American International Journal of Research in Science, Technology, Engineering & Mathematics

Available online at http://www.iasir.net

ISSN (Print): 2328-3491, ISSN (Online): 2328-3580, ISSN (CD-ROM): 2328-3629

AIJRSTEM is a refereed, indexed, peer-reviewed, multidisciplinary and open access journal published by International Association of Scientific Innovation and Research (IASIR), USA

(An Association Unifying the Sciences, Engineering, and Applied Research)

Supercapacitor for Hybrid Energy Storage in a Rural Microgrid

Shailendra Kumar Jha[1], Arbind Kumar Mishra[2], Kjetil Uhlen[3], Petter Stoa[4]

[1](Department of Electrical & Electronics Engineering, Kathmandu University, Nepal)

[2](Institute of Engineering, Tribhuvan University, Nepal), [3](Elkraft, NTNU, Norway), [4](Sintef, Norway)

***Abstract**: The paper presents the need of energy storage and use of supercapacitors for a microgrid. The basic principle and operation of supercapacitors are discussed along with their common application in a power system. The use of supercapacitor for a rural hybrid microgrid in Nepal has been presented. The paper presents the need of hybrid energy storage system comprising of lead acid battery and supercapacitors for the rural mcirogrid. The hybrid energy storage is used to resolve the issues of energy as well as the instantaneous power of the microgrid. The issue of running an agro-processing mill can be resolved connecting a supercapacitor bank to the existing energy storage with lead acid battery.*

***Keywords**: energy storage, instantaneous-power, lead-acid battery, microgrid, supercapacitor*

I. Introduction

Electrical energy uses is growing and so is the generation of energy sources being added to the electrical power system. The urban areas get power from larger grid but for most of the developing countries the rural communities get electrical energy from their local energy sources. Diesel plants or renewable energy sources like wind turbines, photovoltaic system, micro-hydro power plants or biogas power plants, are being used to fulfill the rural electrical requirements. The increasing need of electrical energy in the rural communities have led to the interconnection of these local sources to form local grids also commonly called microgrids or minigrids.

Interconnection of renewable energy sources like wind turbines and photovoltaic systems are more common in microgrids and thus there is an increase in the intermittency of supply. The presences of plug and play type of electrical load are also increasing in rural communities and so are the irregularities in electrical demand going high. Thus to cope with the sudden change in the demand or supply, energy storage systems (ESS) are being deployed. The presence of ESS ensures reliability, stability and quality of supply in an electrical power system [1,2,3,4,5,6]. ESS also helps to maintain energy balance between the intermittent sources and loads. There are many types of ESS being used nowadays and the most common ones are batteries, fuel cells, flywheels, supercapacitors and water reservoirs [1,2,3,4,5,6]. Supercapacitors are new storage devices being introduced to electrical power system [1,2,3,4,5,6,7,8].

Supercapacitors also called ultracapacitors are energy storage devices with capacitance in the range of several thousands of farads. Supercapacitors offer very high capacitances in a small package. Supercapacitors are categorized as electrochemical double layer (ECDL), pseudocapacitors or hybrid capacitors depending on the material used to manufacture the electrodes. ECDL supercapacitor is the most common type and is least expensive

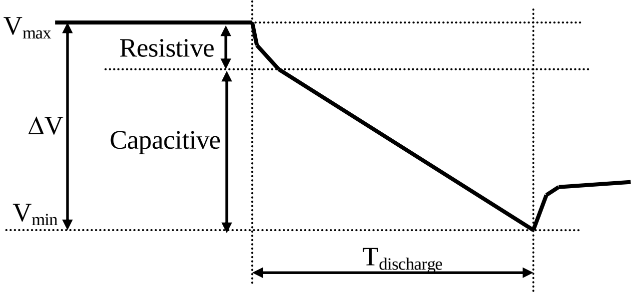

Figure1: Discharge profile of a supercapacitor [7,8]

[1,2,3,4,5,6,7,8]. The ECDL supercapacitors have a double-layer construction consisting of carbon-based electrodes immersed in a liquid electrolyte with separator [1,2,3,4,5,6,7,8]. The electrode material commonly used is aluminum foils, upon which a nonporous material, typically activated carbon, is deposited in order to realize a

Table I: Comparision of supercapacitor and lead acid battery [1,2,4,6]

Performance Characteristics	Lead Acid Battery	Supercapacitor
Discharge time	0.3-3hrs	1-30s
Charge time	1-5hrs	1-30s
Life cycle	10^3 times	> 10^6 times
Efficiency	70%-85%	90% – 95%
Power density	50-200 W/kg	1000-2000 W/kg
Energy density	20-100 Wh/kg	1-10 Wh/kg
Operating temperature	0 to 60°C	-40°C to 70°C
Typical life time	5 years	30 years

high equivalent conductive surface [1,2,4,3,5,6,7,8]. Carbon aerogels and carbon nanotubes are also being used as electrode materials nowadays. The electrolyte is either organic or aqueous. The common organic electrolyte is acetonitrile which allows nominal voltage of up to 3V, while the aqueous electrolytes used are either acids (H_2SO4) or bases (KOH) with a limitation of nominal voltage to 1V[3,4,8]. The discharge profile of a supercapacitor is shown in Figure 1. The voltage profile has a capacitive and resistive component. Energy efficiency is very high, ranging from 85% up to 98% [2,3,6,8].

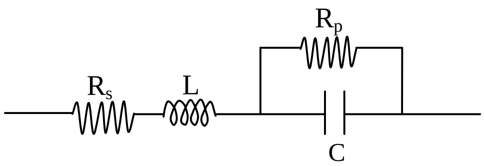

Figure 2: First order circuit model of a supercapacitor [5,6,7]

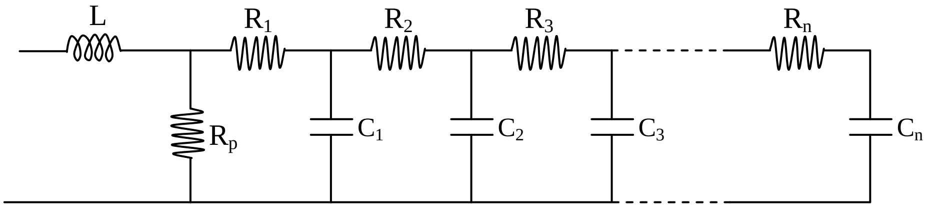

Figure 3: Equivalent circuit of a practical supercapacitor [5,6,7]

When comparing supercapacitors with batteries the main difference is in energy and power density. Supercapacitors have a significantly lower energy density than the batteries but on the other hand they have a higher power density compared with batteries. Table I depicts the comparison of a battery and supercapacitors characteristics. A supercapacitor generally has a better performance characteristics compared to battery, apart from the cost and energy density. Supercapacitors are highly expensive compared to battery and has a limitation of energy storage. Supercapacitors can supply more power for short duration but cannot store more energy for longer discharge hours [1,2,3,4,5,6,7].

There are different accepted model for supercapacitors to be used for simulation and analysis. The network presented in Figure 2 represents the first order model for a supercapacitor. The network model consists of a capacitor C, a series resistor R_s, a parallel resistor R_p, and a series inductor L. R_s contributes to energy loss during capacitor charging and discharging and is called the equivalent series resistance (ESR). R_p is called the leakage current resistance and represents the energy loss due to capacitor self-discharge. The inductor L results primarily from the physical construction of the capacitor and is usually small. The resistor R_p is much higher than R_s in practical capacitors and thus can be neglected for high power applications.

Supercapacitors exhibit non-ideal behavior as a result of the porous material used to form the electrodes, and this causes the resistance and capacitance to be distributed to represent an electrical power transmission line model as depicted in Figure 3. The model represents a more realistic equivalent circuit of a supercapacitor which provides more appropriate electrical response.

II. Sizing of Supercapacitors for Microgrids

Supercapacitors required for any application is sized depending on the requirements of the system. In general the following minimum parameters are to be defined for sizing the supercapacitors [9]:

- Required power (W) or current (I)
- Duration of discharge (t_d)
- Maximum voltage of the supercapacitor (V_{max})
- Minimum voltage of the supercapacitor (V_{min})

The discharge cycle of a supercapacitor encounter two voltage drops, the drop in voltage due to internal resistance, and the drop in voltage due to capacitance. The drop in the in the equivalent series resistance (ESR) is given by

$$dV_{ESR} = I \times ESR \quad (1)$$

The drop in the capacitance is given by

$$dV_{cap} = I \times t_d/C \quad (2)$$

The total voltage drop is

$$dV_{Total} = I \times t_d/C + I \times ESR \quad (3)$$

Here dV_{Total} is the drop in voltage when the capacitor is discharged and is the difference between the V_{max} and V_{min} of the supercapacitor, and C is the capacitance of the supercapacitor. By allowing the capacitor to drop to ½ V_{max}, 75% of the capacitor energy is discharged [9]. Depending upon the requirements supercapacitors needs to be connected in series or parallel to form a stack. For capacitors in series the capacitance is additive at 1/C. For capacitors in parallel the capacitance is additive [9]. The total capacitance of the stack of supercapacitors is given by

$$C_{Total} = C_{cell} \times (\text{no. of cells in parallel}) \quad (4)$$

And $$C_{Total} = C_{cell} \times (1/\text{ no. of cells in series}) \quad (5)$$

If multiple cells are used the equivalent resistance is based on the number of capacitors in series or parallel. For supercapacitors in series the resistance is additive [9]. For supercapacitors in parallel the resistance is additive at 1/ESR [9]. The total resistance of the stack of supercapacitor is given by

$$ESR_{Total} = ESR_{cell} \times (\text{no. of cells in series}) \quad (6)$$

And $$ESR_{Total} = ESR_{cell} \times (1/\text{no. of cells in parallel}) \quad (7)$$

III. Applications of Supercapacitors for rural Microgrids

Supercapacitors can be used for various applications in a rural microgrid considering its limitation of short time storage. The followings are some of its common application in an electrical power system [1,2,3,5,6,7]:

3.1 Short term power supply

For the grid connected rural microgrid the total power in the local community is fed from the grid. On the occurrence of any fault at the grid side the mircogrid is to be disconnected from the grid and there will be shortfall of power for the local load connected to the microgrid. Supercapacitors can be used in this case to supply power for short duration and help in the smooth operation of the islanded microgrid.

3.2 Fulfillment of peak load of power system

The load of a rural microgrid changes throughout the day and also with seasons. Load shedding is to be done during peak hours, or additional generators are to be switched on in a microgrid. Supercapacitors can be solutions to microgrids, where it can save the excess power when the load is low and feedback the power to load during peak hours.

3.3 Fulfillment of high starting current for motors

Electrical loads as motors require high current during starting or when it takes up large load suddenly. During this short period of time the power from a microgrid may not be sufficient and the system voltage would drop resulting in a system collapse. Using supercapacitors in these conditions would provide high current with small investments in a microgrid.

3.4 Optimization of renewable energy sources

Renewable energy sources like photovoltaic system and wind turbines deployed for microgrid provide intermittent output power. Supercapacitors can be connected to the minigrid and would help to provide almost uniform power output from the system.

3.5 Power quality improvement

Power quality issues like voltage sags and swells, frequency fluctuation, flickering and low voltage ride through can be controlled using supercapacitors. Supercapacitors and provide active as well as reactive power and thus can be used for these power quality issues.

3.6 Hybrid energy storage systems

Supercapacitors can be used with batteries to provide backup to a microgrid. The batteries in these cases supply power for longer duration and the supercapacitors provide the surge currents required for the operation of the electrical loads in the microgrid.

IV. Rural Microgrid at Nawalparasi

The rural microgrid was installed in 2011 at Dhauwadi village of Nawalparasi district of Nepal. The system consists of two wind turbines (WT) with rated capacity of 5kW each and a solar photovoltaic (PV) array of

2.16kWp. The system supplies power to 46 households with an estimated load of 33.6kWh per day. The system also has a battery bank which can store and supply 40kWh per day. The estimated energy consumption per day is 11.1kWh for households, 4.9kWh for school, 11kWh for agro-processing mill, 4.2kWh for control purpose in the power house and 2.3 kWh for other purposes. The interconnection of the wind turbines, photovoltaic array, battery and load is as depicted in Figure 4. With intermittent energy sources, wind turbines and PV systems, batteries are being used as backup supply when the sources are not available. During the low power demand in the microgrid the batteries are charged and during the high power demand or unavailability of power from the sources the stored energy can be used to supply the load. Lead acid batteries are being used as electric energy storage devices to improve the reliability of the microgrid. Lead acid batteries have high energy density but very low power density. These batteries can be used to provide low value of current to the load for a longer period. When high current is required for even a short duration more number of such batteries are to be connected in parallel, which makes the system highly expensive. Operation of agro-processing mill in the microgrid at Nawalparasi requires running an induction motor which draws high starting current. Using intermittent sources and lead acid battery, the agro-processing mill at the hybrid microgrid of Nawalparasi has not been functional. Thus, other energy storage along with lead acid battery is required, which can provide high current for short duration.

V. Hybrid Energy storage system for the rural microgrid at Nawalparasi

Supercapacitors and flywheels are commonly used energy storage system to provide high current for short period of time. For smaller systems supercapacitors can preferred over flywheel. Supercapacitors have low energy density but higher power density, and can provide high current for short interval of time. Thus hybrid energy storage can be used for microgrids with intermittent sources like wind turbines and photovoltaic systems. Lead acid battery and supercapacitor can be combined to form hybrid energy storage and provide the energy as well as power demand of the load. A hybrid energy storage system as shown in Figure 5 can be connected to the hybrid microgrid and thus the system performance can be enhanced. Figure 6 shows the daily load curve of the hybrid microgrid and Figure 7 depicts the addition of motor load to the microgrid. The starting surges for the motor load is high should be contributed by the supercapacitor.

Energy storage systems are required to supply power and energy to the load in a microgrid in the absence of sources or if the power supplied by the source is not sufficient as per the load demand. Energy storage devices have rated maximum energy and, maximum current or power it can supply. Depending on the microgrid requirements the energy storage devices are being used either to supply energy to the load or help the microgrid in power quality improvements. For energy supply requirements the ratio of energy to power of the energy storage

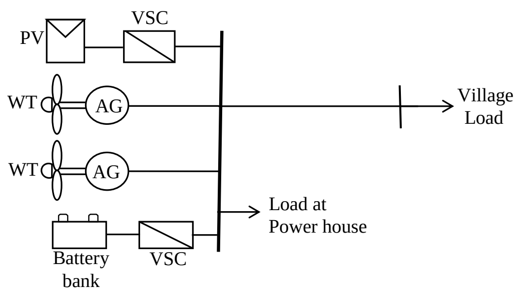

Figure 4: Hybrid Microgrid at Nawalparasi

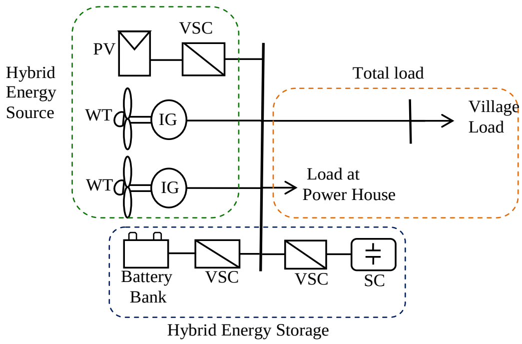

Figure 5: Proposed Hybrid energy storage at Hybrid Microgrid of Nawalparasi

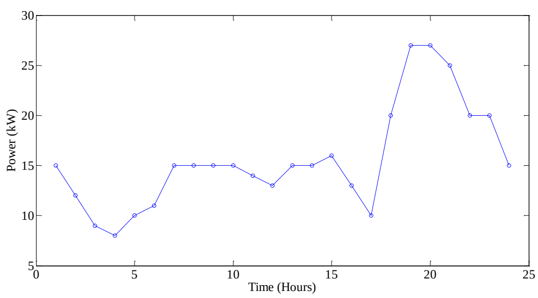

Figure 6: Normal daily load at the rural microgrid

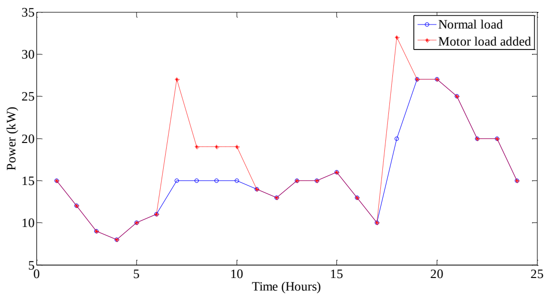

Figure 7: Daily load at the rural microgrid with motor load added

device is more than unity and for power quality requirements the ratio of energy to power is less than unity. For most of the microgrids the power and energy requirements are to be determined considering the operating hours of the load. The discharge time of the energy storage system is to be determined depending upon the operating

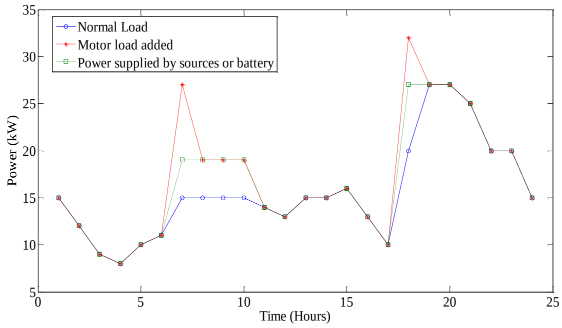

Figure 8: Daily load at the rural microgrid and power supplied by sources or battery

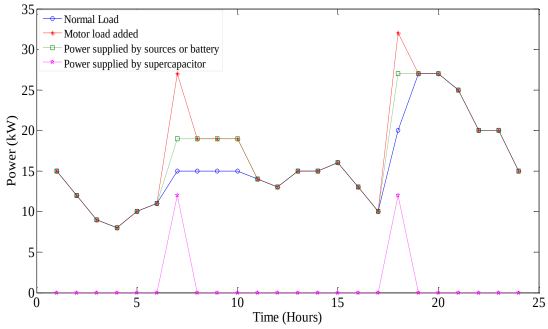

Figure 9: Daily load at the rural microgrid and power supplied by and sources/battery and Supercapacitor

time of the loads. The discharge time for power quality applications are in seconds and that in energy supply requirements are in hours.

The hybrid microgrid at Nawalparasi has an energy storage system which supplies 40kWh of energy per day. The energy storage system in the hybrid microgrid is designed considering the energy need only. The instantaneous power requirements have not been considered. Lead acid battery bank is being used to meet the energy demand of the microgrid with a current limitation. Figure 8 presents the load power requirement and the power supplied by the battery. The proposed hybrid energy storage system is to be designed considering both power and energy requirements and thus supercapacitors are to be included in the existing energy storage system. The supercapacitor is to supply the surge current requirement of the induction to be used at the agro-processing mill. The power factor of the load is considered to be 0.8 in the microgrid. The lead acid battery supplies 40kWh of energy required by all the load of the community, thus additional energy storage is required for the starting of the three phase 400V induction motor of 5hp. The surge current requirement for the motor is considered to be 21A . The system voltage is 3-phase 400V and the discharge time of the supercapacitor assumed to be 10seconds considering the starting requirement of the motor. Using equation 2,4 and 5 the supercapacitor required for the microgrid will be of 2000F and to meet the three phase voltage of 400V, 85 numbers of such supercapacitors are to be connected in each phase. Figure 9 depicts the load requirements and the instantaneous power supplied by the supercapacitor for motor load.

VI. Conclusion

There is a need of energy storage systems in rural microgrids for energy as well as power requirements. Lead acid battery is commonly used to fulfill the energy requirement. The instantaneous power requirement has not been considered in most of the microgrid. To meet the instantaneous power demand for induction motors oversizing of energy storage system is required which makes the overall cost of the microgrid very high. Thus devices with high current density and high energy density both are to be combined to meet the load requirements in the microgrid. Lead acid battery has high energy density but low power density whereas supercapacitors have high power density but low energy density. These two energy storage devices can be combined to form hybrid energy storage to meet the energy and power requirement of the rural microgrid. The rural microgrid at Nawalparasi, Nepal has a lead acid battery to supply energy to the load, but the instantaneous power demand by the agro-processing mill cannot be met. Thus, connecting a supercapacitor to form a hybrid energy storage system helps to provide both power and energy required in the rural microgrid, Other power quality issues like voltage and frequency variations of the microgrid can also be controlled using supercapacitors.

References

[1] Francisco Díaz-González, Andreas Sumper, Oriol Gomis-Bellmunt, Roberto Villafáfila-Robles, A review of energy storage technologies for wind power applications, *Renewable and sustainable energy reviews, vol 16, issue 4*, May 2012.

[2] C.M. Chawhan, R.M. Bhombe, Application of Super Capacitor Energy Storage System in Microgrid, *Int. J. on Recent Trends in Engineering and Technology, Vol. 6, No. 2,* Nov 2011.

[3] Hadjipaschalis I., Poullikkas A., Efthimiou V., Overview of current and future energy storage technologies for electric power applications, *Renewable and sustainable energy reviews, vol 13,* 2009.

[4] Vincenzo Musolino, *Supercapacitor storage systems, modeling, control strategies, applications and sizing criteria, PhD Thesis in Electrical Engineering*, Politecnico di Milano, 2011.

[5] Cultura II A.B., Salameh Z.M., Modeling, Evaluation and Simulation of a Supercapacitor Module for Energy Storage Application, *International Conference on Computer Information Systems and Industrial Applications* (CISIA 2015).

[6] Varsha A. Shah, Prasanta Kundu, Ranjan Maheshwari, Improved Method for Characterization of Ultracapacitor by Constant Current Charging, *International Journal of Modeling and Optimization, Vol. 2, No. 3*, June 2012.

[7] Kim Y., Ultracapacitor technology power electronics circuits, *Power Electronics Technology*, October 2003.

[8] Beguin F.,Frackowiak E., *Supercapacitors Materials System and Applications* (Wiley-VCH Verlag GmbH & Co., 2013).

[9] https://www.tecategroup.com/app_notes/0_Tecate_Group_Ultracapacitor%20sizing.pdf, 14th June 2017.