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Voltage Stabilization of Hybrid Micro-Grid Using Super Capacitors

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Abstract

Scarcity of fossil fuel resources has motivated the researchers to develop renewable energy based power projects. Instead of using a single or independent renewable energy source, it is preferable to use the combination of such energy sources in a distributed way to compensate the power fluctuations of the system and this leads to the concept of hybrid micro-grid energy. Voltage stability is an important parameter for the secure operation of the hybrid-micro grid, and IEEE 1547 Standard defines the limit of the voltage for the successful operation of the micro-grid. Although Vanadium Redox Batteries (VRBs) can help the system to stabilize the voltage when voltage sag occurs when a heavy load is suddenly connected to the system, this stabilization process takes some time. This paper discusses the application of super capacitors to the hybrid micro-grid system, as a higher energy density element, to help the system quickly recover its transient voltage.

Keywords

Super Capacitors, Micro-Grid, Voltage Sags, Voltage Stabilization, Hybrid Micro-Grid

1. Introduction

The centralized power generation system has been used for decades and usually the system utilizes fossil fuel as a resource, but unfortunately, the use of fossil fuel in the power generation poses a threat to human life and more specifically to those people who are situated near the power generation plants. Therefore, due to environmental issues *i.e.* emission of CO_2 and other hazardous gases, the centralized power generation plants are located remotely [1]. In addition to the mentioned problem, the centralized system also faces the problems related to system stability and high transmission line losses because the system is usually located in the remote area [2].

Nowadays, the demand of electricity is also increasing and to overcome the shortage of electricity, develop-

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ment of new centralized systems is not a wise decision. Therefore, instead of increasing the quantity of energy there is a need to improve the quality of energy by employing renewable energy sources *i.e.* wind and solar energy. Since renewable energy technologies unlike fossil fuel based power generation systems are "eco-friendly", locating these "eco-friendly" power generation systems in remote areas is not required. It not only helps in the reduction of the transmission line losses, but also decreases the risk of large blackouts. Hence, this idea leads to the concept of Distributed Generation (DG) using micro-grids because the large scale applications of the DG are possible by employing micro-grid. Micro-grid is developed by grouping a cluster of loads and parallel DG units in local distribution network.

It must be noted that the micro-grid is connected to the grid via Point of Common Coupling (PCC), which, in case of a fault, will disconnect from the grid, and then the micro-grid will operate in the islanded mode. So, micro-grid must be able to operate in grid-connected as well as in islanded mode [3].

In order to keep the micro-grid in the grid-connected mode, certain constraints must be satisfied such as maximum voltage sag and swell, and the limits for maximum and minimum voltages are defined in ANSI C84.1-2006 [4] and referred in IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power System [5]. For the micro-grid to operate in grid-connected mode, it must maintain a particular level of the voltage for its successful operation because according to the mentioned standards, if the frequency and the amplitude of the voltage exceed the defined value, then PCC breaker will open instantly [6]. Therefore, the transient stability of the voltage must be considered as an important parameter for the stable operation of micro-grid. The removal of a heavy load to the system will cause voltage swells, and similarly, voltage sags will occur when a heavy load is connected [7]. Therefore, it is necessary to have the voltage as sine wave and also it must be among certain defined limits.

This paper presents the practical study of a micro-grid model under the influence of load change, and this is due to the fact that the transient voltage of the system is largely affected by the increase of load. The voltage sag due to the increase of load will increase the amplitude of current, which consequently can cause damage to the power electronic converter. This paper proposes to employ super capacitors in a DG hybrid micro-grid system. Therefore, the inclusion of super capacitors to the micro-grid system becomes necessary.

2. A Hybrid Distributed Generation Micro-Grid System

Today, independent PV based renewable energy system is being employed but due to changing intensity of sun, the power of the PV system is not constant.

Therefore, in order to avoid fluctuations, instead of using an independent PV system, a hybrid system, integrating wind energy system (WES) and energy storage (ESS) elements with the PV system, is usually used. Similarly, the power of an independent WES will adversely affect the power system. Hence, a hybrid system formed due to the integration of ESS *i.e.* battery energy storage system (BESS) and flywheel energy storage system (FESS) with renewable energy technologies *i.e.* PV and wind energy is best possible solution to avoid power fluctuation problems in a power system. A hybrid micro-grid system which is shown in **Figure 1** is developed at Goldwind Science & Technology Co., Ltd. 2010.

The micro-grid hybrid system shown in Fig. 1 includes three PV Energy Systems (PVES) with two of them adding about 400 kW to the system *i.e.* PV1 and PV2 while another PV panel system *i.e.* PV3 contributing 100 kW to the system. The mentioned system also includes a wind energy system, with a capacity of 2.5 MW, connected to the 400 V AC channel via step-down transformer.

As discussed before, in order to secure the system from power surges from WECS and power fluctuations from PV system, two different technologies of EES, each with a capacity of 800 kWh, have also been integrated via bi-directional power electronic converters. One of the EES being used in the system employs Vanadium Redox Battery Energy Storage System (VRBESS). VRB's are usually used in the system to due to its capability of providing high energy density, long cycle life of 10,000 cycles (which is 3 times more than that of lithium ion battery), increased operating temperature range and a long time scale of minutes to hours [8]. The complete modeling of the VRB's has been presented in [9] [10]. The capacity of the Iron Phosphate based Lithium Ion Battery Energy Storage System (LIBESS) was same as of VRB's. It must also be noted that the studied micro-grid operates in grid-connected mode. **Table 1** shows the capability and the specifications of the mentioned experimental system.

The mentioned hybrid micro-grid system also includes two units of 65kW Natural Gas Micro Turbine. C65

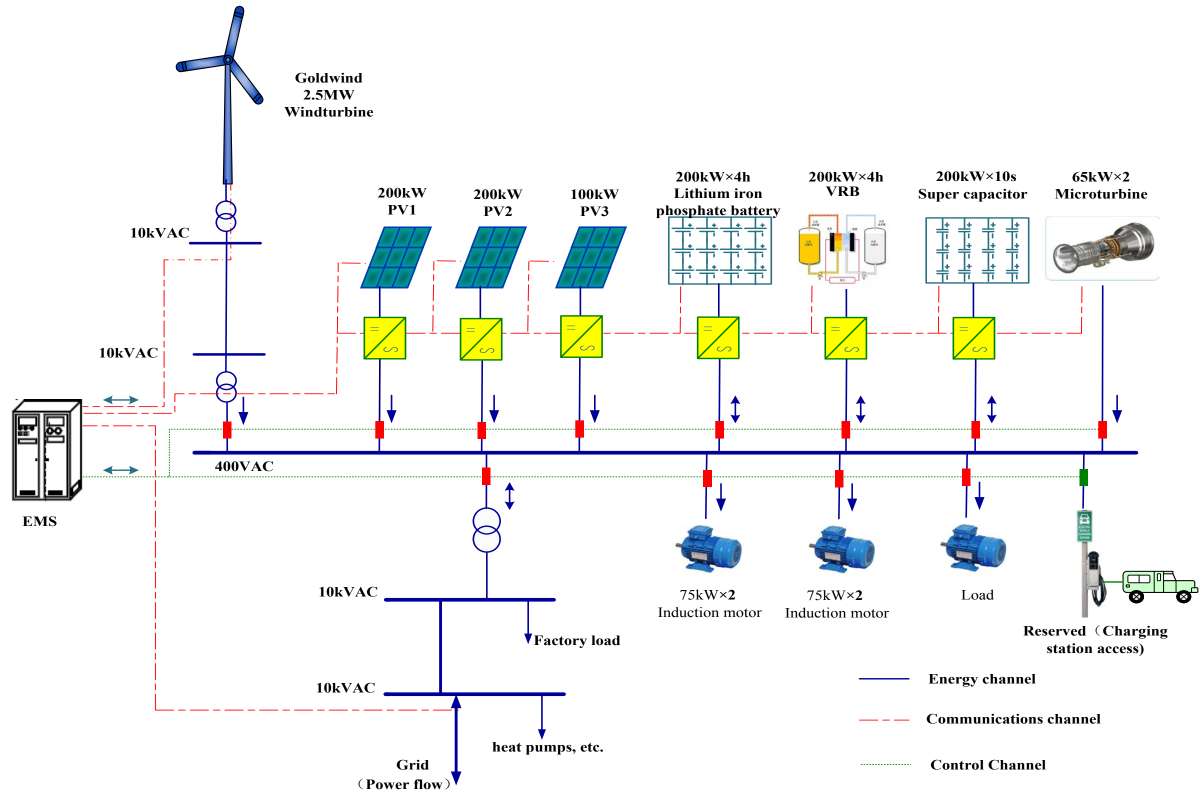

Figure 1. A hybrid micro-grid system topology at Gold wind Co., Ltd.

Table 1. Energy capacity and load specifications for the experimental hybrid micro-grid system at Goldwind Co. Ltd.

Energy Sources/Energy Storage Elements/Load	Number of Units	Specifications Per Unit		Total Power
PV Energy System (PVES)	3	PV1 = 200 kW PV2 = 200 kW PV3 = 100 kW	200 kW × 2 +100 kW	500 kW
Wind Energy System (WES)	2	WT1 = 1.5 kW WT2 = 1.5 kW		2.5 MW
Micro Turbine Energy System (MTES)	2	MT1 = 65 kW MT2 = 65 kW	65 kW × 2	130 kW
Vanadium Redox Battery Energy Storage System (VRBESS)	1	200 kW for a duration of 4 hours		800 kWh
Lithium Ion Battery Energy Storage System (LIBESS)	1	200 kW for a duration of 4 hours		800 kWh
Super Capacitor Energy Storage System (SCESS)	1	200 kW for a duration of 10 seconds		0.55 kWh
Three Phase Induction Motor (TPIM)	4	IM1 = 75 kW IM2 = 75 kW IM3 = 75 kW IM4 = 75 kW	75 kW × 4	300 kW

ICHP combined heat and power (CHP) natural gas based micro turbine has a capability of providing 100A in grid-connected as well as in islanded mode operation of micro-grid whereas, operational voltage range is between 400VAC and 480VAC. One of the advantages is that C65 ICHP has ultra low NOx emissions. **Figure 2** shows the two units of the mentioned micro turbine.

The purpose of this research is to experimentally check the effect of super capacitor units on micro-grid under different load conditions. However, there are different control schemes that have been developed for grid-connected mode and islanded mode of the micro-grid system which has been presented in [11] while [12] discusses the modeling of the PVES and EES.

3. Modeling of the Super Capacitor

The Super Capacitor or Ultra-Capacitor has very higher value of energy density in comparison to the normal capacitors. Unlike a conventional capacitor, the super capacitor doesn't use the dielectric material and it uses "plates".

The equivalent model of the super capacitor is shown in **Figure 3**. The given model has two resistance values and one inductance value. R_S represents the series resistance which is responsible for the internal heating losses in the super capacitor whereas, the parallel resistant *i.e.* R_P represents the self discharge effect and the long term performance is dependent on R_P. The actual behavior of the super capacitor is non-linear and its capacitance value can be considered as a constant value if the significant variations are not present in the parameters such as temperature, voltage and current.

The super capacitor is connected to the grid via bi-directional power electronic converter that can be controlled using a decoupled d-q axis control algorithm [13] in order to compensate the power surges or fluctuations from PVES and WES or load variations. The topology of the super capacitor used is shown in **Figure 4**.

AC filter improves the quality of the current and decreases THD value and then power is fed to the step-up transformer that step ups the voltage from 150VAC to the required grid voltage of 400VAC. The parameters for experiment, transformer and SCESS's converter are given in **Table 2**.

Figure 2. Natural gas based micro turbine units (65 kW × 2) at Goldwind Co. Ltd.

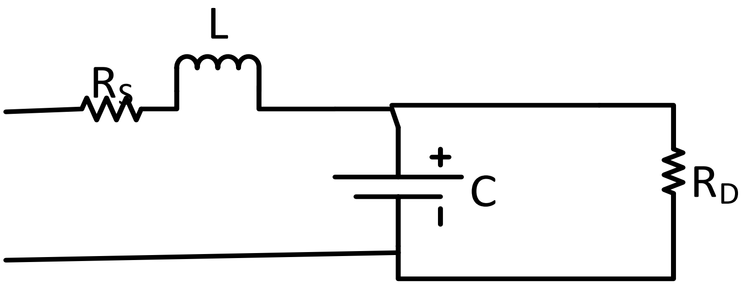

Figure 3. Equivalent model of a super capacitor.

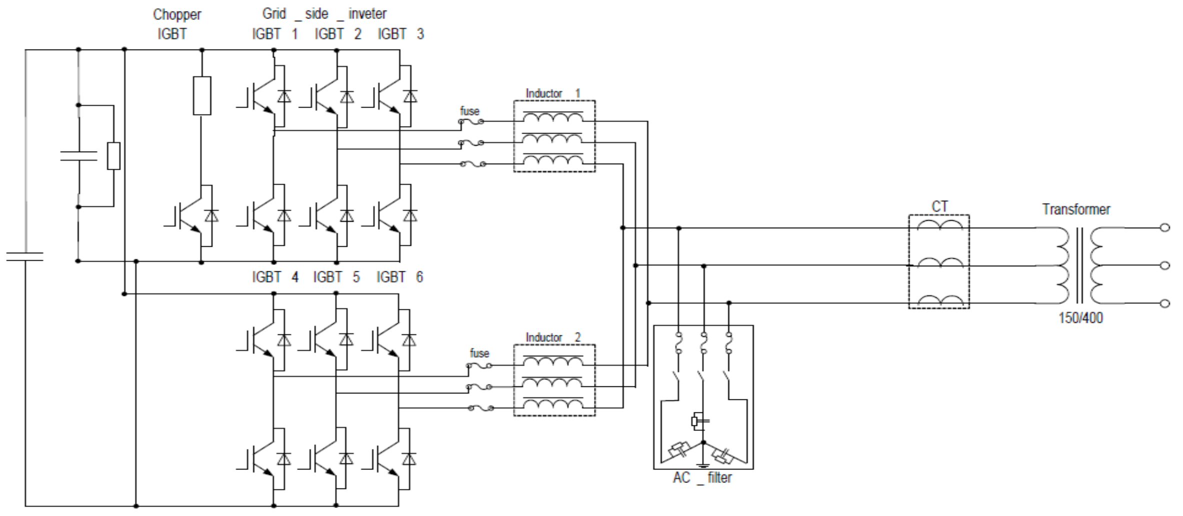

Figure 4. Bi-directional converter topology for SCESS.

Table 2. Parameters.

Parameters for Experiment	Parameters for Converter System	Parameters for Grid Side Transformer	Parameters for Super Capacitor
Altitude (<2000 m)	Rated Voltage (150 V ± 10% Fluctuation)	Type of Transformer (Y-connection)	Rated Capacitance (Approx. 30F)
Protection Type (IP22)	Active Power Capacity (200 kW)	Capacity in Apparent Power (500 kVA)	Operating Temperature Range (−40˚C - +60˚C)
Humidity (10% - 100%)	Rated Frequency (50 Hz ± 5%)		System Working Time (10 s)
Pressure (77,500 Pa - 106,500 Pa)	Switching Frequency (Approx. 2.7 kHz - 3.0 kHz)		
Storage Temperature Range (−40˚C - +60˚C)	Approx. Power Factor (0.9)		
Operating Temperature Range (−30˚C - +50˚C)			

4. Experimental Results

4.1. Transient Response of Micro-Grid under Load Increase of 12 KVA

The transient response of the grid is experimentally studied with and without the super capacitor. In order to check the effect of super capacitor on the grid, an inductive load of about 12 KVA was added to the initial resistive load at t = 80 ms. **Figure 5** shows one phase of the transient voltage response. The response in "red" is the transient voltage with super capacitor whereas the other one represents that of without super capacitor.

It can be noted from **Figure 5** that when the load changes at t = 80 ms approx., the system without super capacitor will take some time *i.e.* approximately 50 milliseconds, to recover the voltage sag while the system with super capacitor has quickly recovered the voltage transient response. The system without super capacitor will take many cycles to restore the voltage to its required level.

4.2. Transient Response of Micro-Grid under Load Increase of 60 KVA

In order to experimentally check the response of the system under the influence of super capacitor, the load is increased to about 5 times the previous value *i.e.* 60 KVA and the transient response of the voltages are shown in **Figure 6**.

Figure 6 shows the three phases of the voltage with phase A in (a), phase B in (b) and phase C in (c). The load change is applied at t = 40 ms approx. and the response show that the system with super capacitor doesn't

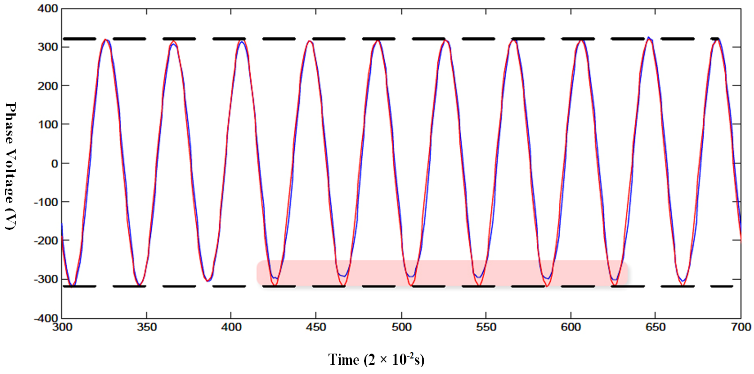

Figure 5. Phase Voltage of the system when load 12 kVA load is added at t = 80 ms ("Blue" without SCESS and "Red" with SCESS).

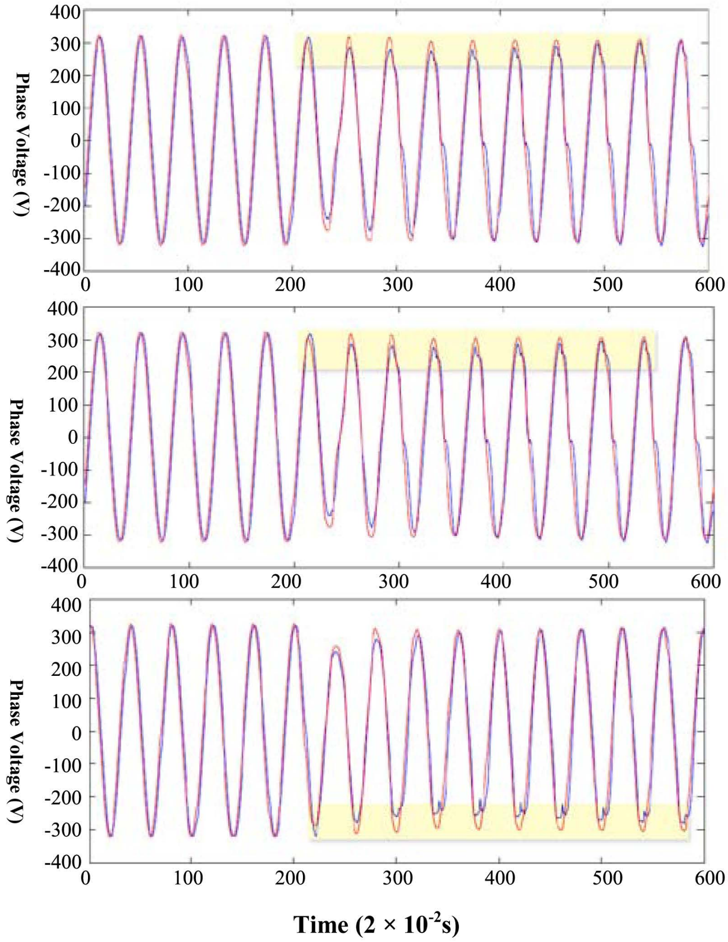

Figure 6. Phase Voltages of the system when load 60 kVA load is added at t = 40 ms ("Blue" without SCESS and "Red" with SCESS) (a) Phase voltage 1; (b) Phase voltage 2; (c) Phase voltage 3.

need 90 milliseconds to recover the voltage and it also shows that it has successfully recovered the voltage sag within a short time of one to two cycles and super capacitor has helped the system to quickly stabilize the response.

4.3. Transient Response of Micro-Grid Due to Sudden Start-Up of an Induction Motor

The starting current for an induction motor has usually a very high value and therefore, the effect of a sudden start of an induction motor on system with and without super capacitor is studied.

Figure 7 shows the voltage and current response comparison for the system with and without the inclusion of super capacitors in the micro-grid. Figure 7(a) and Figure 7(b) show the three phase transient voltages and currents of the system without super capacitor. For the system without super capacitor, it can be seen that when an induction motor suddenly starts-up at t = 0.27 s approx., voltage sags till t = 0.45 s and then it gets stabilized

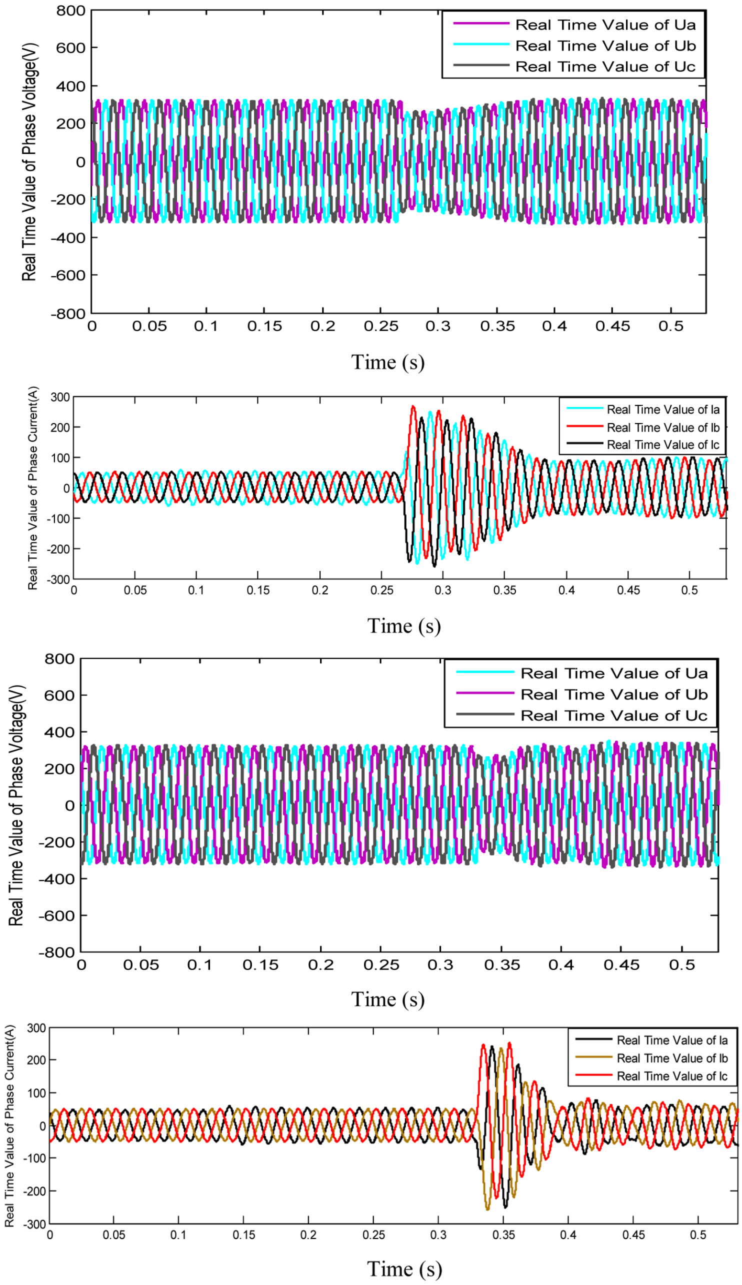

Figure 7. Phase voltages of the system when an induction motor start-ups (a) Three Phase Voltages (without SCESS); (b) Three Phase Currents (without SCESS); (c) Three Phase Voltage (with SCESS); (d) Three Phase Currents (with SCESS).

in about 180 ms but for the system with super capacitor, the induction motor starts-up at t = 0.33 s approx., the voltage sets stabilized in less than 70ms. Similarly, the amplitude of three phase currents increase when the induction motor is connected and current takes less time to stabilized for the system with super capacitor as shown in **Figure 7(d)**.

5. Conclusion

The concept of hybrid micro-grid technology is emerging because of its stable and eco-friendly behavior. Transient analysis of the system is very important in this regard for its successful and stable operation. The parameters such as upper and lower limits of the system's voltages must be taken into consideration, and a careful observation is required to check the transient response of the system under different loads because the hybrid micro-grid must develop a robust system that can work in grid-connected as well as islanded mode. The transient response of the voltage is disturbed for some cycles when a particular load change occurs in the micro-grid system. Although vanadium redox batteries (VRBESS) have higher energy density than lithium-ion batteries (LIBESS), they are not fast enough to stabilize the response. Therefore, in addition to VRBESS and LIBESS, an introduction of a super capacitor (SCESS), as very high energy-density energy storage equipment, will help the system to recover and stabilize three phase voltages rapidly. Hence, using a super capacitor in a hybrid micro-grid system is a requirement of today's micro-grid technology.

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