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Load Frequency Control of a Small Isolated Power Station by Using Supercapacitor Based Energy Storage System

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***Abstract* - Electrical Power System is always subjected to different loading conditions; most of the loads vary in an unbalanced manner. This load variation gives negative impact on the entire power system parameters. There are two conditions which always occur in the power plant; Light load and Peak load condition, out of which the peak load is more hazardous because it can cause system failure or blackouts. Usually at the time of designing any system, primary source must be compatible to provide peak demand even though it occurs only for few seconds or minutes. Standardizing the whole system based on the peak demand goes underutilized most of the times, besides being costly but if we design system of storing electrical energy from primary source at some other energy storage device and then delivering that stored energy to meet the enhanced load in a controlled manner whenever peak demand occurs for a period of time ranging from a fraction of second to several minutes, we can improve operation of system significantly. In this paper a Super Capacitor Based Energy Storage System is used for maintaining constant frequency as well as mitigation of voltage sags. Super capacitors offer high power density, fast transient response, low weight volume and low internal resistance which make them suitable for pulsed load application. This paper also presents a model of a 125KVA Generator set and a simple Super Capacitor energy storage system with a pulse load simulated in MATLAB/ SIMULINK".**

***Index Terms* - Load Frequency Control, Super Capacitor Energy Storage System, MATLAB/SIMULINK.**

1. INTRODUCTION

Electric power systems are undergoing dramatic changes in operational requirements as a result of deregulation. Continuing electric load growth and higher regional power transfers in a largely interconnected network lead to complex and less secure power system operation. At the same time, the growth of electronic loads has made the quality of power supply a critical issue. Power generation and transmission facilities have not been able to meet these new demands as a result of economic, environmental, technical, and governmental regulation constraints. These constraints make a decentralized power generating plant more favourable option [1]. There are a number of ways for installations of a small scale electricity generating plants in locations that are not served by the electricity grid. Typically, the easiest and least expensive solution from the end user's perspective is to arrange for the extension of the electricity grid to the project site. The cost of grid extension increases with the distance from the grid at a rate of millions of Rupees per kilometer. Therefore grid extension often starts to become economically prohibitive farther than three to five km from the grid. When grid extension is not an option, a standalone or distributed power system can be installed to generate electricity at a location close to the site where the electricity is needed [1]. Now a day's electrical power generation from renewable energy sources like wind energy, solar cells, biomass etc having its own importance due to their low administrative, executive costs, and short construction time compared to large power plants [2]. In this paper we are considering a 100 KW biomass gasification power generating plant.

In India, the production of all types of biomass is of around 1000 million tonnes per annum. Agriculture and forestry are the two major producers of biomass. Large quantities of crop residues are burnt in the field after harvest, which creates environmental problems and also results in loss of soil organic matter. Biomass gasification offers a vast potential to convert surplus crop residue into fuel i.e. producer gas for power generation. Biomass gasification based technology can generate electricity in a decentralized mode at low cost as compared to large thermal power plants [3] but the main problem on these plants is to keep the constant speed value. Frequency is an important criterion in electric power systems. The consumers want continuous, stable, quality and reliable energy. For a power system, constant frequency and active power balance must be provided. If the active power balance is provided on the change of instantaneous power

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than frequency can be maintained. In a power system operation such as Biomass gasification based electricity production, load frequency control is very important for supplying efficiently electrical power of good quality. Variations in connected loads have always been the biggest problems to the power system engineers. Therefore, we must require an auxiliary system by which we can control the frequency oscillations. Frequency oscillations due to large load disturbance can be effectively overcome by fast acting energy storage devices, because additional energy storage capacity is provided as a supplement to the kinetic energy storage in the moving mass of the generator rotor. The energy storage devices share the sudden changes in power requirement in the load [4]. A super capacitor energy storage system (SCESS) is composed of multi-component super capacitor (the array of super capacitor unit), the array stores energy in the form of field energy. Once energy is needed, the storage system delivers energy through the control unit. Consequently active power and reactive power of power system is compensated timely and accurately, and energy reaches at a balanced and stable stage.

2. SUPER CAPACITOR ENERGY STORAGE SYSTEM

Super capacitor is also known as Ultra capacitor and Electrical double layer capacitor. Super Capacitors are passive electronic components that, unlike batteries, store energy by physically separating positive and negative charges.

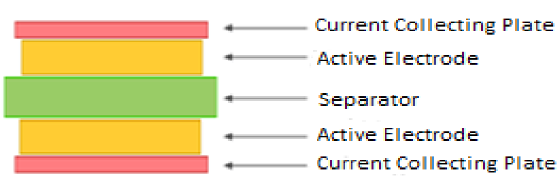

Fig. 1 - EDLC based on electric double layer Technology

They offer high power densities and provide significant energy storage capacities. It stores the energy in the double layer formed near the carbon electrode surface.

The Voltage across Super capacitor is given by-

$$V_c = Q/C \quad (1)$$

3. MODELLING & DESIGNING OF SUPERCAPACITOR BANK

The Supercapacitor Based Energy Storage System (SCESS) is designed for smoothing the power fluctuation via charging and discharging the real power which may be required due to peak demand, transient fault and other reasons. Another important application is voltage leveling

Where Q is the charge stored on the Super capacitor and C is the capacitance of Super capacitor

$$V_c = Q/C \quad (1)$$

Where Q is the charge stored on the Super capacitor and C is the capacitance of Super capacitor

$$E = 1/2\, CV^2 \quad (2)$$

Performance specifications for Supercapacitors include capacitance range and capacitance tolerance, a percentage of total capacitance. Other considerations include working DC voltage, rated current, leakage current, specific power, specific energy, and equivalent series resistance (ESR). Working DC voltage (WVDC) is the maximum voltage that can be applied continuously at any temperature between a lower category temperature and the rated temperature. Rated current is the maximum current that can be applied continuously across these same temperature intervals. Leakage current is the amount of current flowing from one conductor to an adjacent conductor through an insulating layer. Specific power measures the ability to deliver energy quickly. Specific energy measures the amount of energy that can be stored per unit of weight. Equivalent series resistance (ESR), a measure of total loss range, represents the extent to which a Supercapacitor acts like a resistor when charging or discharging [5].

Whereas a regular capacitor consists of conductive foils and a dry separator, the Supercapacitor crosses into battery technology by using special electrodes and some electrolyte.

TABLE – I

Properties	**Super capacitor**	**Battery**	**Flywheel**
Discharge Time	1～30 s	0.3～3 h	0.5～ 2h
Charge Time	1～30 s	1～5 h	0.5～2h
Energy Density （Wh /kg）	1～10	20～100	5～50
Power Density （W /kg）	7000～18000	50～200	180～1800
Cycle Life	> 10^6 times	10^3 times	10^6 times
Efficiency η	> 95%	80～85%	90～95%
Safety	Good	Good	Not good
Maintenance	Very good	Good	Medium

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 [6]. Since the voltage rate 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.

3.1 SIZING OF SUPER CAPACITOR BANK

The maximum energy store in the super capacitor bank [7]-

$$E_{max} = \frac{(C_{eq} \times U_{max}^2)}{2} \quad (3)$$

Where:
E_{max} = is the maximum energy storage capacity
C_{eq} = is equivalent capacitance of super capacitor bank in Farad
U_{max} = is the maximum voltage of the super capacitor

The discharge voltage ratio the super capacitor bank is representation as following:

$$\%d = \frac{U_{min}}{U_{max}} \times 100 \quad (4)$$

Where;
%d = is percentage discharge ratio
U_{min} = is the minimum allowable voltage limit of the super capacitor

The maximum power that can be withdrawn from the super capacitor bank can be expressed as following as per maximum power transfer theorem:

$$P_{Dmax} = \frac{U_{max}^2}{4R_{eq}} \quad (5)$$

Where:
P_{Dmax} = is the maximum dischargeable power in KW
R_{eq} = is equivalent series resistance of super capacitor bank in ohm

Once the voltage constraints have been obtained i.e. $U_{min} < U < U_{max}$ then the useful energy (E_u) that the super capacitor bank can provide can be expressed as following:

$$E_u = C_{eq}\left[\frac{(U_{max} - U_{min})^2}{2}\right] \quad (6)$$

3.2 EQUIVALENT CAPACITANCE OF SUPER CAPACITOR BANK

The equivalent capacitance of the super capacitor bank is represented by the following formula:

$$C_{eq} = \frac{(N_p \times C_{cell})}{N_s} \quad (7)$$

Where:
C_{eq} = is equivalent capacitance of super capacitor bank in Farad
C_{cell} = is cell capacitance of each cell in Farad
N_s = are number of cell connected in series
N_p = is number of parallel arms in super capacitor bank

From equation (7) 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 thereby higher energy storage capacity.

In, general the number of series connected cells N_s in one branch are imposed by the rating of super capacitor cells maximum voltage available in the market or in the stack.

$$N_s = \frac{U_{max}}{U_{cell}} \quad (8)$$

Where:
U_{cell} = is the rating of super capacitor cell

The number of parallel branch N_p in the super capacitor bank can be found by:

$$N_p = \frac{(N_s \times C_{eq})}{C_{cell}} \quad (9)$$

To have sufficient energy storage capacity number of parallel branches must be more than $(N_p \geq 1)$ and rounded upward side to nearest integer.

Total numbers of cell in super capacitor bank would be:

$$N_T = N_s \times N_p \quad (10)$$

N_T = is total number of cell required in super capacitor bank
N_s = are number of cell connected in series
N_p = is number of parallel arms in super capacitor bank

3.3 EQUIVALENT SERIES RESISTANCE OF SUPER CAPACITOR BANK

ESR is consist of electrode resistance, electrolyte resistance and contact resistance that waste power causes internal heating when charging or discharging in super capacitor. ESR is almost less than one million but influences the energy efficiency and power density. While designing the super capacitor cells are connected in series and parallel thereby total series resistance of the bank, which is represented by following formula:

$$R_{eq} = \frac{(R_s \times N_s)}{N_p} \quad (11)$$

Where:
R_{eq} = is equivalent series resistance of super capacitor bank in ohm
R_s = is series resistance of each cell in ohm

From equation (11) it is clear that to have net lower equivalent series resistance of the bank, number of the parallel arms should always higher than N_s thereby lower ohmic losses in the super capacitor bank while charging and discharging.

4. DESIGN & ANALYSIS OF SUPER CAPACITOR BASED ENERGY STORAGE SYSTEM

The real drawback of Electrical Generator Set (EGS) with optimum variable speed is an engine-generator dynamics at sudden transient from low load to high load. In case of sudden power output increase, the engine cannot deliver the requested torque and the result is further decrease of the Engine is namely not able to make sufficient torque and EGS source cannot deliver energy to the load. Problems of EGS behaviour can be solved with speed higher than optimum speed is or the other concept is EGS using an energy storage device [8].

Energy storage can be achieved by Supercapacitors. Supercapacitor represents one of the newest innovations in the field of the electrical energy storage. The proposed supercapacitors energy storage system is designed to have storage of 6 kWh of energy, 400 V connected to Electrical Generator Set (EGS) to supply the load in case of additional power demand. The supercapacitors used are of Maxwell Technologies, United States make having product **(BMOD0094 P075 Power module)** [9] specifications, Nominal capacitance 94 F, Rated voltage 75 V, ESR 13 mΩ, Operating temperature ranges from -40°C to +65°C, Specific power 4.3 kWh/kg, Specific Energy 2.9 Wh/kg, Cycles 1,000,000, Lifespan 17 years (at 25° C), Maximum continuous current 78 A, Maximum peak current (1 sec) 1,600 A, Leakage current, 50 mA. Then the SCESS designed would be as following Table II.

TABLE II
SCESS CONFIGURATION

SI. NO.	ITEM	SYMBOL	VALUE
1	Capacity of Super capacitor Energy Storage bank	U	6 KWh, 400 Volts
2	Maximum Super capacitor Voltage	U_{max}	440
3	Minimum Super capacitor Voltage	U_{min}	220
4	Optimized Super capacitor Voltage	$U_{ScRef.}$	400
5	Equivalent Capacitance of SCESS	C_{eq}	235
6	Number of Units Connected in Series	N_s	6
7	Number of Units Connected in Parallel	N_p	15
8	Total Number of Units Required for Super capacitor the Bank	N_T	90
9	Equivalent Series Resistance of SCESS	R_{eq}	5.2×10^{-3}
10	Discharge Voltage Ratio	d	50%

5. DEVELOPMENT OF TEST MODEL BASED ON SUPER CAPACITOR BASED ENERGY STORAGE SYSTEM

A MATLAB/ SIMULINK simulation model was built for Supercapacitor energy storage system feeding power to the stand alone electrical power generating plant. The test system comprises of 125KVA Generator Set, 400V & 0.8 pf. Feeding into the primary side of the 2-winding transformer connected in the Y/Y, 11/400V, 125KVA the speed and torque of the engine until the undesirable stop. load is connected to 400V secondary side of the transformer.

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 18 Hz carrier frequency, and discretized sample time of 50e^{-6} sec. This PWM generator or modulator can be used to generate pulses for 3-phase, 2-level, or 3-level converters using one bridge or two bridges (twin configuration). In the diagram, the PWM modulator generates two sets of 12 pulses (1 set per inverter) at P1 and P2 outputs. This can operate either in synchronized or un-synchronized mode. When operating in synchronized mode, the carrier triangular signal is synchronized on a PLL reference angle connected to input 'wt'. On the other input three sinusoidal 0.85 pu modulating signals are provided by the 'Discrete 3-phase Programmable Source' to obtain a modulation index of 0.85. The carrier signals are synchronized on the modulating signals. The harmonics generated by the inverter are filtered by LC filter. The three coupling transformer of 100MVA are used to connect the SCESS to the distribution network. A SCESS of 235 F are connected on the dc side to provide the energy/real power. The Super capacitor energy storage arrangement consists of double bridge two level voltage source converter as inverter, supercapacitors bank as energy storage device, a coupling transformer connected in shunt to the distribution network. The voltage source converter converts the dc voltage of the supercapacitors 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 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 and frequency regulation of the 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.

6. SIMULATION AND RESULT ANALYSIS

6.1 SIMULATION RESULT

The power rating of Electrical Generator Set is 100KW; under normal condition 95KW load is connected to the Gen set. We applied 30 KW load to the distribution network for a period of 0.4-0.5 sec. A MATLAB/ SIMULINK modeling is used for the supercapacitor energy storage arrangement and the effectiveness of this arrangement in voltage and frequency regulation can be seen on simulating the test system with and without SCESS.

CASE (1) - *Simulation Results When Super capacitors* *are Charged 40% below the State of Charge or below the* U_{min} -

The SCESS was not charged and the main supply to load is switched off by the three phase circuit breaker for period of 0.4-0.5 second. During this period the voltage and current at the load approaches to zero and the frequency variation crosses its permissible limits at the generator end. Since the SCESS was not able to supply energy to the distribution network as shown in the Fig.1, 2, 3, 4, 5.

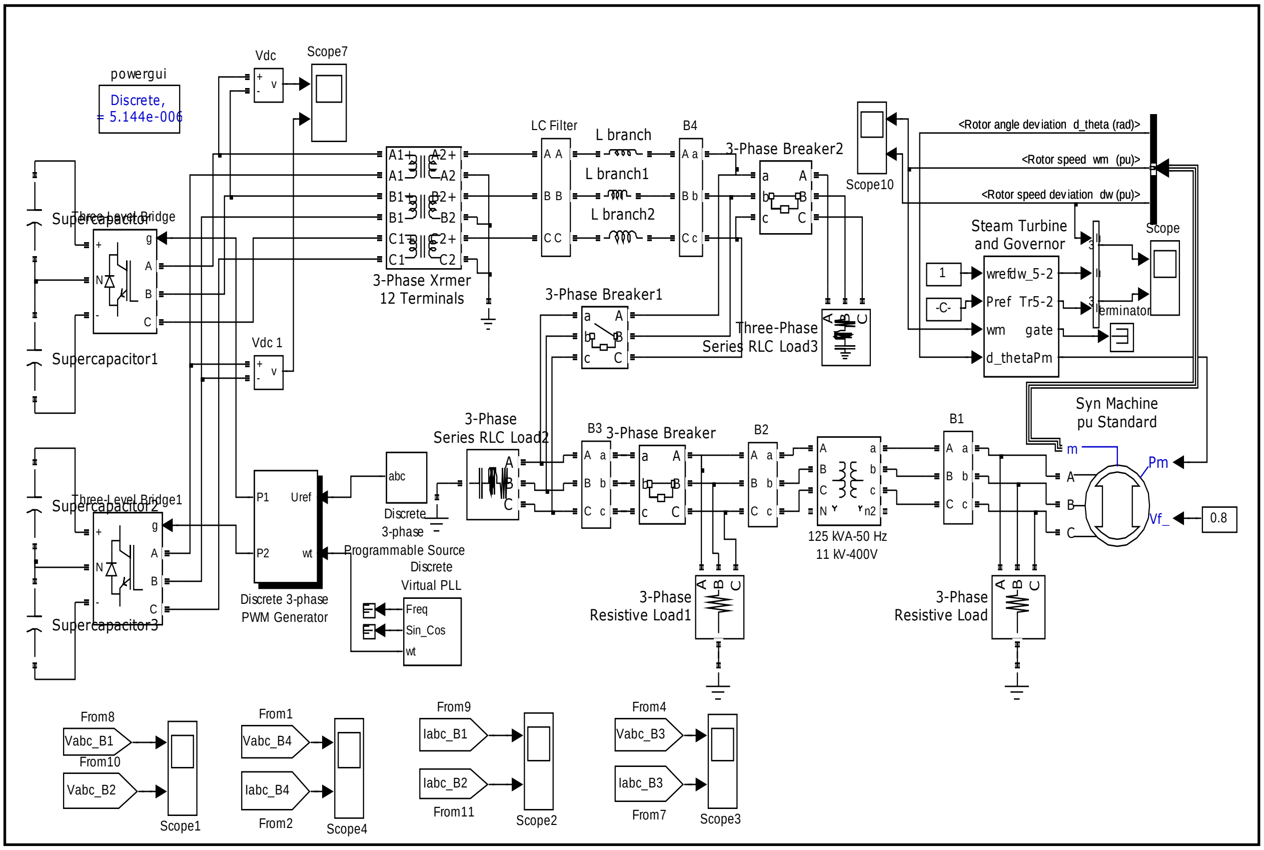

Fig. A. Simulation model based on super capacitor based energy storage system

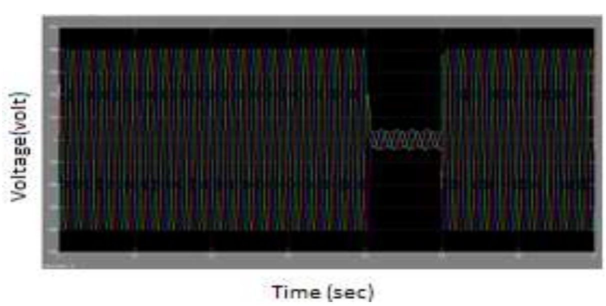

Fig.1 Voltage across the load when supercapacitors are charged below U_{min}

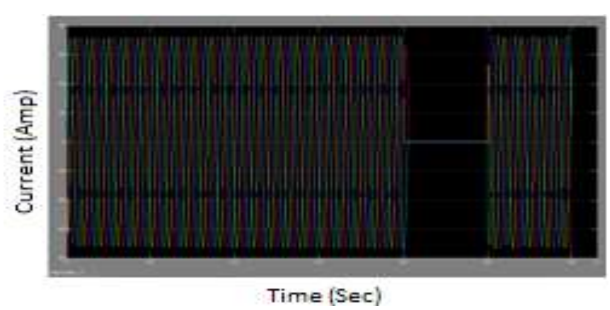

Fig.2 Current through the load when supercapacitors are charged below U_{min}

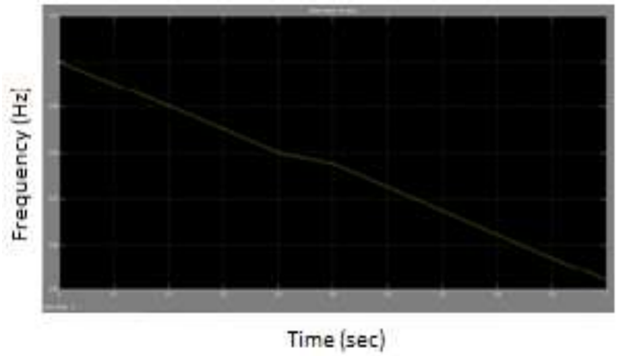

Fig.3 Frequency variation at the generator end when supercapacitors are charged below U_{min}

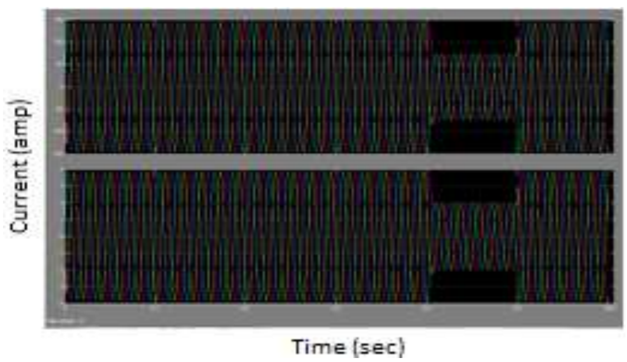

Fig.4 Current through the generator & transformer end when supercapacitors are charged below U_{min}

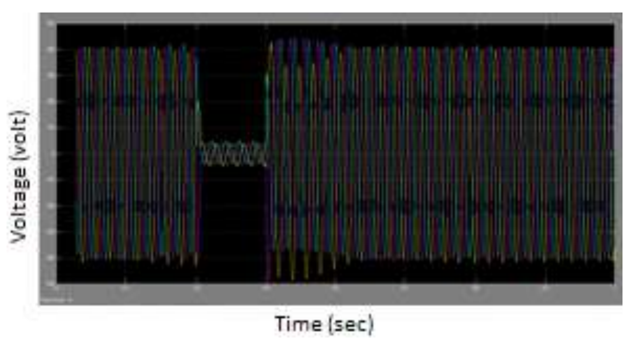

Fig.5 Voltage across the SCESS arrangement when supercapacitors are charged below U_{min}

<u>CASE</u> (2) - *Simulation Results When Super capacitors are Fully Charged –*

The SCESS are fully charged and the main supply to load is switched off by the three phase circuit breaker for period of 0.4-0.5 second. During this period the supercapacitor energy storage arrangement is able to supply energy to the distribution network and all the system parameter maintain its desired value as shown in the Fig.6,7,8,9,10.

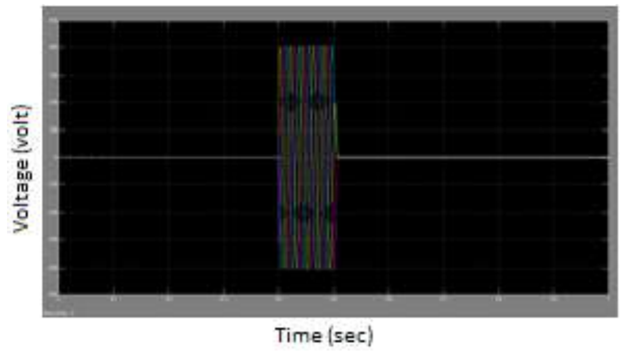

Fig.6 Voltage across the load when supercapacitors are fully charged

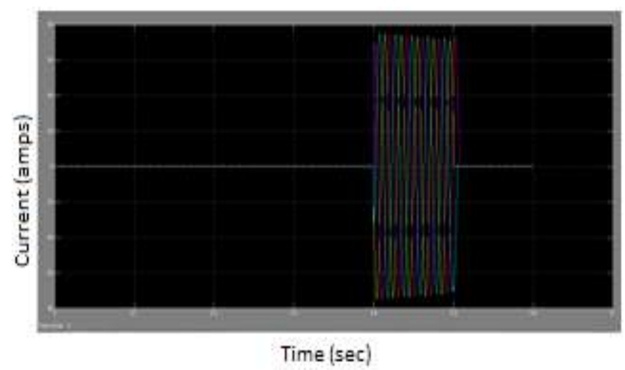

Fig.7 Current through the load when supercapacitors are fully charged

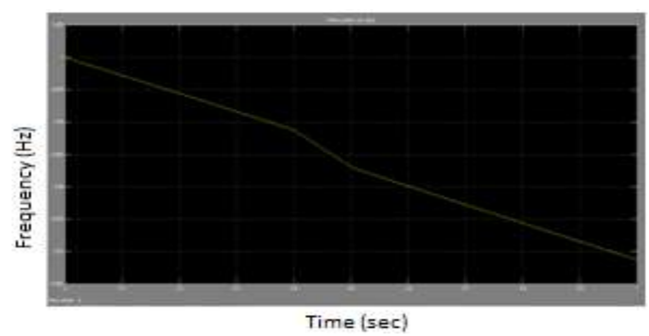

Fig.8 Frequency variation at the generator end when supercapacitors are fully charged

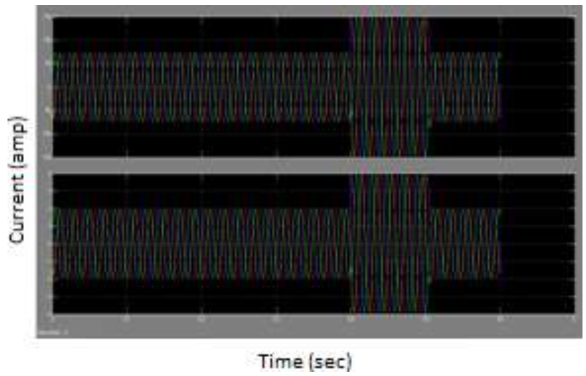

Fig.9 Current through the generator & transformer end when supercapacitors are fully charged

6.2 RESULT ANALYSIS

We applied 30% extra load to the Electrical Generator Set for a period of 0.4 – 0.5 second. It creates 87.5% of voltage drop and 5.33% frequency variation at the generator terminals. During this period current decrease up to 50% of its rated value as shown in the Case (1). When the supercapacitors are fully charged and able to provide power to the load the value of voltage reaches its rated value i.e. 400V and frequency variations came under its permissible limits as shown in Case (2).

7. CONCLUSIONS

The supercapacitor based energy storage system designed for energy stabilization and maintaining the voltage profile as well as frequency regulation of the standalone power plant which supplies power to the distribution network via inverter is of 6KWh (22.7 MJ), 400V. Supercapacitors energy storage system has been used as a storage device and 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 control the supercapacitors to deliver/absorb the real power as per the requirement. As the simulation result shows that SCESS arrangement improves the performance of distribution network also

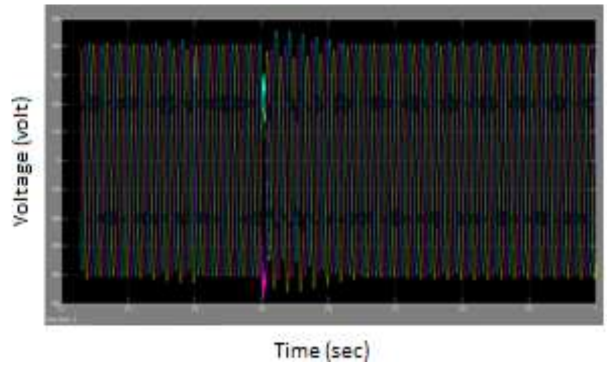

Fig.10 Current through the generator & transformer end when supercapacitors are fully charged

found able to mitigate the voltage sags as well as frequency regulation. Its characteristics make it more suitable with non conventional energy sources for energy stabilizing purpose.

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