Series Voltage Compensator using State Feedback Control

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Abstract* – *This paper deals with the control algorithm of series voltage compensator that is used to maintain the load voltage when the supply voltage deviates from its nominal voltage. The two reference frame-based controllers using the state feedback algorithm are proposed and verified in the simulation and the experiment. The simulation and the experiment show the effectiveness of the proposed control algorithm.

Keywords* – *Series voltage compensator, State feedback control

I. INTRODUCTION

Power quality problem causes the economic damages and these can be relieved using power conversion circuit such as a power compensator. Series voltage compensator (SVC) is one of the power quality devices that can be used to maintain the voltage of the load even in abnormal condition when the supply voltage deviates from its normal value. In general, SVC is composed of the transformer, LC filter and inverter (Fig. 1). SVC monitors the condition of the supply voltage and injects the voltage to keep the load-side voltage. The control of the capacitor voltage of the LC filter is a key to the control performance of SVC. The compensation quality such as fast response and THD is dependent on the control algorithm of switching devices, because the difference of the compensator circuit configuration is negligible.

Various papers proposed the control algorithm about the voltage control [1]-[3]. This paper proposes the new control algorithm using the state feedback theory. Both the stationary and the synchronous reference frame are used and compared each other in several source conditions.

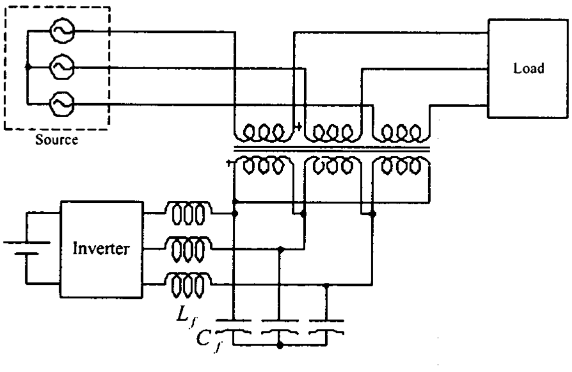

Fig. 1. The circuit configuration of the SVC

II. CONTROL ALGORITHM

In Fig. 2, inverter circuit with LC filter, which reduces the voltage ripple due to the switching of inverter, is shown. This system can be modeled as (1) and (2).

$$L\frac{d\bar{i}_s}{dt} = \bar{v}_1 - \bar{v}_2 \tag{1}$$

$$C\frac{d\bar{v}_2}{dt} = \bar{i}_c \tag{2}$$

(*where* $\bar{a} = e^{j\frac{2}{3}\pi}$, $\bar{v}_1 = v_{a1s} + \bar{a}v_{b1s} + \bar{a}^2 v_{c1s}$, $\bar{v}_2 = v_{a2s} + \bar{a}v_{b2s} + \bar{a}^2 v_{c2s}$, $\bar{i}_s = i_{as} + \bar{a}i_{bs} + \bar{a}^2 i_{cs}$, $\bar{i}_L = i_{aL} + \bar{a}i_{bL} + \bar{a}^2 i_{cL}$,)

In the synchronously rotating reference frame, these equations are summarized to the matrix form as (3). In this paper, the basic equation (3) is used in the stationary and in the synchronous reference frame state feedback control. When ω equals zero, (3) becomes the stationary reference frame equation and when ω equals ω_e , which is the angular frequency of the source voltage, (3) becomes the synchronous reference frame equation. In (3),

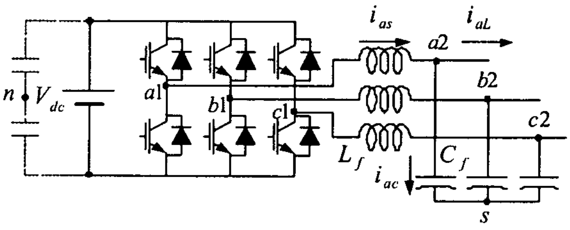

Fig. 2. Inverter with LC filter

$$\frac{d}{dt}\begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{cd} \\ v_{cq} \end{bmatrix} = \begin{bmatrix} 0 & \omega & -\frac{1}{L} & 0 \\ -\omega & 0 & 0 & -\frac{1}{L} \\ \frac{1}{C} & 0 & 0 & \omega \\ 0 & \frac{1}{C} & -\omega & 0 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{cd} \\ v_{cq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{1d} \\ v_{1q} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} -L\frac{di_{dL}}{dt} + \omega L i_{qL} \\ -L\frac{di_{qL}}{dt} - \omega L i_{dL} \end{bmatrix} \quad (3)$$

it can be deduced that the selection of the appropriate inverter voltage can cancel out the disturbance by the load current. In the stationary reference frame equation, there is no coupling between d and q equations. Hence, the three-phase inverter can be modeled as the two single-phase inverters, so any algorithm that can be applied to the single-phase inverter also can be applied to the three-phase inverter. In this paper, the two reference frame-based controllers using the state feedback control are proposed and verified in the simulation and the experiment.

The state feedback has the property that the states converge to zero. Using this property, the additional state is introduced as (4).

$$\frac{d}{dt}\vec{e} = \vec{r} - \vec{y} \qquad (\vec{e}: error\ state) \qquad (4)$$

(3) can be re-written as (5), and (4) and (5) are combined to (6).

$$\frac{d}{dt}\vec{x} = A\vec{x} + B\vec{u} + B\vec{w} \qquad (5)$$

$$\frac{d}{dt}\begin{bmatrix} \vec{x} \\ \vec{e} \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}\begin{bmatrix} \vec{x} \\ \vec{e} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix}\vec{u} + \begin{bmatrix} B \\ 0 \end{bmatrix}\vec{w} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\vec{r} \qquad (6)$$

And using state feedback control ($\vec{u} = -K[\vec{x} \ \ \vec{e}]^T$), error state, $\vec{e}$, converges to nearly zero. Non-measurable states required for state feedback can be estimated using the state observer. The state observer is useful in two respects. First, digital controllers necessarily accompany the computation delay. So using the sampled states for calculation of the next plant input instabilizes the state feedback control. To avoid this instability problem, the prediction of the next sampled value or the predictive state observer may be used. In this paper, the latter is used. Second, the sensor may be omitted, and the control system can be implemented in cost-effective way. The ordinary state observer (7) is used in this study.

Table 1. Simulation Parameters

L_f	C_f	R	T_s
$200\mu H$	$40\mu F$	20Ω	$100\mu s$

$$\frac{d}{dt}\hat{\vec{x}} = A\hat{\vec{x}} + B\vec{u} + B\vec{w} + L(\vec{y} - C\hat{\vec{x}}) \qquad (7)$$

To apply this method to digital control, the continuous equation is discretized using (8)-(9).

$$A_d = L^{-1}(sI - A)^{-1}\big|_{t=T_s} \qquad (8)$$

$$(L^{-1}: Inverse Laplace transform, T_s: sampling time)$$

$$B_d = A^{-1}(A_d - I)B \qquad (9)$$

III. SIMULATION RESULTS

Simulation is carried out using Matlab Simulink. Simulation model is shown in Fig. 3. Parameters used in simulation are the same with the real values in the experiment and arranged in the Table 1.

In the stationary reference frame, coupling between d and q axis does not exist. So the d and q axis equations are the same with each other. Because the references are sinusoidal value, state feedback gain need to be high in order to get the good tracking capability. But in the synchronous frame controller, the references are the dc quantities. Fig. 4 and Fig. 5 show the tracking capabilities of the both controllers. As in the current control using PWM [4], voltage control using state feedback in the synchronous reference frame is superior to the control in the stationary reference frame because there is no phase

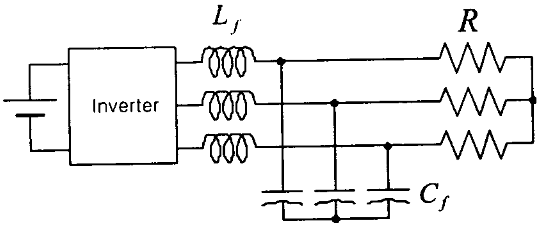

Fig. 3. Simulation model

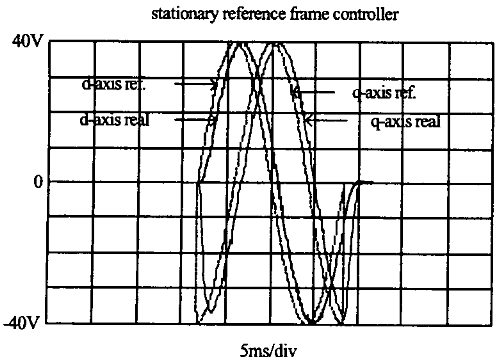

Fig. 5. Tracking capability using the stationary reference frame

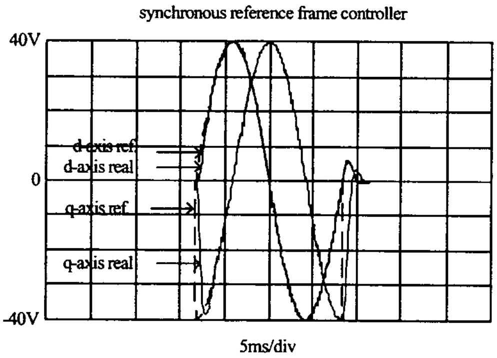

Fig. 5. Tracking capability using the synchronous reference frame

delay in the synchronous reference frame. In this simulation, the capacitor voltage reference is balanced. But when the single-phase sag happens in the source voltage, it generates the voltage component of 120Hz frequency component in the capacitor reference voltage. In this case, the merit of the synchronous frame is weakened.

IV. EXPERIMENTAL RESULTS

In the experiment, the same parameters as the simulation, such as the LC filter parameters and the control gains, are used. For the gating signal calculation, the digital control board using the TI's 100MHz DSP TMS320VC33 was used.

Besides the experiment using the circuit in Fig. 3, the experiment using the circuit in Fig. 1 was carried out. In the experiment using the circuit in Fig. 3, the both reference frame controllers were tested.

Fig. 6 and Fig. 7 are respectively the d and q axis capacitor voltage control waveform using the stationary reference frame. The stationary reference frame control does not show the delay as exactly as in the simulation results. This results from the unmodeled parameter such as the resistance of the inductors. But the comparisons of Fig. 6,7 and Fig 8,9 reveals that the response characteristics of the synchronous reference frame controller are better than those of the stationary reference frame controller.

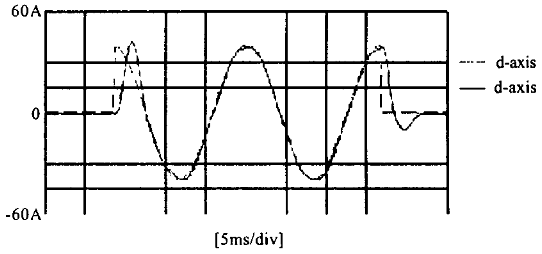

Fig. 9. D-axis capacitor voltage control in the stationary reference frame (experiment)

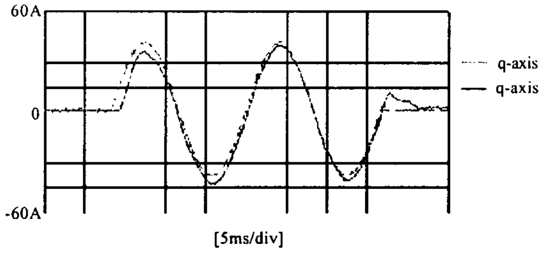

Fig. 9. Q-axis capacitor voltage control in the stationary reference frame (experiment)

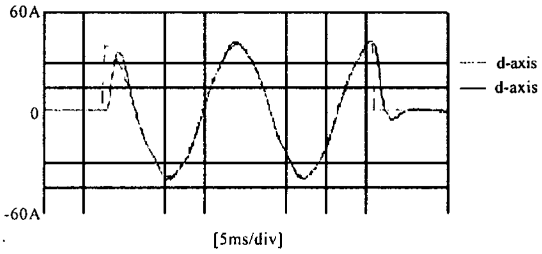

Fig. 9. D-axis capacitor voltage control in the synchronous reference frame (experiment)

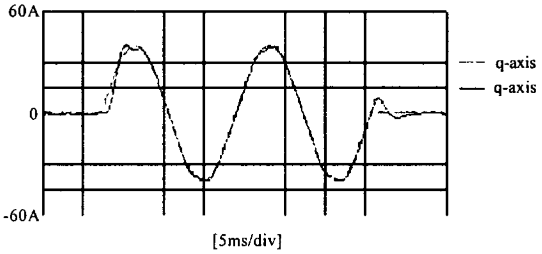

Fig. 9. Q-axis capacitor voltage control in the synchronous reference frame (experiment)

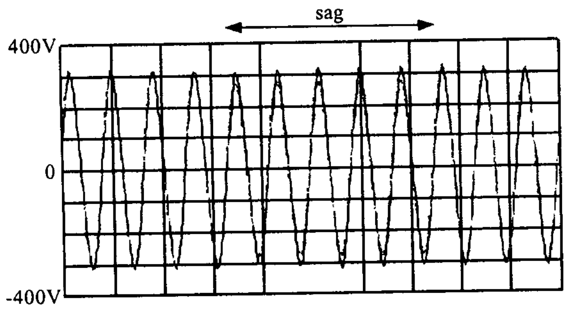

Fig. 10. Line-to-line voltage compensation using the stationary reference frame state feedback controller (experiment)

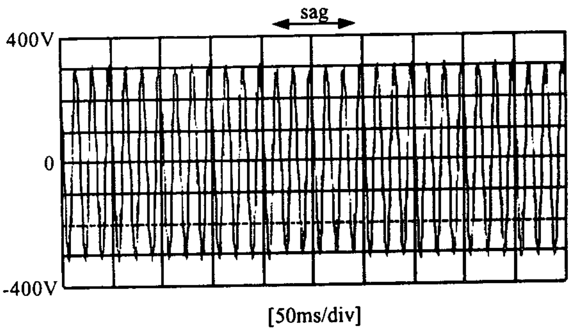

Fig. 11. Line-to-line voltage compensation using the stationary reference frame state feedback controller (experiment)

In the experiment using the circuit in Fig. 1, the voltage sag is generated in the a-phase. Experimentally, the both controllers cannot be distinguished easily. In both control schemes, the a-phase sag was successfully compensated.

V. CONCLUSION

In this paper, the control algorithm of the capacitor in the LC filter using the state feedback has been proposed. This algorithm does not need the current sensors that measure the inverter output current and operates based on the state observer for reducing delay due to digital control and for reducing sensor requirements.

Through the simulations and the experiments, the validity of the proposed algorithm has been verified.

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