Application of Super Capacitor Energy Storage in Microgrid System

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Abstract— **With the advancement in distributed generation systems, Power Electronics and power semiconductor technologies, the microgrid system is considered as a promising solution to meet the growing energy demand. Super capacitor based energy storage system becomes one of the best choices for microgrid because of its high storage capacity, wide working temperature range, cost effectiveness and environmental advantages. The application of super capacitor energy storage system connected to microgrid is proposed in this paper. The proposal explored here is to address energy and carbon emission concerned global issues. The design and development of a dynamic support system for specific microgrid applications are discussed. The hardware and software design and development of a 7.8kW, single-phase converter connected to a 125V, 100Wh super capacitor bank is presented in the paper.**

Index Terms— Combined Heat Pump (CHP), Distributed Generation (DG), Microturbine Distributed Generation (MTD), Microturbine Generator (MTG), Permanent Magnet Synchronous Machine (PMSM)

I. INTRODUCTION

Energy is considered a basic input for any country for keeping the wheels of its economy moving. However, setting up new power plants to meet growing consumption requirements is not financially viable or environmentally feasible. In a country with a growing demand for energy, increased efficiency in utilizing the energy is the only way to meet the shortfall. Microgrid is an integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single, autonomous grid either in parallel to or islanded from the existing utility power grid. In the most common configuration, distributed energy resources are tied together on their own feeder, which is then linked to the grid at a single point of common coupling. The renewable energy systems are connected directly to the distribution network. Renewable sources like hydrogen, wind and photovoltaic systems have their own infrastructure to power loads. Despite the high initial cost, PV systems are being used increasingly to supply electricity for many applications requiring small amounts of power. Microgrid can be viewed as the building blocks of the smart grid or as an alternative path to the much hyped smart "Super Grid". Under normal circumstances, the microgrid is operated in grid-connected mode. Perhaps, the most compelling feature of microgrid is the ability to separate and isolate itself from the utility's distribution system during brownouts or blackouts. This is known as island-mode. The installation of efficient energy storage element is a key to facilitate these two modes of operation.

Figure 1.1 is the typical hybrid microgrid composed of renewable and conventional energy systems. Renewable energy systems have an intermittent character because their output power depends on the availability of the primary source such as wind, sun, biomass, or steam. Therefore, they cannot guarantee the power demanded by the load. Conversely, CHP systems are limited by their insufficient dynamic performances for load tracking.

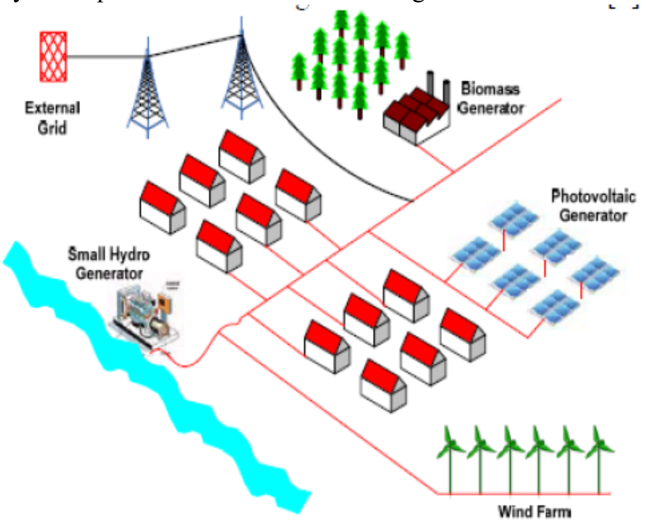

Figure 1 Typical microgrid system

These two limitations can be overcome by the introduction of appropriate dynamic energy storage-based support system in the microgrid.

Hence, a properly rated and designed storage-based support system can allow hybrid microgrid to operate in stand-alone mode, thereby improving the reliability of the overall system. Super capacitor based energy storage system becomes one of the best choices for microgrid for numerous reasons [1].

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II. MICROGRID

A brief overview of the methods used is presented here. A method to improve the load frequency control in a power system with distributed generation (DG). DG is assumed to include photovoltaic generation, wind power generation, fuel cells and etc. In this paper, a simulation is performed using a micro grid model that is composed of a storage system with either photovoltaic generation or wind power generation as the DG. The model for the micro grid is the system of Aichi Institute of Technology in Japan. The effectiveness of load frequency control (LFC) using a storage system is examined using a power transmission simulator. As a result, it was confirmed that the electric power quality is improved when the storage system is used for LFC. Ref [4]

One case is an examination using a power transmission simulator. The system is composed of a synchronous generator, an induction generator, an inverter and a storage battery. Then, the examination of frequency control was executed with these devices. In the storage battery, the frequency control is executed. The frequency control was performed using two methods; a power demand estimation method and a proportion control method that uses the frequency deviation. The power system at the Aichi Institute of Technology

(AIT) consists of a diesel generator, photovoltaic generations, wind power generations and a storage system. Fig. 2 shows the various components of the micro grid at AIT. Fig. 2 shows a schematic of the power system.

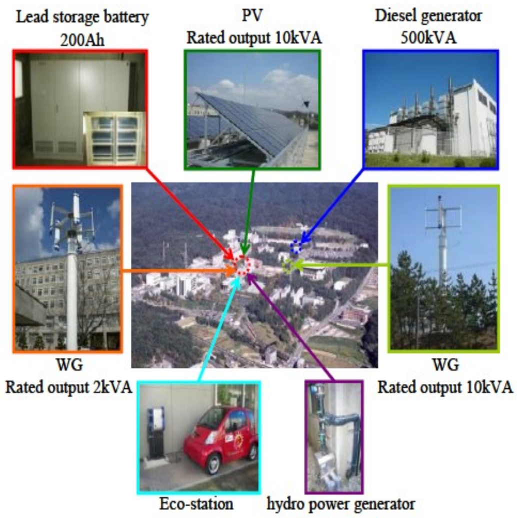

Figure 2 Microgrid at AIT

3.1 Photovoltaic Generation

The photovoltaic generation system has 60 solar panels and a rated capacity of 10 kW. It uses a power conditioning system.

3.2 Wind Power Generation

Two types of wind power generation have been introduced at AIT. The 10-kW system has a 4-m length blade and is 15 m high, with four sheet wind vanes. The 2-kW system has a 2-m length blade and is 9 m high, with five sheet wind vanes.

3.3 Diesel Power Plant

Four diesel generators rated 500 kVA have been introduced into the AIT system. In this study, we simulate one of the four generators.

III. BASIC CONFIGURATION FOR SUPER CAPACITOR ENERGY STORAGE IN MICROGRID SYSTEM

The basic configuration of SCES is shown in Fig.4, consisting of super capacitor series, an AC/DC rectifier, a DC/AC inverter, and a control circuit. It is located in parallel with the bus between the network and the load.

The following is the basic principle of the SCES system. First, three-phase AC power is changed into DC power through the rectifier, and then the DC power is inverted into controllable three-phase AC power. In normal working state, super capacitor stores up DC energy provided directly by the rectifier through the grid. When the system failure or power load fluctuations occur, the energy stored in the super capacitors is released through the inverter.

The super capacitor series store energy in the form of electric field energy, and then release the energy through the control circuit when the energy is lacking or it's necessary to compensate the active and reactive power rapidly and accurately to realize power balance and stability control.

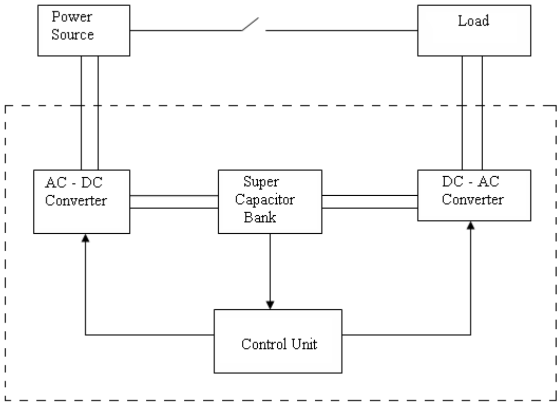

Figure 3 Basic configuration of super capacitor energy storage in microgrid system

IV. MODEL AND DESIGN OF THE MICROGRID SYSTEM

The microgrid system highlighted in this paper contains photovoltaic system and a micro turbine (combined heat and power unit) as generation units, with typical household electrical and thermal loads as consumption units. A centralized energy management system is responsible for the supervision and control of the different systems and the power flow between them and the mains. Figure 5.1 shows the general schematic diagram of the proposed microgrid system for domestic applications. In order to assure the energy supply to the critical loads, the support system is developed to overcome the dynamic limitations of the 30kW micro turbine in the standalone mode of operation of the entire system unit.

The support system is composed of the storage system, the DC-DC converter unit to match the storage system voltage to the DC-link voltage and the DC-AC converter (Inverter) unit with its grid connection filter unit. The ratings of the above mentioned units are designed to meet the energy demand operating condition of the system when operated in

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standalone mode and for the maximum power variations (between the minimum critical load of 9kW and the maximum load of 30kW). In the designed system, the microturbine is controlled in power mode and it does not react to load variation until it receives its new reference, every 5 seconds, from the Microgrid Central Management (MICROGRID MANAGEMENT) system. Accordingly, in the worst case there can be divergence of 21kW between the microturbine output power and the load consumption during 5seconds.

Furthermore, it takes roughly 30 seconds for the microturbine to respond to its new situation and this deviation must also be handled by the support system. For the system under consideration, the maximum amount of energy to be injected or absorbed by the support system is estimated to be 260Wh for three-phase system and 86.66Wh for each of the phases. Single-phase system operation requirement for the design is given in the Table 1.

Table 1 Single-phase system operational requirement for the design

Parameter	Value
Power	7Kw
Energy	86.66Wh
Grid connection voltage	230V

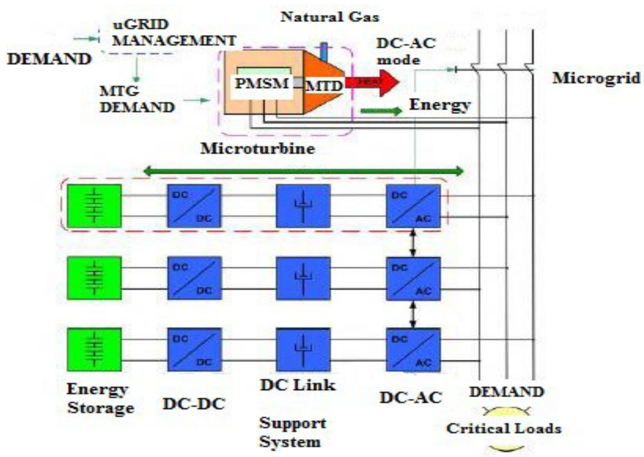

Figure 4 Schematic of the proposed microgrid system

V. ENERGY STORAGE SYSTEM

Discussion on Energy Storage System using Super Capacitors

Supercapacitor is a double layer capacitor; the energy is stored in charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is a 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 the 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 charge ions and forbids no electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other. Usually supercapacitors are divided into two types: double-layer capacitors and electrochemical capacitors. The former depends on the mechanism of double layers, which is the result of the separation of charges of interface between the electrode surface of active carbon or carbon fiber and an electrolytic solution. Its capacitance is proportional to the specific surface areas of electrode material. The latter depends on the 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 3V. 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 2

Table 2 Available supercapacitor in market

Sr. 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

The design of super capacitor bank is based on the energy and voltage requirements. The application demands an inoculation and an amalgamation capability of 86.66Wh. From the energy stance, considering their capacitance value and assuming 50% voltage discharge ratio, the number of super capacitors required can be calculated using equation 1.

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$$N_{Energy} = \frac{W_{ini}}{\frac{1}{2} \times C_C \times U_{Max}^2 \times \left\{1 - \left(\frac{d}{100}\right)^2\right\}}$$

Equation 1

W_{ini}= is the required energy in the application.

C_C= is the capacity of each super capacitor unit.

U_{Max}=is the maximum voltage of a super capacitor.

d=is the voltage discharge ratio

For voltage requirements, the number of super capacitors to be connected in series is calculated taking into account the minimal required super capacitor bank voltage using equation 2. The voltage is set considering that the voltage ratio between the super capacitor bank and the DC-link must be kept within 4-6 following a common design practice related to the choice of the DC-DC converter topology. Hence, the minimal super capacitor bank voltage is set near 60V.

$$N_{Voltage} = \frac{V_{Min}}{U_{Max} \times \frac{d}{100}}$$

Equation 2

V_{Min}=is the minimum voltage of the super capacitor bank.

After evaluating different type of super capacitors, BCAP 3000 of Maxwell has been chosen as a trade-off between weight, size and losses. The parameters for designing the super capacitor bank are presented in Table 3

Table 3 Rating of ESS based on super capacitors

Parameter	Value
W_{ini}	86.66Wh
C_C	3000F
U_{Max}	2.5V
D	50
V_{min}	2.5V

In order to fulfill energy requirement, it is necessary to use 45 super capacitors but to fulfill the voltage requirement it is necessary to use 48 super capacitors. A commercial module HTM P125 Power Module from MAXWELL that better fits these requirements has finally been chosen. Its main characteristics are given in Table 4.

Table 4 Characteristics of the commercial module

Parameter	Value
Voltage	125V
Current	150A
Energy and capacitance	100Wh, 63F

Advantages of Supercapacitor:

1. Super-high Capacity. Its capacity ranges from several farads to tens of thousands farads, 2 000 to 6 000 times larger than the electrolytic capacitor with the same volume.

2. Extremely high power density. The power density of super capacitor is up to 18 kW/kg or so, from which, in a short period of time, several hundred amps to several thousand amps of current can be released. This feature makes it ideal for the occasion of short term but high-power output.

3. Rapid charging and discharging. The super capacitor can store electric energy directly without chemical reactions. The charging time is very short. It can be recharged using large current charging in tens of seconds, which is really a rapid charging. Nevertheless, the battery needs a few hours to complete charging and rapid charging also needs a few dozen minutes.

4. Long cycle life. The required energy and power content provided by super capacitors can be cycled several hundred thousand times and consequently super capacitors are virtually maintenance-free. The cyclic behavior of batteries is poor in comparison to capacitors. Batteries, which are sensitive against abuse such as over-ripples, reverse polarity and deep discharges, can withstand only some hundred up to a few thousand cycles, if kept fully charged and a conditioning discharge followed by an equalization charge is conducted periodically.

5. Little temperature influence on the normal use. Super capacitor has a superior low-temperature performance and a wide range of working temperature from -40 to 85℃. In contrast, the battery range is only from 0 to 40℃.

Table 5 shows the characteristics comparison among the super capacitor, battery, and the flywheel energy storage. It can be concluded from the table that the performance of super capacitor is better, but it costs much more. In the microgrid, the problem of power quality caused by load or the micro sources often has a feature with short duration, but occurs frequently, so that using super capacitors as an energy storage device to do quick compensation is an ideal technical scheme. Although the price of super capacitor is still high, but with the price gradually descending, super capacitor as a high performance, practical and environmentally friendly energy storage device is bound to be an ideal choice.

Table 5 Characteristics comparison among energy storage systems

	SC	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
Cost (p.u)	20	1	8

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6.2 Sizing of PV panels

The total required power is 30kW. Sun power solar cells are selected. Following assumptions were used to calculate the number of panels required [1].

1. All panels have similar electrical characteristics.
2. Solar irradiation intensity is assumed to be 825 W/m^2
3. Each day has a sun shine hour of 4 hours
4. Sun power solar cell efficiency is assumed to be 15%.

Based on the above information, the total area of the solar panels required is approximately 242.42m^2.

6.3 Hardware design of the power electronic interface

The super capacitor bank is connected to the grid through two (DC-DC and DC-AC) converters. They have been rated taking into account that the maximum power demand is 7kW and the efficiency must be as high as 90% for both converters. The selected super capacitor side converter is a 7.8kW bidirectional DC-DC converter with 6 channels. The grid side converter is 7.8kW single-phase DC-AC converter with unipolar modulation and LCL output filter. Both converters are interconnected through a DC-link and they operate with 20 kHz switching frequency. The simplified electrical diagram of the single-phase dynamic support system is presented in the Figure 5.

The most important components of the hardware design are DC-DC inductors, DC link capacitors, the cooling system, the bus-bar, LCL filter, and interface and control boards.

Each channel of the DC-DC converter is connected to the super capacitor bank through an inductor. Inductors have been designed to avoid discontinuous conduction mode of operation of the DC-DC converter.

The semiconductor choice has been based on voltage and current levels (1200V and 42A) and on power losses. SEMIKRON AKM100GB128D Insulated Gate Bipolar Transistor (IGBT) module has been selected.

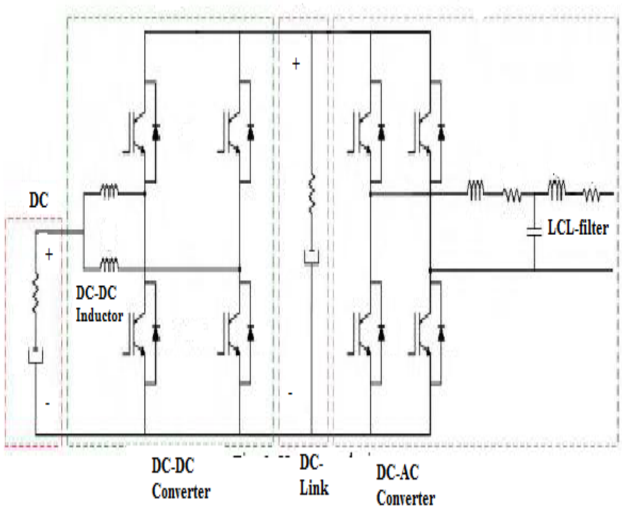

Figure 5 Ciruit design

6.4 Interface and Control Boards

A control unit composed of a floating-point Digital Signal Processor (DSP) and a Field Programmable Gate Array (FPGA) has been used as the support system control unit. In addition, the interface board has been designed in order to interconnect the control unit with the power unit. The interface board contains the drivers of the IGBTs, voltage, current and temperature sensors with their corresponding conditioning circuits, power supplies, digital and analog I/Os. Two different operation modes have been implemented in the support system depending on whether the microgrid is connected to the utility grid or it operates in standalone mode. Management functions have also been implemented to cope with transitions between the operating modes.

When the microgrid is operating in grid-connected mode, the support system operates in storage system management mode. It controls the state-of-charge of the super capacitors according to the set reference. In this mode, DC-AC converter controls the voltage of the DC link while the DC-DC converter manages the state-of charge of super capacitors. The same is shown in the Figure 6

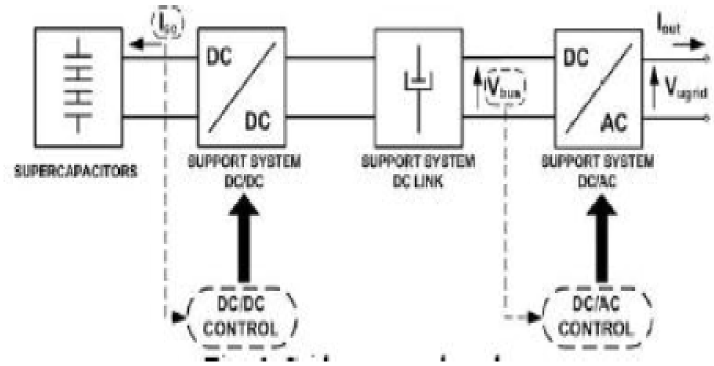

Figure 6 Grid-connected mode of operation

When the microgrid operates in standalone mode, the support system controls the main parameters of the microgrid (voltage and frequency) and assures the instantaneous power balance of the facility. In the islanded mode, the DC-DC converter controls the voltage of the DC-link (by absorbing or injecting energy from the super capacitors) and the DC-AC converter sets the voltage and frequency of the microgrid. The support system in a standalone - mode of operation is shown in the Figure 7

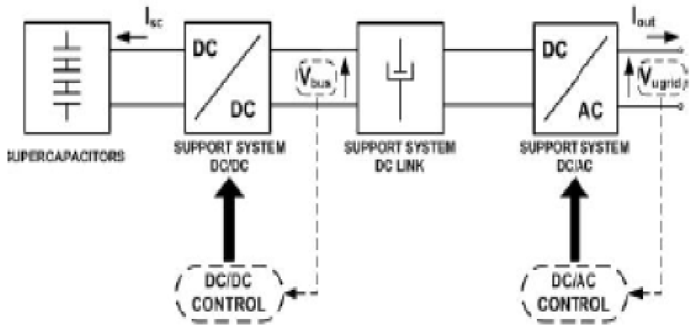

Figure 7 Standalone mode of operation

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6.5 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. Dispatch ability of Power,
4. Ride through capability of Supply
5. Reduced insulation,
6. Transformer connections and ground faults,
7. Design of system elements: transformer, feeders,

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.

VI. RESULT

Release of the microgrid from the utility grid is motivated by an unacceptable grid voltage in the form of amplitude or frequency. A voltage monitoring module is implemented to measure the pre-established threshold value of the R.M.S grid voltage. It is noted that when the grid voltage (Vgrid) decreases to particular limited value of 0.9p.u during 20ms, the support system opens the grid connection contactor and disconnects the microgrid from the utility grid. Furthermore, immediately after the microgrid is disconnected from the utility grid, the support system controller changes over from the storage system management mode to voltage control mode; controlling the main parameters of the system with a smooth transient.

When the service grid resumes normal operating conditions and the support system detects it through the voltage monitoring module, the operations are switched over from standalone to grid-connected mode. Before connecting back, the microgrid needs to be synchronized with the grid voltage to avoid any hard transient to the utility grid. While doing this, the voltage in the microgrid is set to the characteristics of the grid voltage, frequency and phase during 100ms with the aim of decoupling the reference variation from the physical grid reconnection transient. Once the voltage in the microgrid is synchronized with the utility voltage, the support system reconnects the microgrid to the utility grid and it passes from the voltage control mode to the storage system management mode with a smooth transient.

VII. CONCLUSION

1. The design and development process of super capacitor-based support system that guarantees the safe transition between the operation modes (parallel/standalone), and the correct dynamic power balance in the standalone mode is presented in detail. The main components of the support system, namely 120V, 90Wh super capacitor bank, DC-DC converter, and DC-AC converter have been rated and designed for a given application in a physical microgrid system.

2. 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 non delivered power into delivered, to improve power quality of the weak transportation system, of aircraft distribution system UPS, elevator and PDS adopts PI control technique, dynamic voltage restorer in the island mode, switching transients mode, grid connected mode, in standalone 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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