Development Of Novel Power Electronic Topologies For The Integration Of Battery Energy Storage In FACTS Devices

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I. Introduction

In bulk power transmission systems, power electronics based controllers are frequently called Flexible AC Transmission System (FACTS) devices. The use of FACTS devices in a power system can potentially overcome limitations of the present mechanically controlled transmission system. By facilitating bulk power transfers, these flexible networks help delay or minimize the need to build more transmission lines and power plants and enable neighboring utilities and regions to economically and reliably exchange power. Although relatively new, the stature of FACTS devices within the bulk power system will continually increase as power electronic technologies improve and the restructured electric utility industry moves steadily toward a more competitive posture in which power is bought and sold as a commodity. In decentralized control of transmission systems, FACTS devices offer increased flexibility. As the vertically integrated utility structure is phased out, centralized control of the bulk power system will no longer be possible. Transmission providers will be forced to seek means of local control to address a number of potential problems such as uneven power flow through the system (loop flows), transient and dynamic instability, subsynchronous oscillations, and overvoltages and undervoltages. Several FACTS topologies have been proposed to mitigate these potential problems, but transmission service providers have been reluctant to install them, usually due to cost and lack of systematic control.

The integration of energy storage systems (ESS) into FACTS devices, however, may lead to a more economical and/or flexible transmission controller. The enhanced performance will have greater appeal to transmission service providers. The problems of uneven active power flow, transient and dynamic stability, subsynchronous oscillations, and power quality issues can be impacted more effectively by active power control. Integrating an energy storage system, such as batteries, SMES, or super-capacitors, into a FACTS device can provide dynamic decentralized active power capabilities. Power conversion systems required for ESS are similar to the power electronics topologies of FACTS devices; a combined FACTS/ESS system can have a comparable cost and provide better performance than separate stand-alone ESS or FACTS devices [1].

The StatCom is a shunt-connected FACTS device that is used primarily for voltage control. StatComs using voltage-source-converters have been widely accepted to improve power system operation. In bulk power systems, they are used 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]. A basic StatCom/BESS is shown in Figure 1. 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 often cause substantial active power losses.

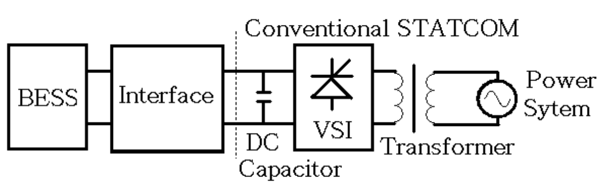

Figure 1: StatCom/BESS configuration

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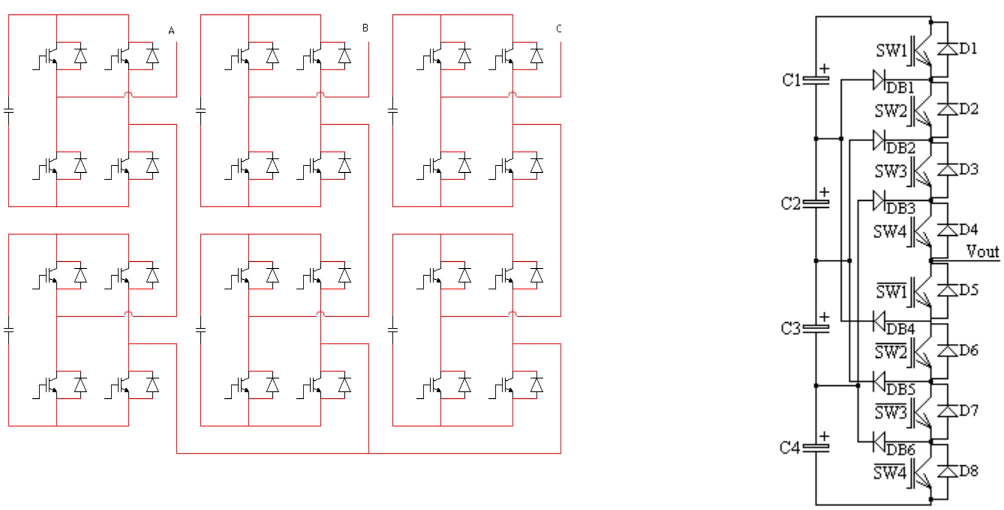
One popular method to eliminate the bulky zig-zag transformers is to use multi-level converters. The general structure of multi-level converters is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. Multi-level StatComs exhibit faster dynamic response, smaller volume, lower cost, and higher ratings than traditional StatComs. 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.

When integrated with a BESS or other energy storage system, the capabilities of the StatCom/BESS can be extended to include active power control to impact oscillation damping and transient stability improvement.

II. MULTI-LEVEL CONVERTERS

One disadvantage of the conventional StatCom/BESS is that the battery voltage can be too high for practical usage in transmission level applications. One approach to decreasing the required BESS voltage is to replace the standard voltage-source-converter (VSC) with a multi-level inverter. In this paper, the design and analysis of the StatCom/BESS is extended to consider a variety of alternate multi-level power electronic topologies to better utilize the BESS. Multilevel converters offer numerous advantages over the traditional two-level converters typically utilized in FACTS devices. Multilevel topologies offer improved voltage quality, decreased switching frequencies, and decreased voltage stress and power losses on the individual devices. Two multilevel inverter structures have been investigated for future development: the cascaded inverter and the diode-clamped inverter. These inverters are shown in Figure 2 (a) and (b).



(a) Cascaded 5-level Converter (b) Diode-clamped 5-level inverter

Figure 2: Multi-level inverters

II.A. Cascaded Multi-level Converter

The cascaded multilevel converter, shown in Figure 2(a), 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.

The features of a cascaded multilevel converter are summarized below:

Advantages:

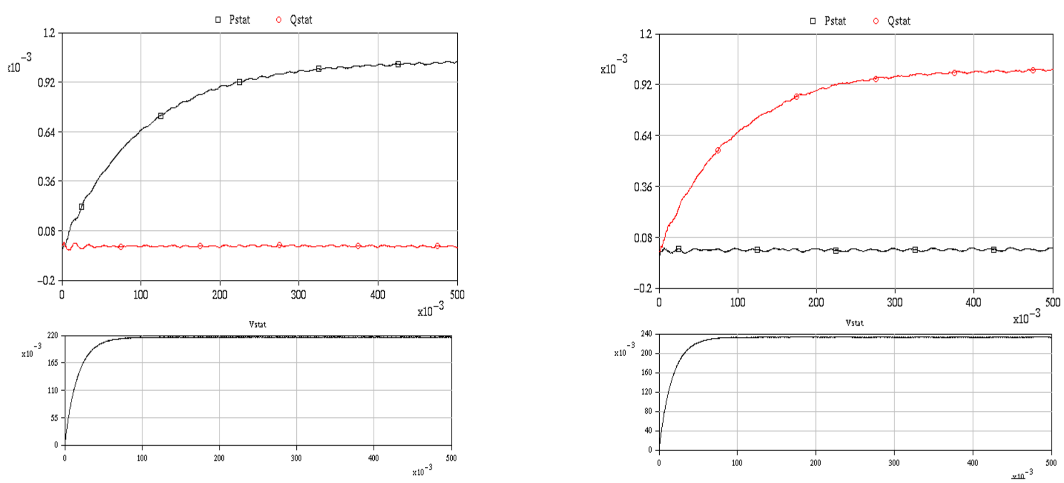
- Uses the fewest components to achieve the same number of levels,
- enables modularity of packaging, and
- does not have the balancing problem with BESS

Disadvantages:

- It needs multiple separate DC sources for active power conversion

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 has two free switching angles, θ_1 and θ_2. The angles are usually chosen to eliminate the fifth and seventh harmonics by solving non-linear equations.

The dynamic response of the cascaded multilevel StatCom/BESS to a commanded step change in power is shown in Figure 3. Note that both active and reactive power can be independently controlled while maintaining the voltage at the desired setpoint.



(a) Step change in active power (b) Step change in reactive power

Figure 3: Dynamic Response of the Cascaded Multilevel Statcom/BESS

II.B. Diode-Clamped Multi-level Converter

The main circuit of a 5-level diode-clamped multilevel inverter is shown in Figure 2 (b). Normally an *n*-level diode-clamped multilevel inverter has *2(n-1)* main switches (SW1-SW8) and *2(n-1)* main diodes (D1-D8). In addition, this topology need *2(n-2)* clamping diodes (DB1-DB6). Assuming that all DC side capacitors have the same voltage *E*, different switching modes provide different output voltages. Table 1 lists five modes for the 5-level diode-clamped multilevel inverter. The voltage V_{out} in the table is the line-to-neutral voltage. The number of inverter level comes from the voltage levels.

The features of diode clamped converters are described below:

Advantages

- The harmonic content is reduced as the number of levels increases,
- reactive power flow can be controlled,
- bi-directional active power flow with BESS can be realized, and
- all capacitors can be pre-charged as a group.

Disadvantages

- requires a large number of high power clamping diodes if the number of levels is high,
- requires a high voltage rating for the blocking diodes, and the capacitor voltages must be externally balanced.

In every operating mode, four switches are in "on" state and the other four are in "off" state. If the inverter output voltage changes only between two contiguous modes, the main switch voltage and main diode voltage will not exceed *E* [6]. Some of the clamped diodes, however, do need to have higher rating than *E*. For example, the DB2 voltage rating should be 2E [7]. From the five modes switching operation, another advantage of multilevel inverter over the series 2-level VSI is that there is no possibility of simultaneous operation of the series switches ("shoot through").

A. PWM Switching Scheme

The fundamental requirement for the diode-clamped multilevel inverter switching scheme is to ensure that the switches operate in the contiguous modes listed in Table 1. The most popular method is sine-triangle pulse width modulation (SPWM). In SPWM, four triangular signals are compared with the sinusoid reference signal to get the switching control signals. These triangular signals are contiguous and have the same peak-to-peak value. According to different phase relationships, there are three cases: a). all triangular signals are in phase; b). the two contiguous triangular signals are out of phase; and c). the positive triangular signals are in phase and the negative triangular signals are in phase, but the positive and the negative are out of phase. Figure 4 shows case c). The voltage E represents the voltage value of one DC-side capacitor in the 5-level diode-clamped inverter shown as Figure 2(b).

Table I: Switching States for Diode-clamped Converter

	SW1	SW2	SW3	SW4	Vout
mode 1	on	on	on	on	2E
mode 2	off	on	on	on	E
mode 3	off	off	on	on	0
mode 4	off	off	off	on	-E
mode 5	off	off	off	off	-2E

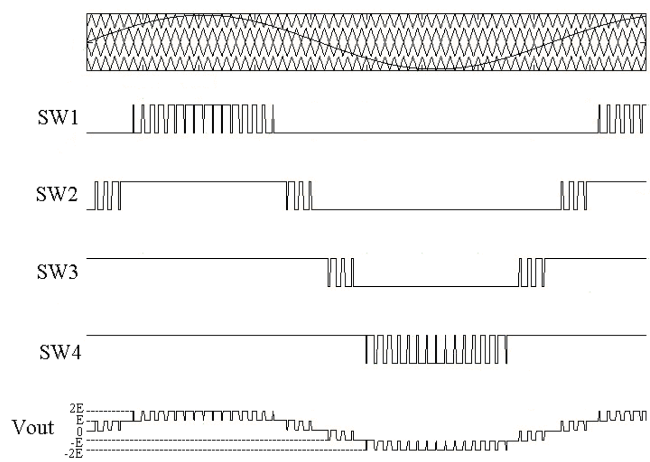


Figure 4: Sine-triangle Pulse Width Modulation Switching Scheme

B. Hysteresis Current Switching Scheme

SPWM can reduce the voltage harmonics component. However, an alternative method to reduce the low-order harmonics content of the inverter output current is to use hysteresis current switching [6]. The objective of this switching scheme is to force the multilevel inverter output current to follow as closely as possible the required reference current. In hysteresis control, the phase output current is compared with the reference current. A hysteresis level is assigned in order to define an acceptable current ripple level. In the following discussion, only SW1 to SW4 of Figure 2(b) are considered, because the other four switches are complementary with them. Obviously, the inverter output current is directly related to the output voltage. The larger the voltage, the greater the current. So, the scheme comes out clearly for the hysteresis current switching. If the phase current becomes greater than the reference current plus the hysteresis level, the most upper switch of ON status will be turned off. If the phase current becomes less than the reference current minus the hysteresis level, the lowest switch of OFF status will be turned on. If the phase current lies within the acceptable current ripple level, all the switches of that phase will be latched to the current ON/OFF status. Table 2 lists all the possible status changes. I_{ref} is the reference current, h is the hysteresis level, and i is the fed-back phase current. The value in the table represents SW1-SW4 switching status. For example, 0011 means that SW1 and SW2 are OFF, while SW3 and SW4 are ON. Figure 5 shows how the hysteresis current control switching scheme works. Note that the switches switch less frequently than with the SPWM method, making this strategy more amenable to higher voltages where the power electronic devices tend to switch more slowly.

Table II: Switching States for Hysterisis Control

$i < I_{ref} - h$	
Switching Current Status (SW1, SW2, SW3, SW4)	Switching Next Status (SW1, SW2, SW3, SW4)
(0000)	(0001)
(0001)	(0011)
(0011)	(0111)
(0111)	(1111)
(1111)	(1111)
$i > I_{ref} + h$	
Switching Current Status (SW1, SW2, SW3, SW4)	Switching Next Status (SW1, SW2, SW3, SW4)
(1111)	(0111)
(0111)	(0011)
(0011)	(0001)
(0001)	(0000)
(0000)	(0000)
$I_{ref} - h < i < I_{ref} + h$	
Keep current status	

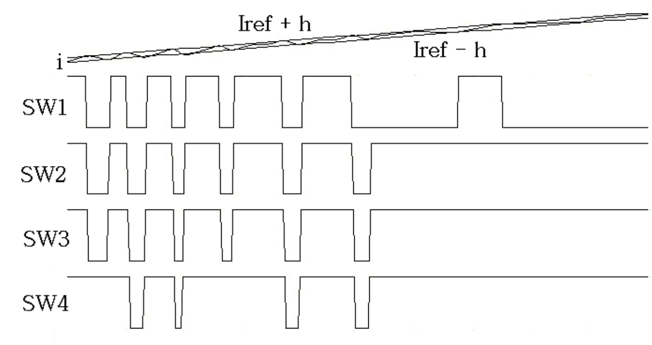


Figure 5: Hysteresis current control switching scheme

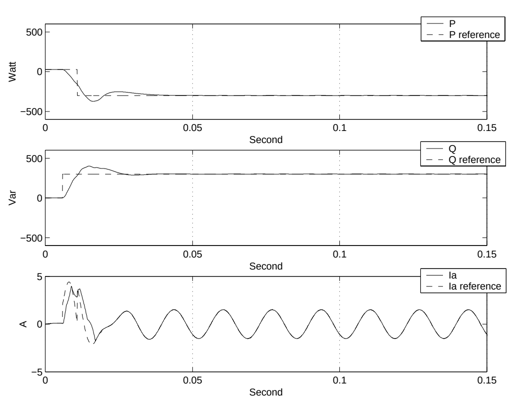


Figure 6: Dynamic PQ and Ia response: P: 0 to -300 W, Q: 0 to 300 Var

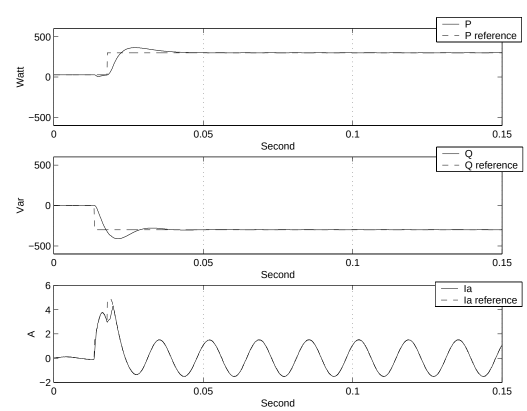


Figure 7: Dynamic PQ and Ia response: P: 0 to 300 W, Q: 0 to -300 Var

Figures 6 and 7 show the dynamic power and current response of decoupled current PI control. In Figure 6, the reference value of the StatCom/BESS's output reactive power has a step change from 0 to 300 Var and then the active power changes from 0 to –300 W. In Figure 7, the reference value of the reactive power has a step change from 0 to -300 Var and then the active power changes from 0 to 300 W.

III. CONVERTER COMPARISONS

For an even comparison between the two multilevel and the traditional two-level inverters, each StatCom/BESS used thirty-four or thirty-six batteries – the same number as the traditional StatCom/BESS which had two strings of seventeen batteries to provide 204 V at 30 A. The operating range of each of the topologies is shown in Figure 8. The traditional StatCom (black) has nearly pure reactive compensation with slight active power losses. The traditional 2-level StatCom/BESS (red) has the most centered operating range with the range being slightly offset from the origin to account for the active power losses in the system. The diode-clamped 5-level StatCom/BESS has the largest reactive power range – comparable to the traditional StatCom. The cascaded 5-level StatCom/BESS has a wider active power range, but a somewhat restricted reactive power range.

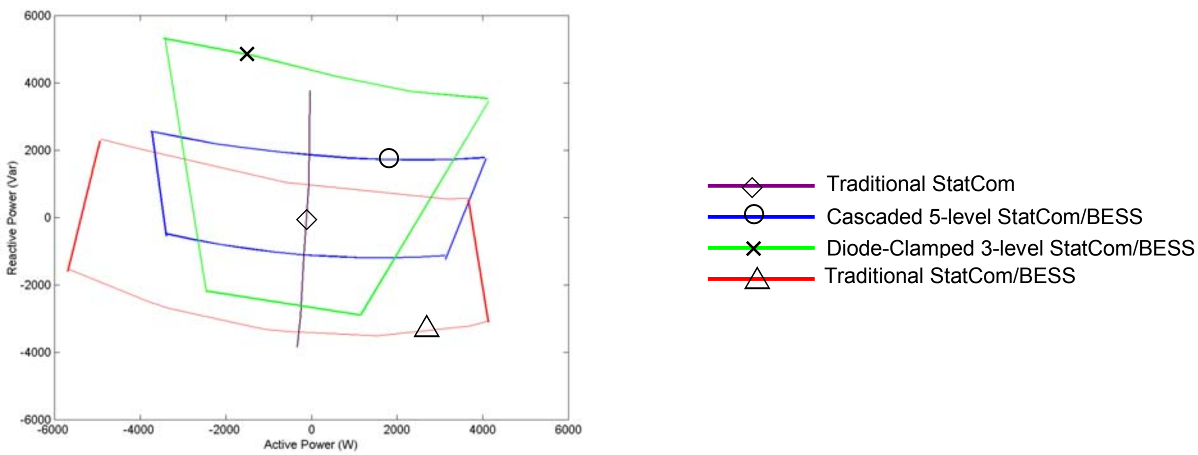


Figure 8: Comparison of Operating Regions of Different Topologies

IV. CONCLUSIONS

The traditional StatCom/BESS offers the greatest operating range, but to do so requires more robust power electronic devices: they must have a significantly higher switching frequency and be able to withstand higher voltages and currents. The multilevel StatCom/BESS' offer somewhat reduced operating ranges, but are able to utilize smaller power electronic devices that do not need high switching speeds. This will considerably reduce the cost of the power electronics as compared to the traditional StatCom/BESS.

V. REFERENCES

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