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A Cascaded Converter-Based StatCom with Energy Storage

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Abstract: Due to the advantages for high power applications, multi-level converters have been introduced to Flexible AC Transmission Systems (FACTS) to enhance power transmission system operation. Although several multi-level StatCom topologies have been proposed to verify the high performance of multi-level converters used in reactive power compensation, they are not capable of controlling active power flow. To make multi-level converters more flexible and effective for active power flow control, energy storage systems are incorporated into StatCom, such as flywheels and batteries. In this paper, battery energy storage systems (BESS) are incorporated into a cascaded converter-based StatCom to implement both active and reactive power flow control using a PQ-decoupled PI control strategy. Furthermore, the dynamics of the integrated system in damping power oscillations are studied using an electromagnetic transient program PSCAD/EMTDC. Simulation results are provided to verify the feasibility and practicality of these ideas.

I. INTRODUCTION

Since a prototype of an advanced static var compensator was reported in 1981 [1], StatComs using voltage-source-converters have been widely accepted to improve power system operation. In bulk power systems, they are indispensable to stabilize the power system and to maintain bus voltage. Several StatComs based on GTOs and zig-zag transformers have been developed and put into operation within the last few years [2]. Typically, a 48-pulse StatCom consists of eight voltage-source-converters connected through eight zig-zag transformers to reduce harmonic distortion. These transformers are the most expensive components in the system and cause substantial active power losses.

One popular method to eliminate the bulky zig-zag transformers is to use multi-level converters. The general structure of multi-level converters is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The advantages of the multi-level structure for the StatCom are [3]:

- elimination of the need for bulky transformers,
- reduction of the output harmonic levels by synthesizing sinusoidal voltages,
- better suitability for high voltage, high power applications, and
- decreased electromagnetic interference levels due to decreased levels of *dV/dt*.

Multi-level StatComs exhibit faster dynamic response, smaller volume, lower cost, and higher ratings than traditional StatComs. Multi-level StatComs, however, do have some limitations in high power transmission system operation. One problem of the multi-level StatCom is that the distributed resistances and switching components cannot be internally compensated [4][5]. Typically active power is absorbed from the system to compensate for the StatCom losses, which adds additional costs to the control hardware and software and decreases the transmission efficiency.

Bulk power systems frequently require active power flow control for better performance such as loop flow reduction, oscillation damping, and transient stability improvement, but a StatCom by itself is not able to affect the active power flow. However, energy storage devices such as batteries or flywheels may enable multi-level StatComs to solve this problem. A multi-level converter connected to an energy storage device can control both active and reactive power flow, providing more flexible and versatile power transmission operation. Recent advances in battery energy storage technology make it possible to use batteries in high power applications.

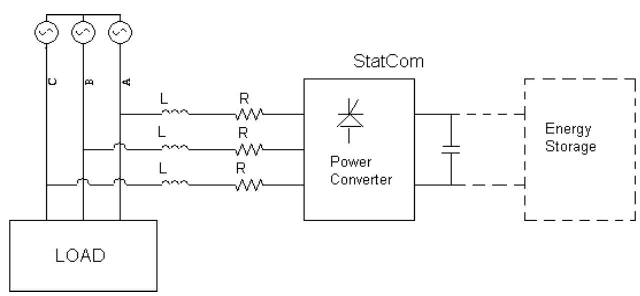

Fig. 1 Simplified Structure of a StatCom with BESS

Taking advantage of a multilevel topology -- cascaded converters and battery energy storage systems (BESS), this paper will

- combine a five-level cascaded StatCom with a battery.
- describe a PQ-decoupled control strategy to implement both active and reactive power flow control with the combined compensator.
- Study the performance of the combined compensator in damping power oscillations, and
- provide simulation results in EMTDC/PSCAD to verify the feasibility and effectiveness of the cascaded converter-based StatCom/BESS.

II. CASCADED STATCOM/BESS

The cascaded multilevel converter shown in Fig. 2 uses several full bridges in series to synthesize staircase waveforms. Because every full bridge can have three output voltages with different switching combinations, the number of output voltage levels is *2N+1* (*N* is the number of full bridges in every phase). For active power conversion, this topology needs separate DC sources. The structure of separate DC sources is suitable for various energy storage devices such as fuel cells, batteries and flywheels. This topology is free from complicated connections and large numbers of components, which is the case with diode clamp and flying capacitor converters. When a cascaded converter is connected with a BESS, it does not have a capacitor voltage balancing problem.

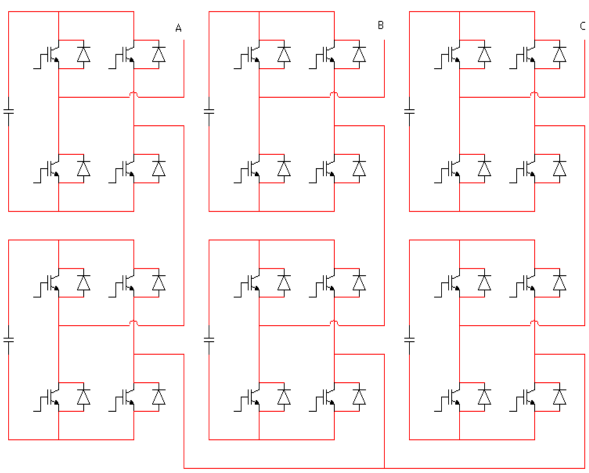

Fig. 2. Topology of a Cascaded 5-level Converter

The features of a cascaded multilevel converter are summarized below:

Advantages:

- Uses the fewest components to achieve the same number of levels,
- enables modularity of packaging, and
- does not have the balancing problem with BESS

Disadvantages:

- It needs multiple separate DC sources for active power conversion

Based on the description above, a 5-level cascaded converter has been combined with separate dc sources (batteries) to form a multilevel StatCom/BESS for future analysis. In this study, six battery cells (72V each) are parallel to the six DC capacitors respectively and a Y-Y transformer interfaces the compensator with 230V AC system. This configuration is derived from the experimental prototype at the University of Missouri at Rolla.

III. CONTROL STRATEGY

The StatCom/BESS is different from a conventional StatCom in that it can operate in four quadrants in the PQ plane. The objective of a control strategy is to enhance the power transmission operation by injecting or absorbing both active and reactive power to or from the grid.

A. System Modeling for Multi-level StatCom/BESS

The implementation of power flow control is based on the assumption of modulation control of the multi-level converter. The output voltage of a five-level inverter can be controlled by extended sinusoidal pulse width modulation (SPWM), which is an extension of conventional SPWM. Since five level converters can output 4 levels symmetric about zero, four high frequency triangle waveforms at different levels will modulate the reference sinusoidal waveform to get suitable switching signals. The amplitude of the converter output voltage is approximately 2Vdc**K*, where *K* is the ratio of the sinusoidal amplitude to four times the triangular amplitude.

When the active and reactive power outputs of the cascaded StatCom/BESS are to be regulated, there are only two variables to control: one is α -- the angle between the StatCom output and system voltage, the other is *k*, which gives the fundamental frequency component of StatCom output voltage. The *k* is adjusted by controlling the PWM gain of the converter. In the dq system reference, the dynamic StatCom/BESS can be modeled as [6][7]:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ V_{dc}\end{bmatrix} = \omega_s \begin{bmatrix} -\frac{R_s'}{L_s'} & \frac{\omega}{\omega_s} & 0 \\ -\frac{\omega}{\omega_s} & -\frac{R_s'}{L_s'} & 0 \\ 0 & 0 & -\frac{1}{C'}\left(\frac{R_b' R_{dc}'}{R_{dc}'+R_b'}\right)\end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc}\end{bmatrix} + \omega_s \begin{bmatrix} \frac{V_{dc}}{L_s'} k\cos(\alpha+\theta) \\ \frac{V_{dc}}{L_s'} k\sin(\alpha+\theta) \\ -\frac{i_d}{C'}k\cos(\alpha+\theta) - \frac{i_q}{C'} k \sin(\alpha+\theta)\end{bmatrix} - \omega_s \begin{bmatrix} \frac{V_s\cos\theta}{L_S'} \\ \frac{V_s \sin\theta}{L_S'} \\ \frac{-V_b}{R_b' C'}\end{bmatrix} \tag{1}$$

where

i_d and i_q are the injected per unit dq StatCom currents,
V_{dc} is 2 times of per unit voltage across the dc capacitor C′,

R′$_s$ and L′$_s$ represent the StatCom transformer losses,
k and α are the fundamental frequency component of the StatCom voltage and angle respectively,
V$_b$ is the per unit battery voltage,
R′$_b$ represents the battery losses,
R′$_{dc}$ represents the seething losses, and
V$_s$∠θ is the per unit system side (ac) bus voltage

To develop a control strategy, this model can be simplified with some assumptions. Since control is defined for a particular StatCom/BESS, the system voltage angle θ can be taken to be zero, thus the StatCom/BESS active power P and reactive power Q on the power system side can be calculated in the reference coordinates as

$$P=V_s i_d \qquad Q=-V_s i_q$$

At equilibrium, there is no active power exchange between the StatCom and battery, thus the model can be linearized to obtain:

$$\frac{d}{dt}\begin{bmatrix}\Delta i_d\\ \Delta i_q\end{bmatrix}=\begin{bmatrix}-\frac{R_s'}{L_s'} & 0\\ 0 & -\frac{R_s'}{L_s'}\end{bmatrix}\begin{bmatrix}\Delta i_d\\ \Delta i_q\end{bmatrix}+\begin{bmatrix}x_1\\ x_2\end{bmatrix}$$
$$\begin{bmatrix}x_1\\ x_2\end{bmatrix}=\begin{bmatrix}\frac{V_{dc0}}{L_s'}\cdot\Delta k_0+\omega_0\cdot\Delta i_q+\frac{k_0}{L_s'}\cdot\Delta V_{dc}\\ \frac{V_{dc0}k_0}{L_s'}\cdot\Delta\alpha_0-\omega_0\cdot\Delta i_d\end{bmatrix} \tag{2}$$

where $[x_1, x_2]^T$ is the control variable vector. In the StatCom/BESS, the DC voltage V_{dc} is held constant by the batteries, so ΔV_{dc} is negligible.

B. PQ Decoupled PI Control Strategy

With the simplified model above, a PI control can be applied to the control variable vector $[x_1, x_2]^T$ to yield equation (3).

$$\begin{bmatrix}x_1\\ x_2\end{bmatrix}=\begin{bmatrix}(k_1+\frac{k_2}{p})\cdot(i_{d\_ref}-i_d)\\ (k_1+\frac{k_2}{p})\cdot(i_{q\_ref}-i_q)\end{bmatrix} \tag{3}$$

where

$$\begin{bmatrix}i_{d\_ref} & i_{q\_ref}\end{bmatrix}^T=\begin{bmatrix}\frac{P_{ref}}{V_s} & \frac{Q_{ref}}{V_s}\end{bmatrix}^T$$

Fig. 3 shows the diagram of the PQ decoupled PI control strategy.

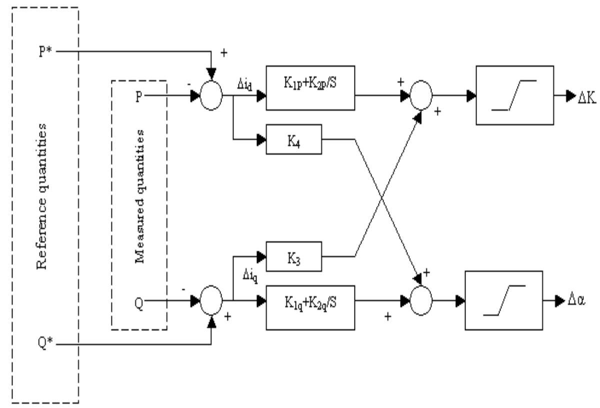

Fig.3 PQ Decoupled PI Control Strategy

IV. CONTROL FOR OSCILLATION DAMPING

A power system may encounter power oscillations following a disturbance. As shown previously [8], modulation of active power can have a more significant influence on damping power swings than reactive power alone. Incorporation of a BESS enables the combined compensator to inject or absorb active power to or from the power network. With the PQ decoupled control depicted above, the cascaded StatCom with BESS can be an effective means of power oscillation damping.

To show the dynamic performance of the cascaded StatCom/BESS, a typical two-machine system equivalent is shown in Figure 4. When bus A is subjected to a three-phase fault to ground, the disturbance will induce a low frequency oscillation and system-wide voltage drop. To damp the power swings, the integrated compensator is hooked on bus A to compensate the active and reactive power flows from bus A to the remaining system.

When P_2 and Q_2 are varying, the StatCom/BESS will compensate for the sudden change in line flow. By choosing P* as $P_{2scheduled}$-P_2 and Q* as $Q_{2scheduled}$-Q_2, both P_2 and Q_2 will be adjusted dynamically and independently to mitigate the oscillation. Since active power is more related to phase angle α, and reactive power is more dependent on modulation gain k, the voltage support is assigned to k, and the oscillatory mode is assigned to α. This control of P and Q will influence the oscillation and voltage drop.

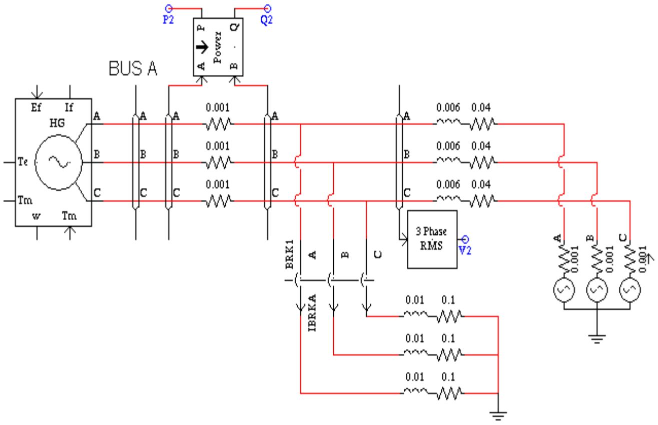

Fig. 4. Equivalent Circuit for Oscillation Damping

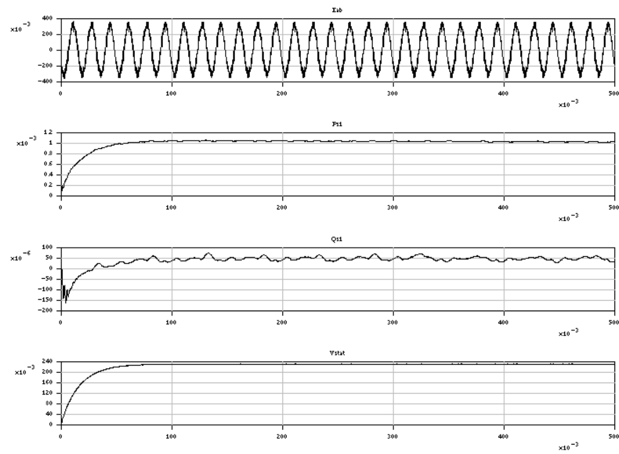

Fig. 6. StatCom/BESS Response to a step change in active power

V SIMULATION RESULTS

A. Power Flow Control

The cascaded StatCom/BESS with PQ decoupled PI control was simulated using EMTDC/PSCAD. The simulation circuit is illustrated in the Appendix, which consists of six batteries, a cascaded 5-level converter, filter, transformer and a power system. In the control implementation, sinusoidal PWM was performed to reduce the harmonic content and to adjust the magnitude of the StatCom output voltage.

Fig. 5 shows the equilibrium point of the StatCom/BESS, in which both active power and reactive power flow to the power bus are zero. Note that the output line voltage of the StatCom/BESS E_{ab} is nearly a sinusoidal.

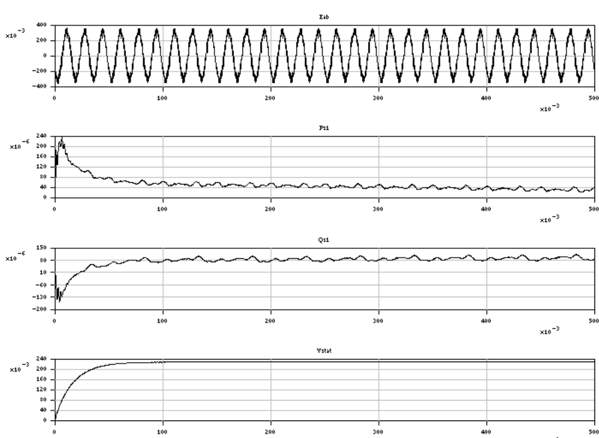

Fig. 5. Active and reactive power injection equal to zero

Fig.6 shows the dynamic response of the output active power and reactive power when the *P* reference steps from 0 to 1 kW and the *Q* reference remains at zero. The waveforms indicate that batteries were charged when the power bus outputs active power.

Fig.7 shows the case when *P* and *Q* references have step changes simultaneously. The *P* reference steps from 0 to –800 W and *Q* reference steps from 0 to –1.5 kW. This result indicates that the multilevel StatCom/BESS injects both active and reactive power into the bus.

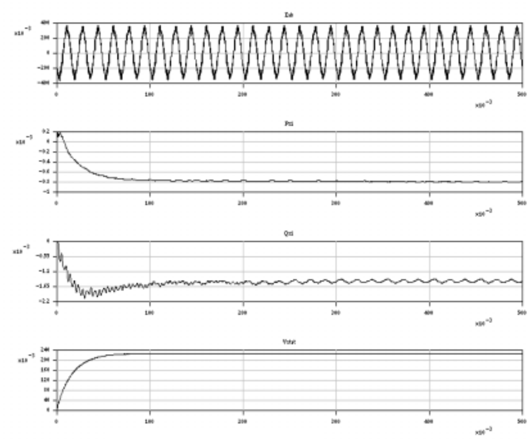

Fig. 7 Simultaneous step change in active and reactive power

B. Power Oscillation Damping

The two-machine AC system shown in Figure 3 is simulated. The inertia of the left machine was tuned to obtain an approximately 4 Hz oscillation from a three phase fault created at time=5 sec and cleared at time=5.15 sec.

The effectiveness of the cascaded StatCom/BESS is shown in Fig. 8 through Fig. 10. Fig. 8 shows P_2, which flows from bus A to the right machine. The presence of the lightly-damped oscillatory mode can be observed in the P_2 waveform. Immediately after the short circuit, the active power flow (P_2) drops quickly and this sudden change perturbs one oscillatory mode, resulting in a lightly-damped oscillation. However, after the disturbance, the active power flow will return to the scheduled value over time. From Fig. 8, it is obvious that the compensator can damp the oscillating magnitude down to 35%, and it mitigates fully the oscillation in 2 seconds.

Fig.9 shows Q_2 which is the reactive power flowing from bus A to the right machine. When the disturbance begins, Q_2 increases quickly but drops drastically after the disturbance. While returning back to its scheduled value, Q_2 suffers large deviation and oscillation. The cascaded StatCom/BESS depresses the sudden change of Q_2 and damps the oscillation effectively.

Fig.10 shows the voltage at bus A. A serious drop of the voltage appears while an oscillation exists after the disturbance. Similar to the effect on Q_2, the combined compensator supports the voltage and damps the oscillation.

Simulation results above indicate that the cascaded StatCom with BESS injects active power to compensate for sudden changes in power flow while the injected active power will return to nominal soon. This ability to output active power instantly is extremely important to system stability improvement.

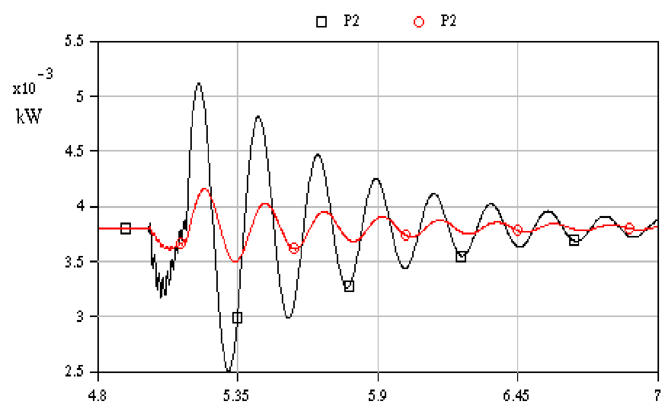

Fig. 8 P_2 (o- with Cascaded StatCom/BESS, □- no control)

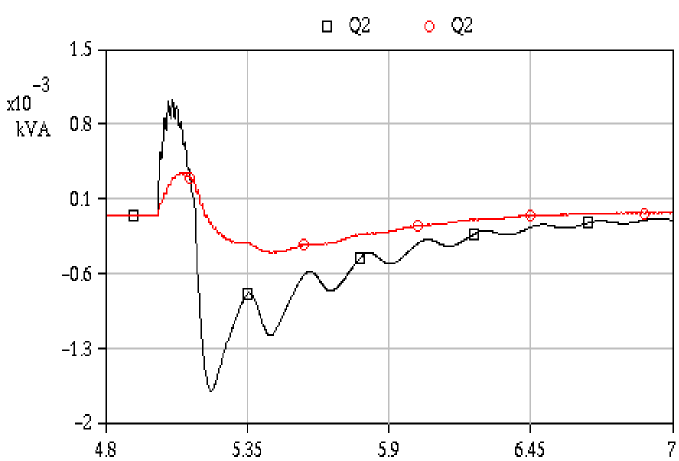

Fig. 9 Q_2 (o- with Cascaded StatCom/BESS, □- no control)

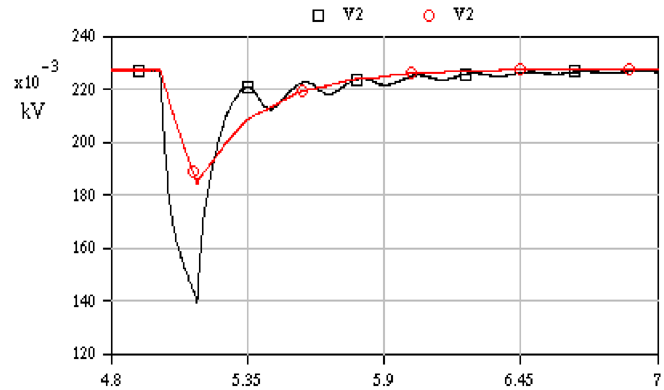

Fig. 10 V_2 (o- with Cascaded StatCom/BESS, □- no control)

V. CONCLUSIONS AND FUTURE WORK

A multilevel StatCom/BESS based on a cascaded converter has been proposed. Both the description and simulation results indicate that a multi-level StatCom/BESS is more versatile and flexible than a conventional StatCom because it can

- Control both active and reactive power simultaneously and independently
- Charge batteries by absorbing active power from the grid
- Be rated higher because of multilevel topology
- Be effective in power oscillation damping
- Support the system voltage during and after a disturbance

ACKOWLEDGEMENTS

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APPENDIX