THE CONTROL OF A STATCOM WITH SUPERCAPACITOR ENERGY STORAGE FOR IMPROVED POWER QUALITY

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ABSTRACT

STATCOMs provide controlled VAr compensator for grid voltage support. This paper describes the control of a STATCOM which incorporates a supercapacitor energy storage unit. This combination can deliver real power to the grid and, with the support of an enhanced communication network between system elements, offers the potential to improve the stability margin of a given power system.

INTRODUCTION

STATCOMs are used for grid voltage support to improve power quality. Their dynamic response is an order of magnitude faster than conventional synchronous generators or thyristor based static compensators. STATCOMs, however, are limited in their ability to improve system stability due to their limited capability for delivering real power [1][2][3][4]. Over the past decade, there have been significant developments in energy storage technologies for example improved battery technologies, fuel cells, flywheel energy storage and superconducting magnetic energy storage for bulk energy storage for power balancing of grid systems [1][2][5][6][7][8]. Some of these energy storage systems have been used with STATCOMs for steady-state voltage control and to withstand power outages [6][7][9]. These systems do however have some limitations due to their slow speed of response.

Supercapacitors are new devices which can store significant amounts of energy and quickly release it. Their main application is for short term “power boost” type applications where they can release a large amount of energy quickly [10], and then recharge, with a smaller current if necessary. This STATCOM plus Supercapacitor Energy Storage (SCESS) requires fast and tight control structures which must operate in coordination with other system elements e.g. system protection, distributed generation etc. It is therefore one of the key elements of a “SmartGrid” - one which integrates energy infrastructure, processes, devices, information into a coordinated and collaborative process which allows energy to be generated, distributed and consumed more effectively and efficiently. It therefore provides the facility for short term fast response bursts of power under abnormal or fault conditions.

The aim of this work is to investigate how supercapacitor based energy storage technology can be used to enhance the operation capability of a STATCOM unit to maintain a high quality distribution voltage and improve the system stability. The main objective here is to determine whether they can be used to improve the power system dynamic behavior during faults, or during large load changes. For this purpose a prototype experimental rig has been constructed.

SYSTEM OVERVIEW

The system comprises a STATCOM with a SCESS. The SCESS consists of a bank of supercapacitors which is interfaced to the DC link of the STATCOM by a bidirectional Dc to DC converter, which controls the charge and discharge of the supercapacitors. The circuit diagram is shown in Fig. 1.

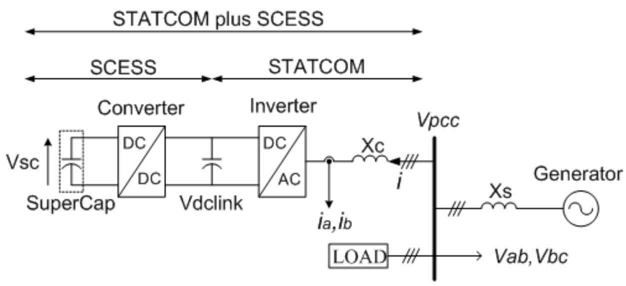

Fig.1 Circuit diagram of an application of STATCOM plus SCESS.

In Fig.1 *Xc* represents a coupling reactance, *Xs* represents the reactance of the power supply (utility) and for this work, the effect of a large local load on the quality of the voltage at the point of common coupling (PCC) is considered. For example, large step changes to the load can cause swells and sags at PCC.

SUPERCAPACITOR ENERGY STORAGE

The power circuit for the SCESS is shown in Fig.2. The current and voltage ripple are used as constraints to derive the inductance (*L*), and nominal DC link voltage respectively. The DC link of the SCESS will be connected to the STATCOM as these two units (STATCOM and SCESS) share the DC link capacitor, a conventional electrolytic capacitor *C*. *Csc* is the supercapacitor module, D is a diode, and IGBT is an Insulated Gate Bipolar Transistor.

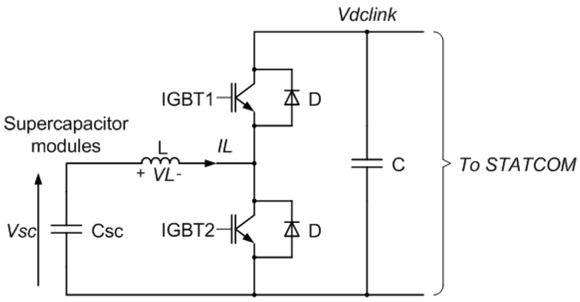

Fig. 2 Circuit diagram of SCESS

The DC-to-DC converter operates in "Buck Mode" to recharge the supercapacitors, whereas "Boost Mode" transfers the stored energy to the DC link maintaining the DC link voltage constant during real power delivery. The supercapacitor voltage *Vsc* will drop to 0V if all the stored energy is utilised. However, this will affect the stability and efficiency of the operation of the DC-to-DC converter. Therefore a lower limit is placed on the supercapacitor voltage; if up to 75% of the stored energy is to be utilised, a reasonable minimum value for *Vsc* is 50% of the maximum value. For the prototype designed here the maximum voltage rating of the supercapacitor is 200V, and the minimum voltage is therefore set at *Vsc_min=100V*. The optimum point where the stored energy can be extracted from the supercapacitors is at a duty cycle of about 0.5 for the DC-to-DC converter [11]. At this optimised operating point the DC link voltage is therefore *Vdclink=400V*.

INDUCTOR DESIGN

The inductance in Fig. 2 is selected according to the following equations [11]. In boost mode, only *IGBT2* is used for control, and the DC link voltage is expressed in (1). Assuming *Vsc* acts as a DC voltage source, when *IGBT2* is *ON*, the inductor current I_L increases ideally as in (2) (assuming the resistance of the inductor is negligible). When *IGBT2* is *OFF*, (3) gives the reduction in inductor current $(\Delta \mathbf{I_L})$.

$$V_{dclink} = \left(\frac{V_{sc}}{1-d}\right) \quad (1)$$

$$\Delta I_{L(ON)} = \left(\frac{V_{sc}}{L}\right) T_{ON} \quad (2)$$

$$\Delta I_{L(OFF)} = \left(\frac{V_{sc} - \dfrac{V_{sc}}{1-d}}{L}\right) T_{OFF} \quad (3)$$

where d is duty cycle of the IGBT, V_{dclink} is DC link voltage, V_{sc} is supercapacitor voltage, $\Delta I_{L(ON)}$ is change in inductor current when IGBT2 "ON" , $\Delta I_{L(OFF)}$ is change in inductor current when IGBT2 "OFF", T_{ON} is ON period of the IGBT, T_{OFF} is the OFF period of the IGBT. Considering at steady state and continuous inductor current with $T = T_{ON} + T_{OFF}$, assuming $\Delta I_{L(ON)} = \Delta I_{L(OFF)}$, the change in inductor current is expressed in (4).

$$\Delta I_L = \left(\frac{V_{sc}}{L}\right) dT \quad (4)$$

The value of inductor L can be calculated from (4). The DC-to-DC converter is normally designed with a current ripple of 1% [11]. However, this can be relaxed for supercapacitors and the desired ripple is set at 2%. With the maximum power designed at 10kW and *Vsc_min=100V*, 2% of the maximum current gives $\Delta I_{L(max)}=2A$. The largest ripple occurs at the maximum duty cycle of 1.0. At a switching frequency of 5 kHz the required inductance is calculated as 10 mH. A similar analysis has been applied to confirm that the ripple is limited to within 2% when operated in buck mode.

DC LINK CAPACITOR DESIGN

The design of DC link capacitor is focused on boost mode operation. In boost mode when *IGBT2* is ON, it is the DC link capacitor that supplies energy to the grid – the supercapacitors are transferring energy to *L*. The amount of charge *Q* stored in the DC link capacitor decreases as it supplies the required real power via the STATCOM to the grid, and the DC link voltage drops. When *IGBT2* is OFF the DC link capacitor is charged from the SCESS (the stored energy in *L*), and the DClink voltage increases. This cycle of store and supply charge causes a ripple voltage, ΔV, shown in Eqn (5).

$$\Delta V = \frac{\Delta Q}{C} = \frac{I_{load} dT}{C} = \frac{PdT}{CV_{dclink}} \quad (5)$$

where ΔV is DC link ripple voltage and ΔQ is change in capacitor charge. P is power rating, I_{load} is load current supplied to grid, and T is switching period. Maximum ripple voltage, ΔV_{max}, occurs when maximum power is supplied to the grid and is at duty ratio $d = 1.0$. With an acceptable ripple voltage of 2%, the required DC link capacitor is calculated as 0.65 mF. A 1 mF electrolytic capacitor from a commercial inverter is therefore used.

SCESS CONTROL

The SCESS is operated in two modes. Boost mode utilises the stored energy in the supercapacitors whereas buck mode recharges the supercapacitors. The control structure for boost and buck operation are shown in Fig.3 and 4. A small signal model of the converter has been derived using state-space averaging technique, according to [12][13] and is given in (6) and (7) for boost and buck mode respectively. An S-domain compensator for the outer voltage loop control can be designed using pole placement techniques. The inner loop uses state equations to calculate the duty cycle (δ) directly. The major difference for the two modes is the outer loop control where boost mode controls the DC link voltage, while buck mode controls the supercapacitor voltage.

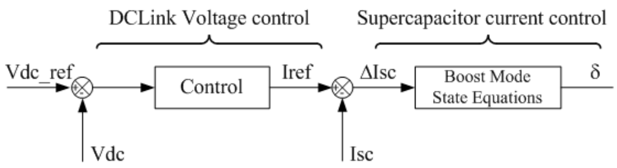

Fig.3 Control Concept for Boost Mode

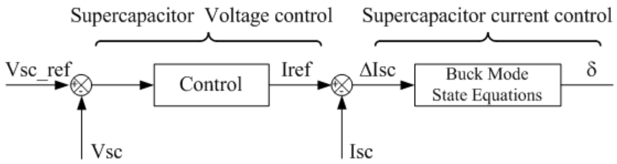

Fig.4 Control Concept for Buck Mode

$$\frac{\Delta V_{dc}}{\Delta I_{ref}} = \frac{\frac{r_s}{2}\left\{(1-d) - \frac{2LI_{dc}}{TV_{dc}(1-d)^2}\right\}\left\{\frac{2f_s}{(1-d) - \frac{2LI_{dc}}{TV_{dc}(1-d)^2}} + s\right\}\left(s + \frac{1}{Cr_s}\right)}{\left\{s + \frac{f_s}{(1-d)}\right\}\left\{s + \frac{(1-d)^3 T}{2CL} + \frac{I_{dc}}{CV_{dc}}\right\}} \quad (6)$$

$$\frac{\Delta V_{sc}}{\Delta I_{ref}} = \frac{\frac{dR_s}{T(1-d)}\left\{1 + s\left(\frac{T(1-d)}{2} + \frac{LI_{sc}}{dV_{sc}}\right)\right\}\left(s + \frac{1}{C_{sc}R_s}\right)}{s^2\left\{1 - \frac{dR_s I_{sc}}{V_{sc}(1-d)}\right\} + s\left\{\frac{2L(C_{sc}V_{sc} + I_{sc}(T(1-2d) - CR_s)) - C_{sc}R_s T d V_{sc}(2d-1)}{2C_{sc}LTV_{sc}(1-d)}\right\} - \frac{d(2d-1)}{2C_{sc}L(1-d)}} \quad (7)$$

Vdc is the DClink voltage, I_{dc} is the DC link current, I_{sc} is the supercapacitor current, r_s is the series resistance of DClink capacitor, R_s is the series resistance of the supercapacitor modules.

STATCOM CONTROL DESIGN

Two control loops are employed for the STATCOM: - the DC link voltage (*Vdclink*) control and current control as shown in Fig 5 and Fig. 6 respectively [14].

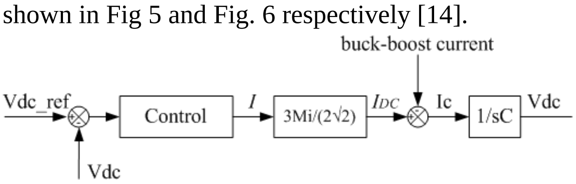

Fig.5 Vdclink Control Design

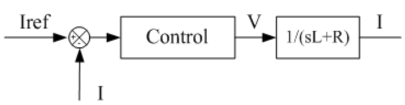

Fig.6 Current Control Design

The outer voltage loop usually employs a slow bandwidth PI compensator (< 20Hz), and is designed using the value of DC link capacitance only. The inner current controls for the STATCOM use a vector control strategy, aligned to a rotating synchronous reference frame fixed to the voltage vector at the point of common coupling, *Vpcc*. When this approach is used, the STATCOM current is decomposed to a power component (*d* component) and a reactive power component (*q* component). Each component is controlled using its own control loop, simplified in Fig. 6, and the PI controllers are designed to achieve a 100Hz bandwidth. Note that Mi is the nominal operating point for the modulation index of the STATCOM, (1/sC) is the impedance of the DC link capacitor, and (sL+R) is the impedance of the coupling reactor.

CONTROL OF STATCOM PLUS SCESS

A feedforward control technique has been applied to the STATCOM with SCESS unit as indicated in Fig. 7 and 8.

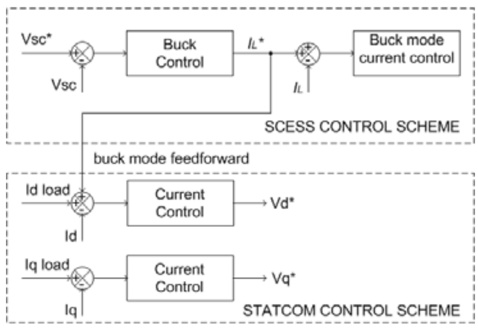

Fig. 7 Control of STATCOM plus SCESS (Mode 2)

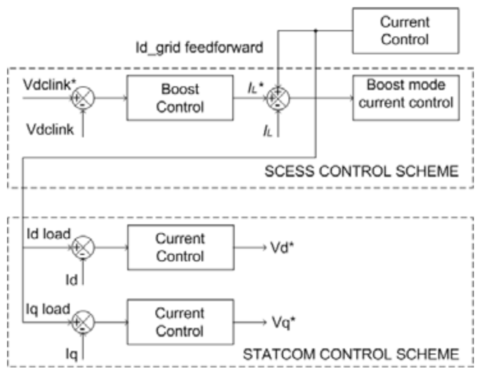

Fig. 8 Control of STATCOM plus SCESS (Mode 3)

The overall control has three modes of operation i.e. (1) normal STATCOM operation (i.e. supplying reactive power only to the grid), (2) recharging of the supercapacitors, and (3) supplying real power to the grid. For mode (1) the STATCOM controls the DCLink voltage using the scheme illustrated in Fig. 5, and the SCESS can be ignored. In mode (2) "buck mode", the SCESS is controlled in buck mode according to Fig. 4. A feedforward of the supercapacitor charge current is added to the STATCOM control as shown in Fig. 7 to draw real power from the grid to the DClink via operation of the STATCOM DC link voltage controller and transfer it in the supercapacitor unit. In mode (3) "boost mode", the mode is triggered by an external demand – in this case the measurement of a local load current – which acts as a feedforward demand for the controller. To prevent the SCESS "boost mode" control and STATCOM control fighting each other, the STATCOM DC link controller is disabled. The energy from the supercapacitors is fed to the grid via the boost mode of Fig.3 with a feedforward demand as shown in Fig. 8.

EXPERIMENTAL RESULTS

The experimental rig comprises ten 20V, 95F, 19kJ supercapacitor modules manufactured by ELIT connected in series. The grid voltage is 110V, and *Vdclink* is 400V. The system is setup to supply and absorb real power to/from grid with a line current of 7A. Fig.9 shows experimental results of the STATCOM with SCESS when it delivers real power to the grid – in this case corresponding to a d-axis current demand of 7A made at t=0s. The figure shows ac line current and phase voltage at PCC, and it can clearly be seen that the STATCOM is injecting real power into the system – the phase voltage and line current are 180^{o} out of phase. The DC link voltage is also illustrated in Fig 9; the Boost mode operation of the SCESS clearly regulates the DC link voltage at 400V during this operation.

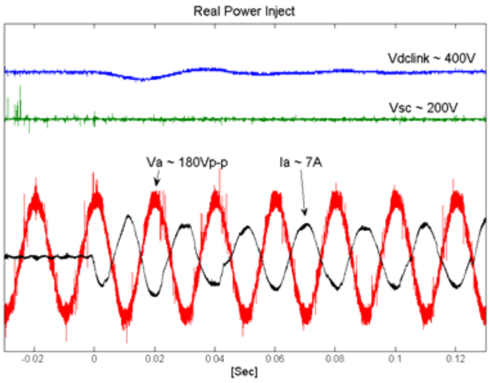

Fig. 9 *Vdclink*, *Vsc*, *Va*, and *Ia* during STATCOM plus SCESS inject real power to grid.

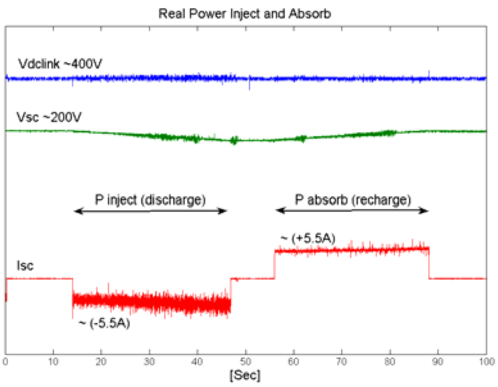

Fig. 10 *Vdclink*, *Vsc, and Isc* during STATCOM plus SCESS inject and absorb real power.

Fig.10 shows the DC link and supercapacitor voltage corresponding to supercapacitor current during real power injection and recharging – the DC link is maintained constant while the supercapacitor voltage responds to the discharge and recharge current.

CONCLUSIONS

A supercapacitor energy storage system has been incorporated with a STATCOM. This allows the STATCOM to deliver real power to the grid for short periods of time. The supercapacitors are interfaced to the DC link via a DC-to-DC converter; the control design for this converter based on a state space small signal model and works effectively to maintain the DC link voltage during boost mode, and recharges the supercapacitors during buck mode. Experimental results confirm that the STATCOM plus SCESS can deliver real power to the grid, to help maintain voltage quality at the point of common coupling during large load changes. To achieve maximum grid benefit, the command values for this device must come from a fast, grid based communication scheme, making them an ideal candidate for the "SmartGrids" concept. Both active and reactive power can be injected dynamically onto grid, a key to improving the dynamic stability of the power system.

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