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CONTROL OF STATCOM WITH ENERGY STORAGE DEVICE

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Abstract: In this paper the control method of a STATCOM with an energy storage device is discussed. To determine the switching level control, UPWM (Unique Pulse Width Modulation) and SPWM (Sinusoidal Pulse Width Modulation) methods are compared. A linearized model of a STATCOM with a battery is set up to derive monitoring level control strategies. All the control methods are verified by the PSCAD/EMTDC software package.

Keywords: STATCOM, FACTS, power systems, control

I. INTRODUCTION

The STATic synchronous COMpensator (STATCOM) has been studied in recent years. Many papers have discussed its theory, modeling, control and applications [1-5]. A common STATCOM consists of a voltage source inverter (VSI) and a DC voltage source (usually a DC capacitor). By injecting a current of variable magnitude and almost in quadrature with the line voltage, at the point of connection with the transmission line, a STATCOM can inject reactive power to a power system. Because a DC capacitor is not a bulk energy storage device, a common STATCOM does not have the ability of active power compensation. It can only affect the active power flow in the power system indirectly by regulating the voltage at the point of connection with the transmission line. If a bulk energy storage device such as a battery is connected to the DC capacitor, the power regulation ability of a common STATCOM can be expanded to both reactive and active power compensation.

Now, a project expanding the compensation ability of a common STATCOM by connecting a battery to its DC side is being undertaken at the UMR. A 10KVar IGBT based experimental STATCOM has been set up. A DC 204V battery bank is supplied from Sandia National Labs. Compared with that of a common STATCOM, the control of a STATCOM with a battery is more complex. At the switching level, the number of control variables of a STATCOM with a battery increases by one because the output has expanded from one dimension to two dimensions (from only reactive power to the complex power plane). At the monitoring level, the model of the new setup may need rebuilding and all the control design methods need to shift from a SISO to a MIMO system. This paper firstly introduces how we determined the switching method for our experimental setup by comparing the voltage regulation effect of the UPWM and SPWM methods. Then a linearized model of a STATCOM with a battery is proposed. Based on the linear model, a PQ decoupled PI controller is derived. A PV decoupled PI controller is also presented in this paper. All the control strategies are verified by computer simulation.

II. SWITCHING LEVEL CONTROL

A STATCOM, no matter whether connected to a battery or not, usually uses a high power voltage inverter to accomplish the dc to ac voltage conversion. There are different switching methods that can trigger the inverter and modulate the output voltage of the inverter. For a STATCOM with an energy storage battery, the switching method must provide control of the output voltage magnitude and phase angle.

A. The 180° conduction mode and unique pulse width modulation (UPWM)

The 180° conduction method is widely applied in bulk system STATCOMs, which are tied into transmission systems. The switching signals applied to the three-phase inverters are illustrated in Figure.1.

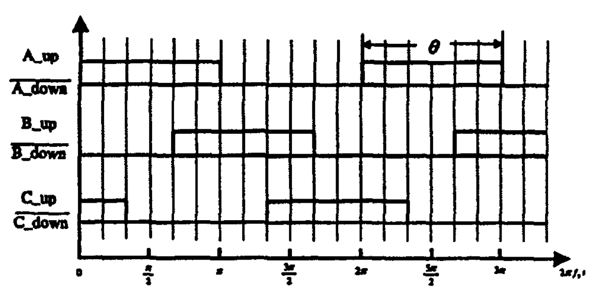

Fig. 1 Switching signals in 180° conduction mode

We can see that in every period, each thyristor switches on and off once. Therefore, the switching loss of the inverters is a minimum. The fundamental harmonic of the line-to-neutral output voltage of the inverter can be expressed as :

$$v_{l\_a} = \frac{2}{\pi} U_{dc} \sin\frac{\theta}{2} \cos(2\pi f_0 t) \qquad (1)$$

where, U_{dc} is the dc side voltage, f_0 equals 60Hz and θ is the conductive angle (see Figure 1). In the 180° conduction mode, θ equals 180°.

The 180° conduction mode is actually a type of unique pulse trigger mode. A common STATCOM that operates in 180° conduction mode usually regulates its output voltage by adjusting the phase angle α between the inverter's output voltage and the power system voltage at the point of connection. This phase angle causes the active power exchange between the STATCOM's dc side capacitor and the power system. Therefore, U_{dc} is changed, and the inverter's output voltage is also changed.

From equation (1), we can see that the STATCOM's output voltage magnitude is also relative to the conductive angle θ. If the conductive angle θ does not remain a constant 180°, but is adjustable, then both the STATCOM's output voltage magnitude and phase angle are controllable. We call this type of voltage modulation as unique pulse width modulation (UPWM). Ideally, UPWM has the merit of unique trigger modes and minimum the switching losses. But unfortunately, UPWM can not modulate the inverter's output voltage magnitude effectively.

The problem lies in equation (1), which is only valid when the load connected to the inverter is resistive. Let's consider the situation of $\theta = 120^\circ$ and take A phase leg of a STATCOM's voltage inverter as an example.

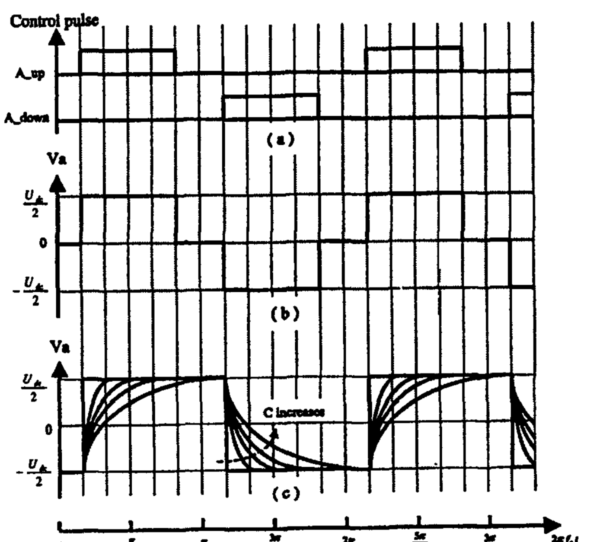

Fig.2 Operation of the inverter with resistive and capacitive load when $\theta = 120^\circ$

When $\theta = 120^\circ$, in every period, there are two time intervals (see Fig.2(a), when $150^\circ < 2\pi f_0 t < 210^\circ$ and $330^\circ < 2\pi f_0 t < 390^\circ$) in which both thyristors in phase leg A are turned off. If a resistive load is connected to the inverter's output terminal, in these intervals, there is no current passing through A phase leg (see Fig.3) and the potential of point a equals zero. The line-to-neutral voltage of phase A is as shown in Fig.2 (b). At this time, equation (1) is valid.

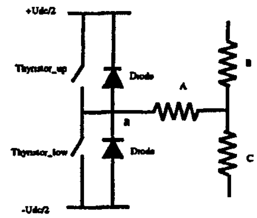

Fig.3 Phase leg A of the voltage inverter with resistive load

If the load is capacitive (see Fig.4), then, when the two thyristors are turned off, the charge, which occurs when one of the two thyristors is on, is stored in the capacitive load. Therefore, the potential of point a will keep the value at the instant just before the both-thyristor-off intervals begin (see Fig.2(c)). In another words, the inverter's output voltage is not only determined by the variation of the conductive angle of the control pulse. It also has relations with the charge and discharge procedure of the capacitive load. The bigger the capacitive load is, the more distortion of the output voltage from a square wave is expected (as shown in Fig.2(c)).

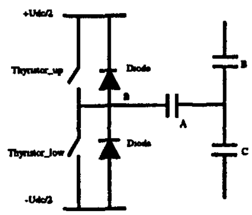

Fig.4 Phase leg A of the voltage inverter with capacitive load

If the load is inductive as shown in Fig.5., the variation of the output voltage of the inverter is even more complex. Because the current flowing in an inductor can not be cut off immediately, even in the two-thyristor-off intervals, there still is current flowing through the inversely shunted diodes.

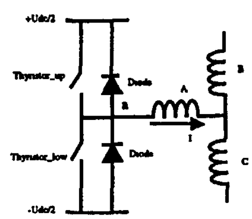

Fig.5 Phase leg A of the voltage inverter with inductive load

When the two thyristors are turned off while there is current flowing from point a to neutral, the lower diode must be on and the potential of point a should be $-\frac{U_{dc}}{2}$ (neglecting the voltage drop across the diode). If the current direction is inverse, the upper diode must be on and the potential of point a should be $+\frac{U_{dc}}{2}$. So, the line-to-neutral voltage of phase A is like shown in Fig.6(c).

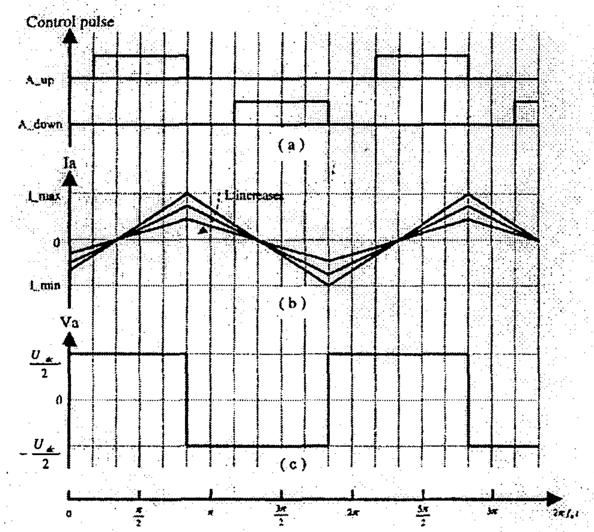

Fig.6 Operation of the inverter with inductive load when $\theta = 120^{\circ}$

Simulations of UPWM have been carried out by PSCAD/EMTDC. In the simulation, V_{dc} equals 400V. Table 1. gives out the simulation results. The expected output voltages (fundamental harmonic) of the inverter, which are calculated by equation (1), are shown in the row of "Theoretical value". From Table 1, we can see that the calculated values match the simulation results only when the load is resistive. The simulation results with the inductive and capacitive loads illustrate the preceding analysis.

Table.1 Simulation results of UPWM (Volt)

Conductive angle	180 (deg)	150 (deg)	120 (deg)	90 (deg)
Theoretical value	254.648	245.971	220.532	180.063
R_Load	251.848	243.272	218.188	178.129
L_Load	254.066	254.058	254.059	252.114
C_Load	251.942	251.943	251.942	251.942

This discussion was intended to highlight that UPWM switching control is not capable of providing effective waveform control, therefor, a different approach to switching control is required.

B. The sinusoidal pulse width modulation (SPWM)

SPWM actually is a kind of multi-pulse trigger mode. In one period, every thyristor in the inverter switches on and off many times. Thus, an inverter operates in SPWM mode has a greater switching loss than that of the UPWM mode. But when a voltage inverter works in SPWM operation mode, any of its phase leg must have one thyristor on at any time instant. There is no time intervals in which both thyristors in one phase leg are off. So the phenomena which happen in UPWM operation mode will never happen in SPWM operation mode. The SPWM method can regulate the output voltage magnitude of a voltage inverter effectively. The principle of SPWM can be found in any book on power electronics. Thus, further discussion is omitted.

III. MONITORING LEVEL CONTROL

In order to derive the monitoring level control of a STATCOM with a battery, a dynamic model of the STATCOM and the battery need to be set up.

Fig.7 shows the schematic of a STATCOM with a battery, which is connected to a power system by a transformer. In Fig.7, v_a, v_b, v_c represent the three phase line-to-neutral system voltages at the connection point. e_a, e_b, e_c represent the fundamental harmonic of the three phase line-to-neutral output voltage of the STATCOM's inverter. L and R represent the impedance of the transformer. The battery is represented by an ideal DC voltage source V_s and a resistor R_s in Fig.7. R_s can also account for any losses in the inverter. We use a simple model to represent the battery because we consider that the STATCOM is used in a transmission system for improving system's transient stability. In the short period of the system transient, there should be no significant variation to the potential of the battery.

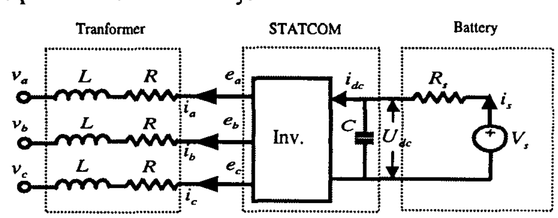

Fig.7 Scheme of a STATCOM with a battery

If, we assume the STATCOM is working in a balanced condition, then, we can define a reference frame transformation and make the attained dynamic model of the STATCOM and battery simple. The reference frame coordinate is defined where the d-axis is always coincident with the instantaneous system voltage vector and the q-axis is in quadrature with it. The transformation of variables is defined in equation (2) [6]:

$$[c]=\frac{2}{3}\begin{bmatrix}\cos\varphi & \cos(\varphi-\frac{2\pi}{3}) & \cos(\varphi+\frac{2\pi}{3})\\ -\sin\varphi & -\sin(\varphi-\frac{2\pi}{3}) & -\sin(\varphi+\frac{2\pi}{3})\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix} \quad (2)$$

$$[c]^{-1}=\frac{3}{2}[c]^T,\quad \begin{bmatrix}i_d\\ i_q\\ 0\end{bmatrix}=[c]\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix},\quad \begin{bmatrix}e_d\\ e_q\\ 0\end{bmatrix}=[c]\begin{bmatrix}e_a\\ e_b\\ e_c\end{bmatrix},\quad \begin{bmatrix}|v|\\ 0\\ 0\end{bmatrix}=[c]\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}$$

where φ is the angle between instantaneous system voltage vector and the A-phase axis of the abc coordinate.

In the reference frame coordinate, the equations of the AC side circuit in Fig.7 can be written as:

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega_0 \\ \omega_0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{(e_d - |v|)}{L} \\ \frac{e_q}{L} \end{bmatrix} \quad (3)$$

where $p = d/dt$ $\omega_0 = 2\pi f_0$, $f_0 = 60Hz$. The DC side circuit equation can be written as:

$$\begin{aligned} pV_{dc} &= \frac{1}{C}(i_s - i_{dc}) \\ &= \frac{1}{R_s C}(V_s - U_{dc}) - \frac{1}{C} i_{dc} \end{aligned} \quad (4)$$

The instantaneous active power on the ac side of the inverter is calculated by:

$$\begin{aligned} P_{ac} &= e_a i_a + e_b i_b + e_c i_c \\ &= \frac{3}{2}(e_d i_d + e_q i_q) \end{aligned} \quad (5)$$

and the power on the dc side of the inverter can expressed by:

$$P_{dc} = U_{dc} i_{dc} \quad (6)$$

Considering that the instantaneous active power exchanged between the ac and dc side of the inverter should be the same, equation (7) must hold:

$$P_{ac} = P_{dc}$$

$$U_{dc} i_{dc} = \frac{3}{2}(e_d i_d + e_q i_q) \quad (7)$$

So,

$$i_{dc} = \frac{3}{2}\left(\frac{e_d i_d + e_q i_q}{U_{dc}}\right) \quad (8)$$

When an inverter of a STATCOM operates in SPWM mode, its output voltage must satisfy the following equations:

$$\begin{aligned} e_d &= \frac{1}{2} U_{dc} M \cos\alpha \\ e_q &= \frac{1}{2} U_{dc} M \sin\alpha \end{aligned} \quad (9)$$

where M is the duty cycle ratio of the sinusoidal reference wave and α is the firing angle of the sinusoidal reference wave referring to the system voltage vector.

Combining equation (4) with equation (3) and substituting equation (9) and equation (8) into them, we can set up a dynamic model for a STATCOM with a battery:

$$p\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix} = [A]\begin{bmatrix} i_d \\ i_q \\ U_{dc} \end{bmatrix} + \begin{bmatrix} \frac{U_{dc}}{2L} M\cos\alpha \\ \frac{U_{dc}}{2L} M\sin\alpha \\ -\frac{3i_d}{4C} M\cos\alpha - \frac{3i_q}{4C} M\sin\alpha \end{bmatrix} + \begin{bmatrix} -\frac{|v|}{L} \\ 0 \\ \frac{V_s}{R_s C} \end{bmatrix}$$

$$[A] = \begin{bmatrix} -\frac{R}{L} & \omega_0 & 0 \\ -\omega_0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{1}{R_s C} \end{bmatrix} \quad (10)$$

Equation (10) describes the dynamics of an affine nonlinear system. After linearization in the neighborhood of an equilibrium point, the control system shown in equation (10) can be transformed to a linear system as shown in equation (11):

$$p\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix} = [A_0]\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix} + [B_0]\begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta U_{dc} \end{bmatrix} = \begin{bmatrix} i_d - i_{d0} \\ i_q - i_{q0} \\ U_{dc} - U_{dc0} \end{bmatrix}, \quad \begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix} = \begin{bmatrix} M - M_0 \\ \alpha - \alpha_0 \end{bmatrix}$$

$$[A_0] = \begin{bmatrix} -\frac{R}{L} & \omega_0 & \frac{M_0\cos\alpha_0}{2L} \\ -\omega_0 & -\frac{R}{L} & \frac{M_0\sin\alpha_0}{2L} \\ -\frac{3M_0\cos\alpha_0}{4C} & -\frac{3M_0\sin\alpha_0}{4C} & -\frac{1}{R_s C} \end{bmatrix}$$

$$[B_0] = \begin{bmatrix} \frac{U_{dc0}\cos\alpha_0}{2L} & -\frac{U_{dc0} M_0 \sin\alpha_0}{2L} \\ \frac{U_{dc0}\sin\alpha_0}{2L} & \frac{U_{dc0} M_0\cos\alpha_0}{2L} \\ -\frac{3(i_{d0}\cos\alpha_0 + i_{q0}\sin\alpha_0)}{4C} & \frac{3M_0(i_{d0}\sin\alpha_0 - i_{q0}\cos\alpha_0)}{4C} \end{bmatrix}$$

where $[\Delta i_d \;\; \Delta i_q \;\; \Delta U_{dc}]^T$ is the state variable vector, and $[\Delta M \;\; \Delta\alpha]^T$ are the control variables. All the symbols with a subscription 0 in equation (11) represent the values at the equilibrium point. We will use the linear model to derive the monitoring level control of a STATCOM with a battery.

A. The PQ decoupled PI control

In Fig.7, the active power P and reactive power Q on the power system side can be calculated in the reference frame coordinate by equation (12):

$$P = \frac{3}{2}|v| i_d, \quad Q = \frac{3}{2}|v| i_q \quad (12)$$

Thus, realizing PQ decoupled control means realizing i_d, i_q decoupled control.

We assume that there is no active power exchange when the STATCOM and battery are working at the equilibrium point. Thus, $i_{d0} = 0$ and $\alpha_0 = 0$. Therefore, we can simplify the matrix A_0 and B_0 in equation (11) into the form:

$$
[A_0]=\begin{bmatrix} -\frac{R}{L} & \omega_0 & \frac{M_0}{2L} \\ -\omega_0 & -\frac{R}{L} & 0 \\ -\frac{3M_0}{4C} & 0 & -\frac{1}{R_s C} \end{bmatrix}
$$

$$
[B_0]=\begin{bmatrix} \frac{V_{dc0}}{2L} & 0 \\ 0 & \frac{V_{dc0}}{2L} \\ 0 & -\frac{3M_0 i_{q0}}{4C} \end{bmatrix} \qquad (13)
$$

By substituting equation (13) into equation (11) and rewriting the first two rows of equation (11) yields:

$$
p\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix}=\begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix}+\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad (14)
$$

$$
\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} \frac{U_{dc0}}{2L}\cdot \Delta M_0+\omega_0\cdot \Delta i_q+\frac{M_0}{2L}\cdot \Delta U_{dc} \\ \frac{U_{dc0}M_0}{2L}\cdot \Delta\alpha_0-\omega_0\cdot \Delta i_d \end{bmatrix}
$$

where $[x_1 \quad x_2]^T$ is an introduced new control variable vector. Therefore, the i_d, i_q decoupled control has already been realized.

If we set

$$
\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} (k_1+\frac{k_2}{p})\cdot(i_{d\_ref}-i_d) \\ (k_1+\frac{k_2}{p})\cdot(i_{q\_ref}-i_q) \end{bmatrix} \qquad (15)
$$

where $[i_{d\_ref} \quad i_{q\_ref}]^T=\left[\frac{2P_{ref}}{3|v|} \quad \frac{2Q_{ref}}{3|v|}\right]^T$, P_{ref}, Q_{ref} are the PQ reference, and k_1 k_2 are integration and proportion gain, a PQ decoupled PI control strategy is finally obtained.

B. The PV decoupled PI control

If it is assumed that the firing angle α mainly affects the variation of the active power P exchanged between the power system and the STATCOM, and the duty cycle ratio M mainly regulates the magnitude of the STATCOM's output voltage and therefore the system voltage magnitude, then, we can derive an approximate PV decoupled PI control as shown in equation (16):

$$
\begin{aligned} \Delta\alpha &= (k_1+\frac{k_2}{p})\cdot(P_{ref}-P) \\ \Delta M &= (k_1+\frac{k_2}{p})\cdot(V_{ref}-V) \end{aligned} \qquad (16)
$$

where V_{ref} and V represent the system voltage reference and system voltage magnitude respectively.

IV. SIMULATION RESULTS

The control functions of the PQ and PV decoupled PI control strategies are simulated by PSCAD/EMTDC. The simulation system is illustrated in the appendix, which includes a battery, a common STATCOM, transformer and a power system. The SPWM generator circuit is also attached. All the parameters used in the simulation are the same as those of the hardware setup.

The PQ decoupled PI control block diagram that is used in simulation is shown in Fig.8:

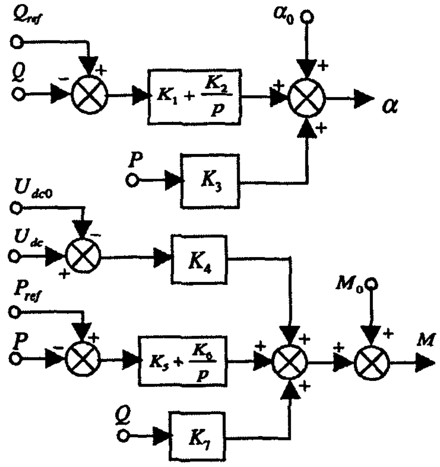

Fig.8 PQ decoupled PI control block diagram

Fig.9 and Fig.10 show the dynamic response of the STATCOM's output active power and reactive power when the P reference has a step change from 0 to 5KW and then the Q reference decreases from 0 to -5KVar.

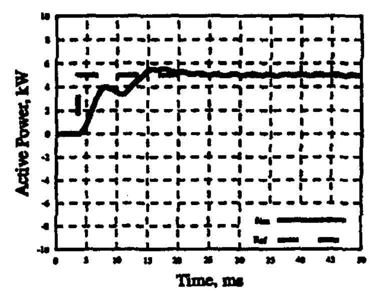

Fig.9 Dynamic response of the active power output (0 to 5KW)

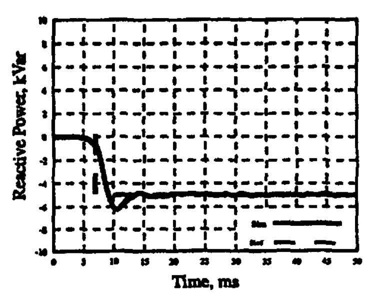

Fig.10 Dynamic response of the reactive power output (0 to -5KVar)

when the P reference drops from 0 to -5KW and then the Q reference increases from 0 to 5KVar , the transient of the STATCOM's output power are shown in Fig.11 and Fig. 12:

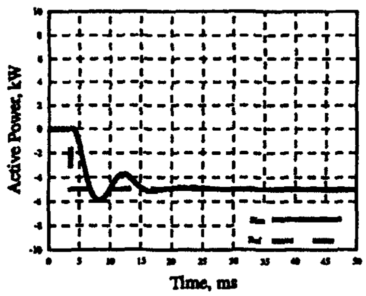

Fig.11 Dynamic response of the active power output (0 to -5KW)

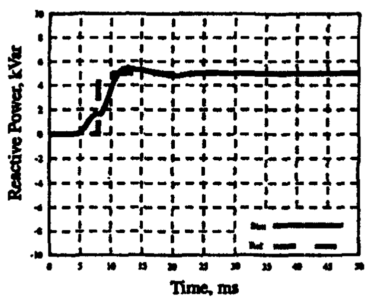

Fig.12 Dynamic response of the reactive power output (0 to 5KVar)

The PV decoupled PI control block diagram that is used in simulation is shown in Fig.13:

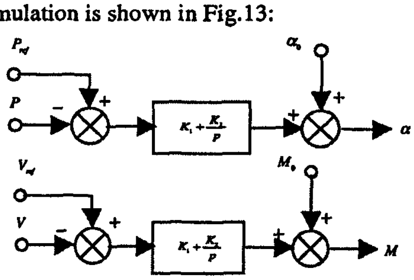

Fig.13 PV decoupled PI control block diagram

Two situations are simulated to test the functions of the above control law. The first situation is that the P reference step-jumps from 0 to 5KW while the system voltage is required to be brought down from 230V to 210V (about from 1 p.u. to 0.913 p.u.). The second situation is that the STATCOM begins to absorb 5KW active power from the power system while the system voltage is raised from 230V to 250V (about from 1 p.u. to 1.087 p.u.). Fig.14 to Fig.17 show the curves of the P and V in transient.

All the simulation results prove that both the PQ and PV decoupled PI control strategies we derived in last section produced the desired results.

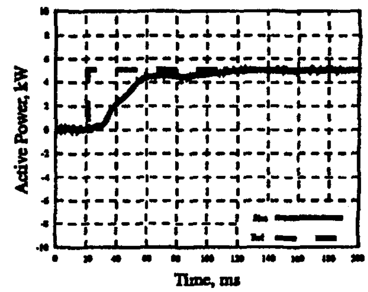

Fig.14 Dynamic response of the active power output (0 to 5KW)

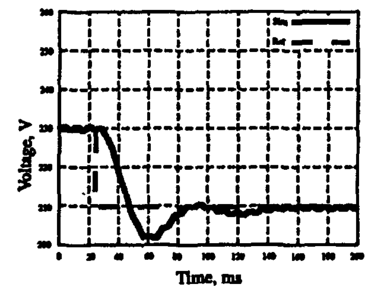

Fig.15 Dynamic response of the system voltage (230 to 210V)

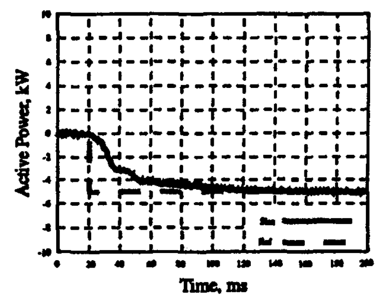

Fig.16 Dynamic response of the active power output (0 to -5KW)

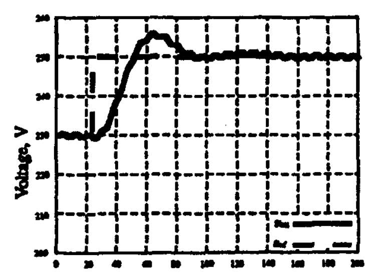

Fig.17 Dynamic response of the system voltage (230 to 250V)

V. CONCLUSION AND FUTURE WORK

This paper discusses the control of a STATCOM with a battery. In switching level control, SPWM has the ability to regulate both the output voltage magnitude and phase angle of the STATCOM if there is no DC voltage regulator to feed the STATCOM's inverter with variable DC voltage. The simulations of two PI control strategies prove that four-quadrant power compensation can be obtained by using a STATCOM with a battery. In the future, hardware tests will be carried out to further verify the accessibility, and global control strategies will be designed.

VI. ACKNOWLEDGEMENTS

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APPENDIX THE SIMULATION SYSTEM IN PACAD/EMTDC