].

By and large, batteries have relatively high energy density, low power density, slow dynamic characteristic. If batteries are cycled at very high current rates then batteries life detoriates very fast in case of full discharge and also may lead to safety problem due to thermal runaway. Therefore, the battery packs have to be oversized to ensure life and to avoid thermal runaway [5].

The recent development of Supercapacitors has given new dimensions in the field of energy storage technologies, which can store a very large amount of energy and can release large amount of instantaneous power/energy in the regulated manner with the help of custom power devices, independent of number of charge and discharge cycle, very high efficiency, life about 20-25 years and charge and discharge times are fractions of a second to several minutes [6, 7].

Due to higher specific power density and fast dynamic characteristics, the supercapacitors have been considered for transient power supply and recovery in the distribution network. Combination of supercapacitors and batteries energy storage system therefore in the DSTATCOM reduce the strain on the batteries simultaneously supercapacitors have capability of absorbing and supplying the large current pulses and battery can provide the average power demand. This in turn allows the DSTATCOM provide real power and reactive power in to distribution network via the inverter.

Therefore the DSTATCOM based on SCESS/BESS would inject an appropriate voltage magnitude with appropriate phase angle in shunt to the distribution system, when the voltage sag occurs; the voltage injection is achieved through the injection of real and reactive power.
The aim of this research is to investigate how the supercapacitors based energy storage technology can be used to enhance power quality of distribution system by means of precise & fast regulation of voltage sags/swells and control of SCESS/BESS voltage level.

II. BATTERIES AND SUPERCAPACITORS CHARACTERISTICS

For the DSTATCOM, the main energy required to improve the performance of the distribution network in steady state conditions must be storage in batteries since batteries do not posses instantaneous charge and discharge capabilities. Supercapacitors are being used to store the energy so that it can supply power when there is transient changes takes place in distribution network as it have very fast charge and discharge capabilities. Batteries have a high energy density, while supercapacitors store small amount of energy but have a very high power density. These properties allow the arrangement of these two energy storage devices to exhibit both high power and high energy density. As the supercapacitors ESR is an order of 10 mΩ therefore supercapacitors can supply very large currents to the load. The normalized voltage swing (U_{min} /U_{max}) at open circuit for batteries is higher than 0.85.While the supercapacitors voltage swing is 0.5 and is limited by the electronics which do not allow the supercapacitors depth of discharge to go above 75%.The specifications of the supercapacitors and batteries are given respectively in Table I and Table II.

Table I

125 V Supercapacitors Module Specifications [10]

Parameter	Value
Nominal Capacitance	63 F
Rated voltage	125 V
ESR	18 mΩ
Operating temperature range	-40°C to +65°C
P_{max}	4,700W/kg
E_{max}	2.53Wh/kg
Cycles	1,00,000
Lifespan	1,00,000 hours
Maximum continuous current	150 A
Maximum peak current(1 sec)	750 A
Leakage current	5.2 mA

Table II

Specifications of the Batteries [8, 9]

Parameter	Ni-MH	Ni-Cd	Li-Ion	Lead Acid
Energy Density(Wh/Kg)	60-120	45-80	90-150	30-50
ESR(mΩ)	200-300	100-200	100-130	<100
Fast Charge Time (h)	2-4	0.25-1	1-2	8-16
Life cycle	300-500	1500	300-500	200-300
Self Discharge (%/Month)	20-30	15-20	5-10	4-6

III. CONSTRAINTS AND OBJECTIVE OF THE CONTROL STRATEGY OF SCESS

The purpose of connecting the SCESS in the power system for smoothing the power fluctuation via charging and discharging the real power which may be due to peak demand, transient fault and other reasons. Another application is voltage management across the load terminal. The supercapacitors voltage U_{sc} will drop to 0 V if all the stored energy

is utilized then the constraint rated power output capability would be violated i.e. $P_{stored} \geq P_{rated.}$ Therefore a lower limit is fixed on the supercapacitors voltage U_{min}, is 50 % of U_{max}, so that 75 % of stored energy can be utilized efficiently.
The supercapacitors are charged to reference voltage $U_{scref.}$, after being installed. As the SCESS is used for stabilization of distribution system power fluctuation so both the charging and discharging allowance should be considered [11]. Thus, voltage of supercapacitors should be charged to an optimized value $U_{scref.}$, which is expressed as following:

$$\frac{C_{eq}\,U_{max}^2}{2} - \frac{C_{eq}\,U_{scref\,.}^2}{2} = \frac{C_{eq}\,U_{scref\,.}^2}{2} - \frac{C_{eq}\,U_{min}^2}{2} \qquad (1)$$

Where
C_{eq} is equivalent capacitance of supercapacitors bank in Farad.
U_{max} is maximum voltage of the supercapacitors bank in Volts.
U_{min} is minimum voltage of the supercapacitors bank in Volts.
U_{scref} is optimized value of the voltage for charging and discharging in Volts.
The optimized value is expressed as the following:

$$U_{scref} = \sqrt{U_{max}^2 + U_{min}^2 /_2} \qquad (2)$$

IV. DESIGN OF SUPERCAPACITORS ENERGY STORAGE SYSTEM

The purpose of SCESS is stabilization of voltage across the load terminal, since the voltage of supercapacitors cell is low therefore the supercapacitors bank would consist of number of supercapacitors cells in series and parallel so that the required voltage level and sufficient useful energy can be stored.
In general, the number of series connected cells N_s in one branch are imposed by the rating of supercapacitors cells maximum voltage available in the market or in the stack.

$$N_s = U_{max} / U_{cell} \qquad (3)$$

Where,
N_s are number of cell connected in series.
U_{max} is maximum voltage of the supercapacitors bank.
U_{cell} is rating of supercapacitors cell.
The number of parallel branch N_p in the supercapacitors bank can be found by

$$N_p = N_s C_{eq} / C_{cell} \qquad (4)$$

To have sufficient energy storage capacity number of parallel branches must be more than or equal to the one ($N_p \geq 1$) and rounded upward side to nearest integer.
The equivalent capacitance of the supercapacitors bank is represented by the following formula

$$C_{eq} = (N_p \times C_{cell}) / N_s \qquad (5)$$

Where,
C_{eq} is equivalent capacitance of supercapacitors bank in Farad.
C_{cell} is capacitance of each cell in Farad.
N_s are number of cell connected in series.
N_p is number of parallel arms in supercapacitors bank.
From equation (5) it is clear that to have net higher equivalent capacitance of the bank, number of the parallel arms (N_p) should be always higher than N_s ,in that way higher energy storage capacity.
Total numbers of cell in Supercapacitors bank would be

$$N_T = N_s \times N_p \qquad (6)$$

Where,
N_T is total number of cells required in supercapacitors bank.

But when the supercapacitors works at minimum voltage point, rated power output capability is still required, so

$$N_T \times U_{min}^2 / 4R_{eq} \geq P_{scess} \qquad (7)$$

V_{min} limitation under power request is expressed as

$$U_{min} \geq 2\{\sqrt{(R_{eq} P_{sces} / N_T)}\} \qquad (8)$$

The appropriately designed SCESS should consider both the power demand and energy capacity and the overall efficiency of SCESS, therefore the useful energy stored in the SCESS is expressed by (9) while keeping the voltage constraints $U_{min}<U<U_{max}$

$$E_u = \eta_s C_{eq} (U_{max} - U_{min})^2 / 2 \qquad (9)$$

Where,
η_s efficiency of supercapacitor bank[12].

The proposed supercapacitors energy storage system is designed to have storage of 20 kWh (72 MJ) of energy, 220 V voltage and peak power of 10 kW connected to distribution system to supply the load in case of voltage variation and additional power demand. The supercapacitors used are of Maxwell Technology make having product specifications, Nominal capacitance 63 F, Rated voltage 125 V,ESR 18 mΩ ,Operating temperature range -40°C to +65°C, P_{max} 4,700W/kg, E_{max} 2.53Wh/kg ,Cycles 1,00,000, Lifespan 1,00,000 hours, Maximum continuous current 150 A, Maximum peak current(1 sec) 750 A, Leakage current 5.2 mA .Then the SCESS designed would be following as shown in Table III:

Table III

SCESS Configuration

Item	Symbol	Value
Maximum supercapacitors Voltage	U_{max}	508 V
Minimum supercapacitors Voltage	U_{min}	254 V
Optimized Supercapacitors Voltage	$U_{scref.}$	402 V
Equivalent capacitance of SCESS	C_{eq}	558 F
Number of units connected in series	N_s	5
Number of parallel arms in SCESS	N_p	45
Total number of units required in supercapacitors bank	N_T	225
Equivalent series resistance of SCESS	R_{eq}	2×10^{-03} Ω
Current flowing through SCESS at 508 V	I_{min}	19.70 A
Current flowing through SCESS at 254 V	I_{max}	39.40 A
Power loss in the SCESS at 508 V	$P_{loss-508}$	0.775 W
Power loss in the SCESS at 254 V	$P_{loss-254}$	3.10 W

V. SIMULINK MODELING OF THE HYBRID DSTATCOM AND ITS CONTROL

A DSTATCOM which consists of a two level voltage source converter as inverter, supercapacitors bank as energy storage device, battery as energy storage device, a three phase coupling transformer connected in shunt to the distribution network .The voltage source converter converts the dc voltage of the supercapacitors bank/battery bank into sets of three phase ac voltages as output. These voltages are in phase and coupled with the distribution system through reactance of the coupling transformer .The proper adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of the active and reactive power exchanges between the DSTATCOM and the distribution network [13, 14, 15].
The VSC connected in shunt with the distribution network can be used for voltage regulation and compensation of reactive power, power factor correction and elimination of harmonics. The continuous voltage regulation of the

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 8, August 2013

distribution network is performed by injecting the shunt current for elimination of the voltage sag across the system impedance. The value of current can be controlled by adjusting the output voltage of the converter. The efficacy of the DSTATCOM in correcting voltage sag depends on the value of equivalent thevenin impedance of the system or the fault level of the load bus. When the shunt injected current is in quadrature with the load terminal voltage, the desired voltage correction can be achieved without injection of the active power into the distribution network. On the other hand, when the value of shunt current is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system.

VI.DEVELOPMENT OF THE TEST SYSTEM

Fig. I shows the test system used to carry out the various Hybrid DSTATCOM simulations in MATLAB/Sim-Power SIMULINK. The test system comprises of a 33 kV,50Hz transmission system-section of 25 km long and T-section of 2 km long, feeding into the primary side of 2-winding transformer connected in Y/Δ,33kV/440V,100MVA the load is connected to 440 V, secondary side of the transformer.

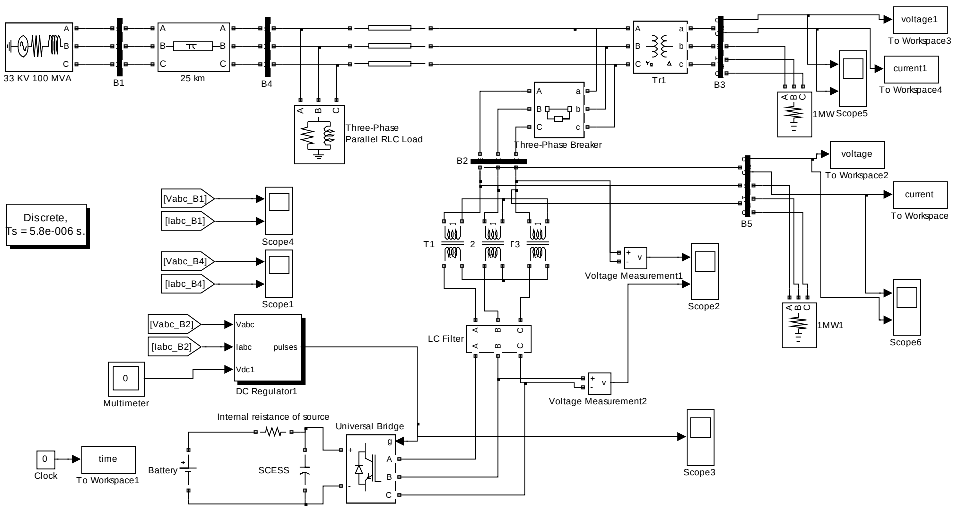

Fig. I Developed Test system for Hybrid DSTATCOM.

The DC voltage is applied to IGBT/Diode's of two-level inverter generating 50 Hz. The IGBT of the inverter uses pulse width modulation at 1680 Hz carrier frequency, discretized sample time of $5.8e^{-6}$ sec. The load voltage is regulated at 1 pu by PI voltage regulators of dc regulator, the input of DC regulator are voltage of PCC, current of PCC, SCESS voltage and the output is a vector containing the three modulating signals used by the discrete pulse width modulation generator to generate the 6 IGBT pulses. The harmonics generated by the inverter are filtered by LC filter. The three coupling transformer of 440V/33 kV, 100MVA are used to connect the DSTATCOM to the distribution network. A SCESS of 558 F and BESS of 508 V are connected on the dc side to provide the energy/real power. The effectiveness of this arrangement in voltage regulation can be seen on simulating the test system with and without SCESS/BESS.

VII. SIMULATION AND RESULT ANALYSIS OF HYBRID DSTATCOM

CASE: I SIMULATION RESULTS WHEN SUPERCAPACITORS ARE NOT CHARGED

The first simulation was performed when the hybrid DSTATCOM's supercapacitors was not charged and the main supply to load is switched off by the three phase circuit breaker for period of 0.2-0.3 second, during this period the voltage across the load approaches to zero and current through the load also becomes zero as shown in the Fig. II and Fig. III.

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 8, August 2013

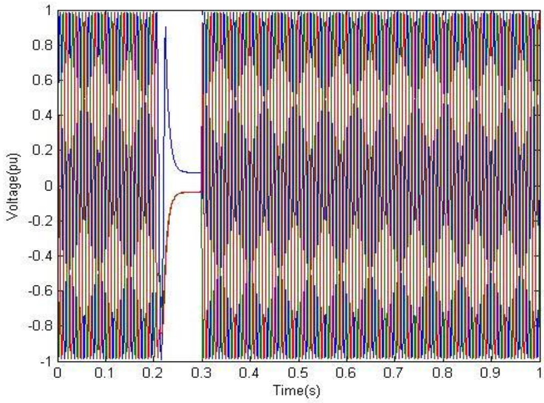

Fig. II Voltage across the load when supercapacitors are not charged

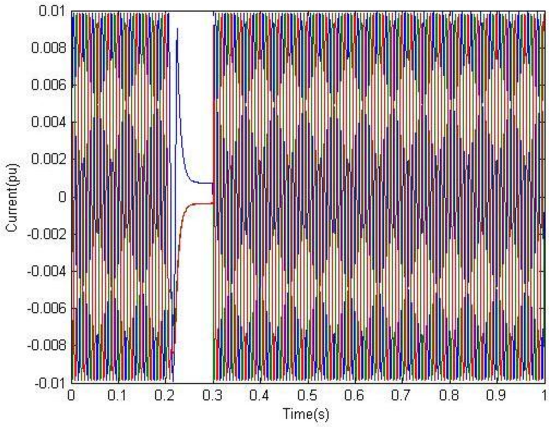

Fig. III Current through the load when supercapacitors are not charged.

CASE: II SIMULATION RESULTS WHEN BATTERIES ARE NOT SUPPORTING THE HYBRID DSTATCOM

Similarly, a new set of simulations was carried out but the now in the hybrid DSTATCOM, the batteries are not supporting and a transient load was switched in test system though the supercapacitors energy storage are able to supply power to load but the amplitude of voltage is near about 0.9 pu of required value for the duration 0.2-0.3 sec in which main line supply was also cut-off with the help of three phase circuit breaker. The voltage and current waveforms are shown respectively in Fig. IV and Fig. V.

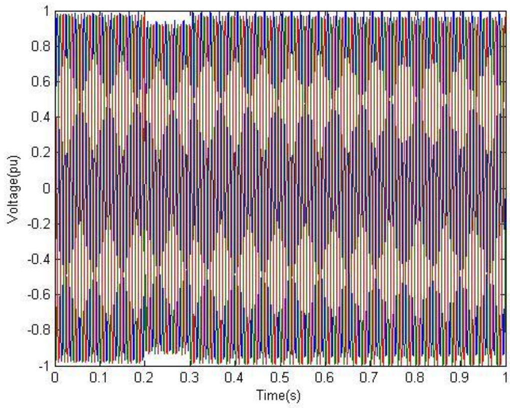

Fig. IV Voltage across the load when batteries are not supporting the Hybrid DSTATCOM.

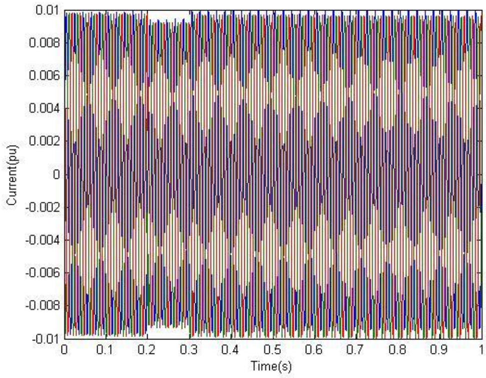

Fig. V Current through the load when batteries are not supporting the Hybrid DSTATCOM.

CASE: III SIMULATION RESULTS WHEN SUPERCAPACITORS ARE CHARGED BELOW U_{MIN}.

Similarly, a new set of simulations was carried out but the now hybrid DSTATCOM supercapacitors had discharged below the U_{min} level, while the three-phase circuit breaker for duration 0.2-0.3 sec in which main line supply was cut-off, but now the voltage across the load in phases is able to maintain but for the third phase hybrid DSTATCOM was not able to supply the power properly as required. The voltage and current waveforms are shown respectively in Fig.VI and Fig.VII.

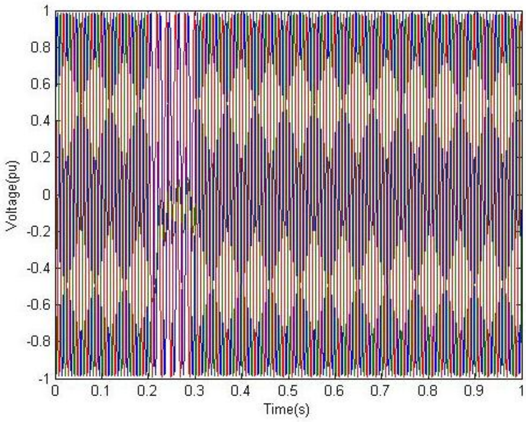

Fig.VI Voltage across the load when supercapacitors are charged below $U_{min.}$

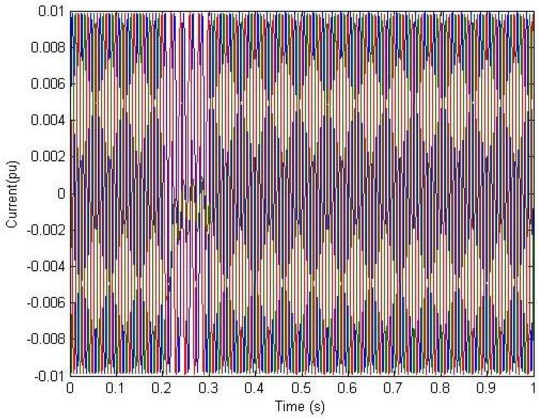

Fig.VII Current through the load when supercapacitors are charged below U_{min}

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 8, August 2013

CASE: IV SIMULATION RESULTS WHEN BOTH SUPERCAPACITORS AND BATTERIES ARE SUPPORTING THE HYBRID DSTATCOM

Similarly, a new set of simulations was carried out but the now in the hybrid DSTATCOM the both supercapacitors and batteries are supporting apart from the steady load, transient load was switched in test system for the duration 0.2-0.3 sec in which main line supply was also cutoff with the help of three phase circuit breaker. The hybrid DSTATCOM is quite efficient to support the load without any unbalance in phase and having no harmonics also able to maintain its amplitude of 1.0 pu. The voltage and current waveforms are shown respectively in Fig. VIII and Fig. IX.

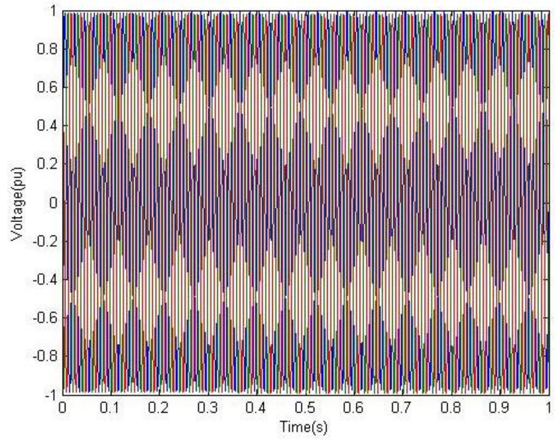

Fig. VIII Voltage across the load when both supercapacitors and batteries are supporting the Hybrid DSTATCOM

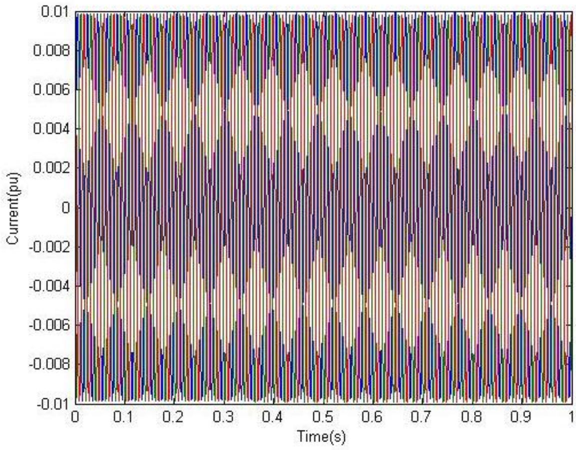

FIG. IX CURRENT THROUGH THE LOAD WHEN BOTH SUPERCAPACITORS AND BATTERIES ARE SUPPORTING THE HYBRID DSTATCOM

VIII. CONCLUSIONS

Combination of supercapacitors energy storage and battery energy storage system has been used as a storage device in the DSTATCOM. This allows the DSTATCOM to deliver the real power into distribution network for higher rate of change of dynamic conditions in case of transient conditions as well as for average power demand in case of steady conditions . The highly developed graphic facilities available in MATLAB/SIM-Power Simulink were used to conduct all aspects of model implementation and to carry out extensive simulation studies in the developed test systems. A PWM –based control scheme has been implemented to control the switches (IGBT/Diode) in the two level voltage source converters which controls the supercapacitors to deliver/absorb the real power as per the requirement and also maintains the loads power factor unity. As the simulation result shows that combination of SCESS and BESS in the DSTATCOM improves the performance of distribution network also found able to mitigate the voltage sag and at the

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 2, Issue 8, August 2013

same time maintaining the load power factor unity. These characteristics make it suitable for custom power applications where very sensitive loads are connected.

REFERENCES

[1] Srithorn, P. Sumner, M. Liangzhong Yao Parashar, R., "Power System Stabilisation Using STATCOM with Supercapacitors", Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE , Edmonton, Alta, Dated: 5-9, page(s):1-8 Oct.2008.

[2] Srithorn, P. Sumner, M. Liangzhong Yao Parashar, R., "The Control of a Statcom with supercapacitor energy storage for improved power quality" Smart Grids for Distribution, 2008. IET-CIRED Seminar, Frankfurt, , page(s): 1-4, Dated: 23-24 June 2008.

[3] Nasiraghdam,H., and Jalilian A. "Balanced and Unbalanced voltage sag Mitigation Using Dstatcom with Linear and Nonlinear loads" International Journal of Electrical, Computer and Systems Engineering 1;2© www.waset.org.,Page(s) 86-91 Spring 2007.

[4] Kuldeep Sahay & Bharti Dwivedi "Energy Storage Technology for Performance Enhancement of Power System" Electrical Power Quality and Utilisation Magazine Vol. IV, No.1 2009.

[5] Srdjan M. Lukic, Sanjaka G.Wirasingha, Fernando Rodriguez, Jian Cao, and Ali Emadi, "Power Management of an Ultracapacitor/Battery Hybrid Energy Storage System in an HEV", Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE, On page(s): 1-6, Publication Date: 6-8 Sept. 2006.

[6] Zhai, N.S. Yao, Y.Y. Zhang, D.L. Xu, D.G., "Design and Optimization for a Supercapacitor Application System", International Conference on Power System Technology, PowerCon 2006, Chongqing, page(s): 1-4 Dated 22-26 Oct. 2006.

[7] Kuldeep Sahay & Bharti Dwivedi "Supercapacitors Energy Storage System for Power Quality Improvement: An Overview, in International Journal of Electrical Systems Vol. V, Issue IV, 2009.

[8] www.national.com.appinfo/power/files/f19.pdf

[9] www.azsolarcenter.org/images/docs/tech-science/papers/batteries/apx-a.pdf

[10] www.maxwell.com

[11] Xiao Li Changsheng Hu Changjin Liu Dehong Xu, "Modeling and control of aggregated Super-Capacitor Energy Storage system for wind power generation", Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, Orlando, FL, page(s): 3370-3375, Dated: 10-13 Nov. 2008.

[12] Kuldeep Sahay and Bharti Dwivedi, "Design and Analysis of Supercapacitors Energy storage System for Energy stabilization of Distribution Network", Electrical Power Quality and Utilisation Journal Vol.XV, No.1, 2009.

[13] Ravi Kumar, S.V. and S.Siva Nagaraju "Power Quality Improvement using D-Statcom and DVR" International Journal of Electrical and Power Engineering 1(3):368-376, Medwell Online Journals, 2007

[14] Van Voorden, A.M. Elizondo, L.M.R. Paap, G.C. Verboomen, J. Van der Sluis, L., "The Application of Super Capacitors to relieve Battery-storage systems in Autonomous Renewable Energy Systems", Power Tech, 2007 IEEE Lausanne, , page (s): 479-484 Date: 1-5 July 2007.

[15] Kuldeep Sahay and Bharti Dwivedi, "Design and Implementation of Supercapacitors Energy Storage System for Management of Power System Network", Journal of Electrical and Control Engineering, Vol.2, No.4, Pages 20-25, 2012.

BIOGRAPHY OF THE AUTHOR

Kuldeep Sahay, Ph.D. is associated with Institute of Engineering & Technology, Lucknow since 1996, where he is presently Professor in the Department of Electrical Engineering, An Autonomous Constituent College of Gautam Buddh Technical University (Formerly Uttar Pradesh Technical University), Lucknow. He has authored numbers of research paper in National and International Journal having good citation and a book. His research interests are in the area of Mathematical modelling of Energy Storage System, Integration of Renewable Energy System with Grid.

Prof. Sahay for his overall contribution in research and academics has been awarded "Shikha Rattan Puraskar" and "Rashtriya Gaurav Award" by India International Friendship Society, New Delhi, in 2011. E-mail:-ksahay.iitd@gmail.com.