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Controller Design for Supercapacitor as Energy Storage in Medium Voltage AC System

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Abstract

This paper analyzes the supercapacitor based voltage support system for medium voltage AC system. For the last decade supercapacitors have become an integral part of low voltage power electronic systems where high power density from dc storage device is required frequently. So far their use has been limited to delivering or absorbing pulses of power during transient operation, such as starting up of an electrical motor, storing regenerated energy or supplying instant power in low voltage range within small scale distributed generation system. Not much work has been done in investigating performance of supercapacitor storage in medium voltage ac systems subject to extreme conditions such as sudden load demand in the MW range or network faults. The power source has been designed to ride through 2 seconds voltage sag caused either by high load demand or remote system fault. This paper attempts to investigate how efficiently supercapacitor storage can be utilized to meet the power demand in ac grid.

Keywords

Supercapacitor, Energy Storage, Voltage Source Converter, DC-DC converter.

1. Introduction

In distributed generation system the performance of instantaneous energy sources plays a significant role to balance active power mismatch. In this regard Supercapacitors have been popular candidates for meeting the need for sudden power demand due to their very high efficiency of around 95% [1]. From last some years Supercapacitors have become an integral part of low voltage power electronic systems where high power density from dc storage device is required frequently. So far their use has been limited to delivering or absorbing pulses of power during transient operation, such as starting up of an electrical motor, storing regenerated energy or supplying instant power in low voltage range within small scale distributed generation system [2]. Voltage sags have been found especially troublesome because they are random events lasting only a few cycles. The process equipment may not keep continuing its normal operation during these sags for many cycles and will trip or shut down, although the supply voltage is totally recovered a few cycles after the sag occurrence. Therefore, from the point of view of industrial customers, voltage sags and momentary interruptions might produce the same effect to their processes [3]. Not much work has been done in investigating performance of supercapacitor storage in medium voltage (10-40KV) ac systems subject to extreme conditions such as sudden load demand in the MW range or network faults [4]. This paper attempts to investigate how efficiently supercapacitor storage can be utilized to meet the power demand in ac grid, while also ensuring appropriate control during grid fault conditions. Many surveys regarding power quality problems related to voltage sags and momentary interruptions have been presented. They are usually useful for determining the solution required for tackling the existing problem at a certain industrial facility, with special emphasis on the rating and ride-through capability of proposed mitigation equipment. These surveys agree usually in at least one point, faults on overhead transmission lines contribute to the great majority of voltage sags verified in the distribution network and these sags are the most critical power quality problem to industrial customers. Prior works have incorporated super capacitor storage with different energy sources in a common dc bus and their focus is to manage the power flow to and from the dc bus or the condition of multiple sources like batteries, photovoltaic, wind, gas cogeneration and flywheels [5]. Some discussed multiple modes of operation like power dispatch, voltage regulation and control of power flow to and from different sources and loads in small scale dc or ac distributed network, also some proposed a fault protection scheme applicable to a dc bus serving

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variety of loads and generators using modern voltage source converters as current limiting circuit breakers [6, 7]. Their method of fault interruption and isolation is based upon predefined protection zones that are not device based but by embedded circuit breakers within the voltage source converters. Their energy sources were local generators and no dc storage capable of providing instantaneous power was considered. The work discussed focused on power balancing and control of energy flow among multiple energy sources. As Supercapacitors are capable of providing a huge amount of power within a very short time, it is possible for them to discharge a large energy into a fault before circuit breaker can open. Hence uncontrolled support of the grid can be dangerous. On the other hand it is still necessary to ensure sufficiently fast release of power during sudden increase of load demand. There is very little research in this area where an intelligent controller on the dc side can determine whether or not to support a sagging voltage in the grid (depending on cause load or fault), and how much energy to deliver at any instant [8].

This paper begins to address some of the following important issues:

- Design and develop a controller intelligent enough to maintain continuity of power to loads.
- Manage fault in low and medium voltage system.
- To intelligently manage the supply of energy to loads and maintain stability using ramp-rate limits.

2. System configuration

Figure 1 shows the configuration of the reference system, which is also a typical configuration of energy storage for grid support and peak power shaving. A 13.8KV grid is fed by a 4KV, 5MVA steam driven main generator (G). A supercapacitor storage and DC-DC chopper represents the alternate energy storage system coupled with the grid through 0.77KV/13.8KV step up transformer. No long term backup energy storage has been considered, the power source has been designed to ride through 2 seconds voltage sag

Three modes of operation have been considered:

1) Normal operating mode: - In this mode there is no real power exchange between the supercapacitor and the grid as the main generator can deliver all of the required power.
2) Energy discharge mode: - Supercapacitor energy storage delivers energy to the grid to compensate the voltage sag due to a high load demand that exceeds the capacity of the main generator.
3) Charging mode: - Supercapacitors charge up during this mode if there is excess energy available in the grid due to a low load demand.

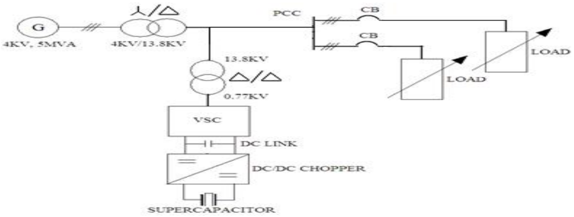

Figure1: System configuration Supercapacitor energy storage design

Figure 2 describes the simple model of supercapacitor storage used.

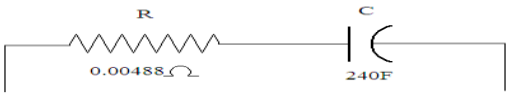

Figure 2: Model of supercapacitor storage

The storage is sized to support a 1MW load for 2 seconds, which is sufficient for a system with similar rating and applications in peak power shaving and absorbing excess power. The total supercapacitor stack voltage is taken to be V_0 =500V and the minimum allowable voltage of the storage is V_1 = 400V, considering the combined efficiency (81%) of the DC-DC chopper and the inverter [4].

Total Energy required,

$$E = \left(\frac{(1\times10^6)}{0.81}\right)\times\left(\frac{2}{3600}\right)$$

$$= 685.87\text{W-h}$$

$$= 2.47\text{MJ}$$

Total capacitance required (C) is calculated from the energy equation:

$$E = \frac{1}{2}C(V_0^2 - V_1^2) \qquad \ldots\ldots (1)$$

$$2.47\times10^6 = \frac{1}{2}\times C\times(500^2 - 400^2)$$

$$C = 54.86\text{F}$$

But due to the limited current capability this storage has been oversized with the number of parallel strings of modules N_p=16, and modules in series N_s=11.This provides a total capacitance of 240F and a total effective series resistance of 0.00488OHM.

Energy Storage and inverter control

The basic control strategy is described in figure 3. The inverter and the DC-DC converter topology is chosen as such since it is the most popular and cost effective configuration when dealing with ac/dc power quality improvement converters. The PWM control of the voltage source converter and voltage control of the dc link is used due to its simplicity and successful application in similar systems. The bidirectional chopper controls the power flow between the supercapacitor and the grid. The approach followed in this work was to develop an appropriate control of DC link voltage (V_{dc}) separately using the inverter control block to minimize the interaction between the control of the DC-DC chopper and the inverter that would work as a voltage source inverter only during normal operating mode. The grid voltage used as the input signal for the inverter control is calculated as follows:

$$V_G = \sqrt{1/3(V_a^2 + V_b^2 + V_C^2)} \qquad \ldots\ldots\ldots \quad (2)$$

Supercapacitor charge/discharge control uses the demanded power (P) at the grid to control the power flow to and from the supercapacitor the input signal V_{dc} is only used to ensure that the control for voltage source inverter is working properly and is able to control V_{dc} at the required level.

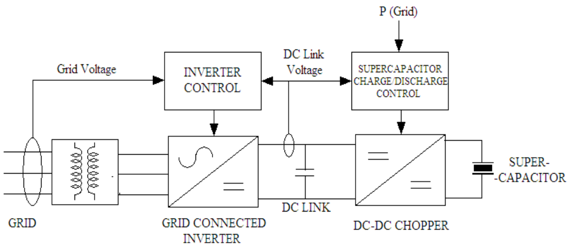

Figure 3: Energy storage and Inverter control

The pulse width modulation (PWM) voltage source converter (VSC) provides a power electronic interface between AC power system and supercapacitor. In the PWM generator, the sinusoidal reference signal is phase modulated by means of the phase angle, α, of the VSC output ac voltage. In this work, the amplitude modulation index of the sinusoidal reference signal is chosen 1.0. The modulated sinusoidal reference signal is compared with the triangular carrier signal in order to generate the gate signals for the IGBT's. The frequency of the triangular carrier signal is chosen 450 Hz. The DC voltage across the capacitor is 1000 Volt, which is kept constant throughout by the 6-pulse PWM converter.

The supercapacitor is charged or discharged by adjusting the average (i.e., DC) voltage across the coil to be positive or negative values by means of the DC-DC chopper duty cycle D, controlled by a conventional PI controller as shown in Figure 3, where ΔP indicates the real power deviation of grid. When the duty cycle is larger than 0.5 or less than 0.5, the supercapacitor is either charging or discharging respectively. When the unit is on standby, the supercapacitor current is kept constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the supercapacitor to be zero. In order to generate the gate signals for the IGBT's of the chopper, the PWM reference signal is compared with the saw tooth carrier signal. The frequency of the saw tooth carrier signal for the chopper is chosen 100 Hz.

Voltage source converter control

Voltage source inverter is the interface between the grid and the supercapacitor energy storage unit. The reference signal for the PWM control for the voltage source inverter is phase modulated by means of the phase angle, α described in figure 4.

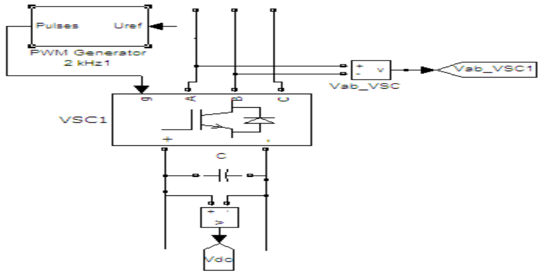

Figure 4: Control for voltage source inverter

2.4 DC-DC Chopper control

Figure 5 shows the control strategy for the DC-DC converter. DC-DC converter works as a simple buck-boost converter with P_grid as the main driving control signal obtained from calculating the three phase power in the grid. There is a window for the controller (3.8MW to 4.1MW) within which is operates in the normal operating mode. So the converter will operate in energy discharge mode when P_grid > 4.1MW and will operate in charging mode if P_grid < 3.8MW.

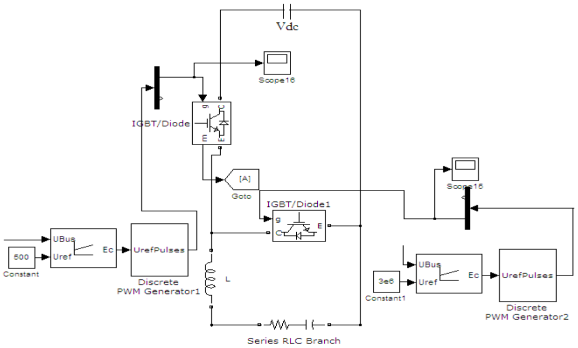

Figure 5: Control for DC-DC converter

The process of constant voltage charging control

The triangular wave comparison method is used in the constant voltage charging mode, through the realization of double-loop control. The outer ring is the output DC voltage control, and the inner loop is the output DC current control. The output of the PI regulator in the outer loop is the DC current signal i_d. After the comparison between i_d and the actual DC output current signal, the error current is amplifies through the PI regulator. Then take the amplified error comparing with the actual DC output voltage, and the new error will go through the triangle-wave comparator to generate PWM waveform to control the switching device S2. By doing so, the actual voltage will track the command voltage as shown in Figure 6.

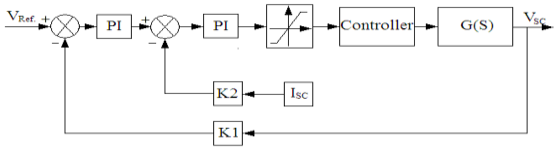

Figure 6: Block diagram of constant current charging mode

The process of discharging control

The direct current control is used in the discharging control, through the realization of double-loop control. The outer ring is the output voltage control, and the inner loop is the input current control. Compared the actual output voltage with the command voltage signal, then put the error goes through PI regulator to get the DC current signal i_d. Compared i_d with the actual input current, and put the error goes through PI regulator. Then put the output go through the triangle-wave comparator to generate PWM waveform to control the switching device S2. By doing so, the actual input current will track the command current to control the output voltage. The control process is shown in Figure 7.

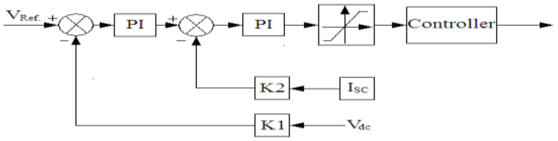

Figure 7: Block diagram of discharging control

3. Performance analysis

Supercapacitor voltage, grid voltage, grid power and dc link voltage observed for analysis of system performance in sudden load increase. The simulation is carried out in Matlab Simulink.

At 1.8 seconds line load increased from 4.0MW to 4.7MW and continued till 3.8 seconds, in this period the converter operated in energy discharge mode and supplied excess energy from supercapacitor, in this period the grid voltage and power is observed in Figure 8, at same time supercapacitor started discharging and its voltage is observed in figure 9.

Figure 8: Energy discharged from supercapacitor.

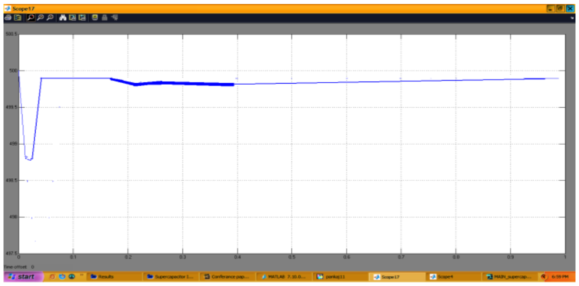

Figure 9: Supercapacitor voltage.

In load demand increased period the boost converter operated, the IGBT firing pulses observed in Figure 10. In that period dc link voltage observed steady in figure 11.

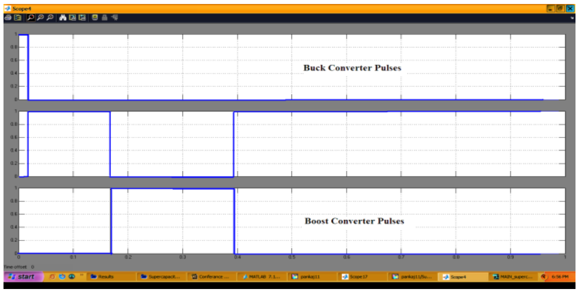

Figure 10: Buck-Boost converter firing pulses in energy discharge mode

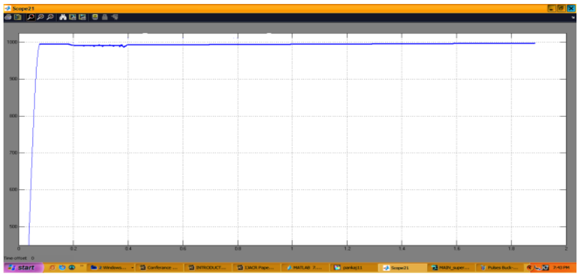

Figure 11: DC link voltage.

4. Conclusion and Future Work

In energy discharge operating mode the grid voltage maintains its desired value with negligible fluctuations also supercapacitor fed extra energy demand of grid for 2 seconds without disturbing dc link voltage. The grid voltage waveform is also clean with very little distortion. Until now the basic operation and control for supercapacitor based energy storage has been developed in the medium voltage system. Further Work being done to study the effects of a fault and develop the controls for efficient management of power between the loads even during a fault condition and maximum utilization of resources and robustness in the stability of grid voltage.

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