Paper

A New Instantaneous Power Flow Control Method Using Variable Inductance Realized by Variable Active-Passive Reactance (VAPAR)

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Rapid power flow control of power systems is the key concept of Flexible AC Transmission System (FACTS). The power flow is essentially restricted by a line inductance. The authors have previously proposed the Variable Active Passive Reactance (VAPAR) (1) which can generate a virtual variable inductance. In this paper, a new instantaneous power flow control method using variable inductance is proposed. The theoretical analysis shows that the power flow follows in inverse ratio of the line inductance even in a transient state assuming the simple power system with two voltage bus connected by an inductive power line. Simulations and experiments were carried out using the feedfoward-based power controller to verify the effectiveness of this method. Then, the characteristics of the power control were analyzed for different line impedances by simulations. The results show that the power flow can be quickly controlled using variable inductance in the case of a small line resistance, while transient oscillations are observed in the power flow only when a line resistance is rather large.

Keywords: FACTS(Flexible AC Transmission System), Power flow control, Transmission system, Variable inductance

1. Introduction

Rapid power flow control of power systems is the key concept of Flexible AC Transmission System (FACTS). To control the power flow in power systems, there are several methods such as SVC (2), the phase-shifter (3) (4), UPFC (5) and so on. In each case, the power flow is controlled by injecting reactive and/or active current, and/or by inserting reactive and/or active voltage to the power system.

The power flow is essentially restricted by the line impedance. The authors have previously proposed the Variable Active Passive Reactance (VAPAR) (1) which can generate a virtual variable inductance.

In this paper, a new instantaneous power flow control method using variable inductance is proposed. The theoretical analysis shows that the instantaneous power flow follows in inverse ratio of the line inductance even in a transient state assuming the simple power system with two voltage bus connected by an inductive power line.

Simulations and experiments were carried out using the feedfoward-based power controller to verify the effectiveness of this method. The characteristics of the power control were analyzed for different line impedances by simulations. The results show that the instantaneous power flow can be quickly controlled using variable inductance by a feedfoward-based power controller in the case of a small line resistance, while transient oscillations are observed in the power flow only when a line resistance is rather large.

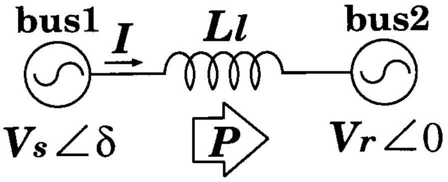

Fig. 1. Power flow in simple power system.

2. Concept and principle of instantaneous power flow control using variable inductance

Consider a simple model of a power system which has two infinite buses connected with a reactive transmission line shown in Fig.1. The steady-state power flow P through the transmission line can be given by the following equation, if the resistance of the power line can be negligible,

$$P = \frac{V_s V_r}{X} \sin \delta \quad \cdots\cdots (1)$$

where V_s:voltage amplitude at sending side(bus1),
V_r:voltage amplitude at receiving side(bus2),
X:total reactance of the transmission line,
δ :power angle between the two busses.

Note that this equation expresses the power flow only in a steady state.

In Eq.(1), four parameters V_s,V_r,X, and δ are assumed variable. To control the instantaneous power

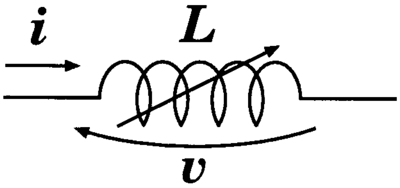

Fig. 2. A variable inductor.

flow several methods have been proposed. Each method is based on reactive and/or active power theorem. The instantaneous power flow can be controlled by inserting series reactive voltage and/or injecting parallel reactive current to the power line. However, active voltage and/or current are/is necessary to improve transient response because the line inductance needs active power in a transient state (5). Therefore, two values, both reactive and active voltage and/or current, have to be controlled simultaneously in a transient state. Here if the inductance is variable, the excellent power control may be achieved only to control one parameter, the line inductance. The basic analysis of power control using variable inductance will be discussed in the next section.

3. Variable Inductance

3.1 Basic characteristics of Variable inductance

In general, the voltage equation of an inductance L as shown in Fig.2 is given by the following equation:

$$v = \frac{dLi}{dt} \quad \cdots\cdots (2)$$

$$= L\frac{di}{dt} + i\frac{dL}{dt} \quad \cdots\cdots (3)$$

If L is constant, Eq.(3) can be modified as $v = L\frac{di}{dt}$ which is a well-known equation for a constant inductance.

Integrating Eq.(2), the following equation can be obtained if dc component of current i can be negligible:

$$\Phi = Li = \int v dt \quad \cdots\cdots (4)$$

where Φ is the total flux linkage. If the inductance is virtually realized as described in the next section, Φ can be considered as a virtual flux linkage. When v is a voltage source $v(t)$, Φ becomes a function derived from Eq.(4). For example, if v is given as:

$$v = \sin \omega t,$$

Φ becomes as follows:

$$\Phi = \frac{1}{\omega} \cos \omega t + C,$$

where C is an integration constant. When only L changes, $\Phi = Li$ does not changes after the change of L. Consequently, the sudden change of L causes quick change of the current i without any unstable phenomenon.

From Eq.(4), the current equation of a variable inductance can be given by the following equation:

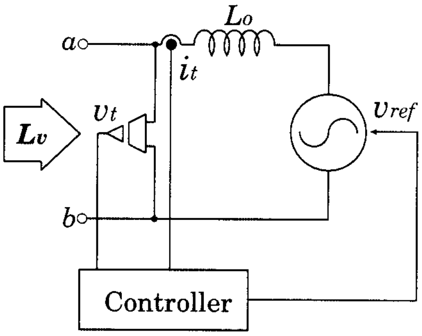

Fig. 3. Principle of VAPAR

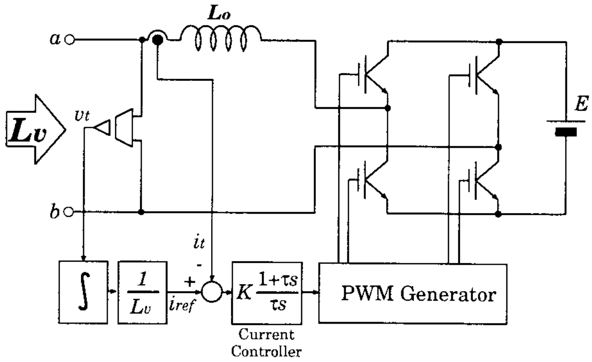

Fig. 4. Practical configuration of VAPAR

$$i = \frac{1}{L}\int v dt \quad \cdots\cdots (5)$$

Note that Eq.(5) can be applied even if inductance is changing.

3.2 Realization of variable inductance using VAPAR

The authors have proposed the Variable Active–Passive Reactance Circuit (VAPAR) (1) which can generate variable inductance suitable for power circuit. Fig.3 shows the principle of VAPAR. In the actual system, the controlled voltage source is replaced by a PWM voltage-fed inverter as shown in Fig.4. The control of VAPAR is performed by calculating the current reference i_{ref} from the terminal voltage v_t according to the following equation:

$$i_{ref} = \frac{1}{L_v}\int v_t dt \quad \cdots\cdots (6)$$

The virtual inductance is realized to control the terminal current. The details have explained in the reference (6).

Of course that VAPAR can generate not only positive inductance but also negative inductance. (7)

4. Instantaneous power flow control using variable inductance

4.1 Concept and theory of instantaneous power flow control using variable inductance

Consider the power system as shown in Fig.5 which adds a variable inductance L_v to Fig.1, the simple power system. The instantaneous current of the power line (i) and the voltages of bus1 (v_s) and bus2(v_r) in Fig.5 can

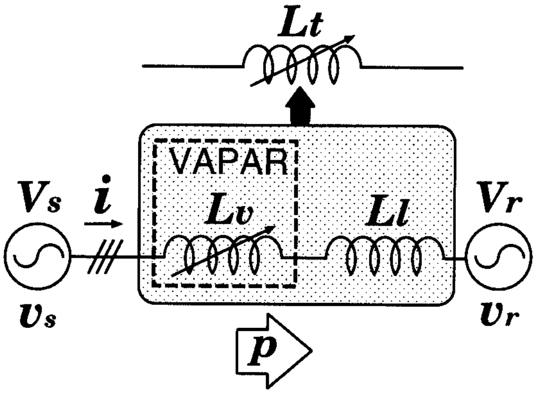

Fig. 5. Power system model with variable inductance.

be transformed to the two-phase ($\alpha\beta$) coordinate using the following transformations:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \cdots (7)$$

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} v_{r\alpha} \\ v_{r\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{ru} \\ v_{rv} \\ v_{rw} \end{bmatrix} \quad (9)$$

The bus1(sending side) and bus2(receiving side) are assumed to be balanced ideal voltage sources which are expressed as follows:

$$\begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix} = \begin{bmatrix} V_s \sin \omega t + \delta \\ V_s \sin(\omega t - 2\pi/3 + \delta) \\ V_s \sin(\omega t - 4\pi/3 + \delta) \end{bmatrix} \cdots\cdots (10)$$

$$\begin{bmatrix} v_{ru} \\ v_{rv} \\ v_{rw} \end{bmatrix} = \begin{bmatrix} V_r \sin(\omega t) \\ V_r \sin(\omega t - 2\pi/3) \\ V_r \sin(\omega t - 4\pi/3) \end{bmatrix} \cdots\cdots\cdots\cdots (11)$$

Substituting Eq.(10) and Eq.(11) to Eq.(8) and Eq.(9), voltages in two phase coordinate can be obtained as follows:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{\frac{3}{2}} V_s \sin(\omega t + \delta) \\ -\sqrt{\frac{3}{2}} V_s \cos(\omega t + \delta) \end{bmatrix} \cdots\cdots (12)$$

$$\begin{bmatrix} v_{r\alpha} \\ v_{r\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{ru} \\ v_{rv} \\ v_{rw} \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{\frac{3}{2}} V_r \sin \omega t \\ -\sqrt{\frac{3}{2}} V_r \cos \omega t \end{bmatrix} \cdots\cdots\cdots\cdots (13)$$

Because the voltage-current relationship of a variable inductance follows Eq.(5), i_α and i_β becomes as,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \frac{1}{L_t(t)} \int (v_{s\alpha} - v_{r\alpha}) dt \\ \frac{1}{L_t(t)} \int (v_{s\beta} - v_{r\beta}) dt \end{bmatrix} \cdots\cdots\cdots (14)$$

where $L_t(t)$ is variable inductance composed of virtual variable inductance $L_v(t)$ and line inductance L_l. Substituting Eq.(12) into Eq.(14), the integration part of the right term becomes as the Eq.(15) if the dc components of the system assumed to be zero. This condition is satisfied even if the resistance is very small after the transient period.

$$\begin{bmatrix} \int (v_{s\alpha} - v_{r\alpha}) dt \\ \int (v_{s\beta} - v_{r\beta}) dt \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{\frac{3}{2}} \frac{1}{\omega} \{-V_s \cos(\omega t + \delta) + V_r \cos \omega t\} \\ \sqrt{\frac{3}{2}} \frac{1}{\omega} \{-V_s \sin(\omega t + \delta) + V_r \sin \omega t\} \end{bmatrix} \cdots (15)$$

The current can be calculated as follows if only L_t varies as a function $L_t(t)$:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{\frac{3}{2}} \frac{1}{\omega L_t(t)} \{-V_s \cos(\omega t + \delta) + V_r \cos \omega t\} \\ \sqrt{\frac{3}{2}} \frac{1}{\omega L_t(t)} \{-V_s \sin(\omega t + \delta) + V_r \sin \omega t\} \end{bmatrix} \cdots (16)$$

The instantaneous active power p_s and reactive power q_s flowing from the bus1(sending side) can be expressed as follows:

$$\begin{bmatrix} p_s \\ q_s \end{bmatrix} = \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \cdots\cdots\cdots\cdots (17)$$

Substituting Eq.(16) into Eq.(17), the following equation is obtained:

$$\begin{bmatrix} p_s \\ q_s \end{bmatrix}$$
$$= \begin{bmatrix} \sqrt{\frac{3}{2}} V_r \sin \omega t & -\sqrt{\frac{3}{2}} V_r \cos \omega t \\ \sqrt{\frac{3}{2}} V_r \cos \omega t & \sqrt{\frac{3}{2}} V_r \sin \omega t \end{bmatrix}$$
$$* \begin{bmatrix} \sqrt{\frac{3}{2}} \frac{1}{\omega L_t(t)} \{-V_s \cos(\omega t + \delta) + V_r \cos \omega t\} \\ \sqrt{\frac{3}{2}} \frac{1}{\omega L_t(t)} \{-V_s \sin(\omega t + \delta) + V_r \sin \omega t\} \end{bmatrix}$$
$$= \begin{bmatrix} \frac{3}{2} \frac{1}{\omega L_t(t)} V_s V_r \sin \delta \\ \frac{3}{2} \frac{1}{\omega L_t(t)} (V_s V r \cos \delta - V_s^2) \end{bmatrix} . \cdots\cdots\cdots\cdots (18)$$

Eq.(18) can be modified as follows where V_{sl} and V_{rl} are the line-line voltages (rms) of the sending and receiving sides respectively:

$$P = \frac{V_{sl} V_{rl}}{X} \sin \delta$$

Table 1. Parameters used in simulations and experiments

Parameters expressed with % are based on 100V, 1kVA, 50Hz
$V_s = V_r = 81.6$V(Phase voltage (rms))
100V (line-line voltage(rms))
Frequency 50Hz
Phase difference$\delta = 16\,$deg
Line inductance $L_l = 21.6$mH(67.9%)
Line resistance $R_l =$ 0.01Ω(0.1%,in simulations only)
or 2.3Ω(23%)
VAPAR
$L_v = 10$mH(31.4%) $\Longleftrightarrow$ 30mH(94.2%)
$K = 90$, $\tau = 1.33$msec
$L_v = -2$(-6.28%)$\Longleftrightarrow$ -10mH(-31.4%)
$K = -81.3$, $\tau = 1$msec
$L_o = 2$mH(5.28%), R_o(Resistance of L_o) $= 0.1\Omega$(1%)
$f_s w$=12kHz, E_{dc}=40V (in experiments only)

This equation expresses the steady-state power flow. Therefore, the **instantaneous power flow** of the power line can be controlled by changing the line inductance **without** any unstable oscillation. It is because a variable inductance supplies or consumes only reactive power in a steady state, however it supplies or consumes both active and reactive power in a transient state (6).

From Eq.(18), the reactive power of the sending side simultaneously varies with the change of active power. This may not be serious problem because reactive power can be easily compensated by parallel compensator.

5. Simulations and experiments of proposed method

To verify the proposed method, simulations and experiments are carried out using the power system as shown in Fig.5. The variable inductance is realized by VAPAR composed as shown in Fig.4.

5.1 Simulations In the simulations, the PWM voltage source inverter is assumed to be an ideal voltage source. Table 1 shows parameters used in the simulations. The control gain and time constant are decided to be large enough so that the VAPAR can be regarded to be an ideal variable inductance in the simulations and experiments. Simulations were performed using two different line resistance 0.01Ω and 2.3Ω, and experiments were performed using the line resistance 2.3Ω. The line resistance 2.3Ω(23%) is too large therefore it may not be used in practice. This selection of the line resistance is intended to examine the most unfavorable case.

Fig.6 show simulation results. When the line resistance is negligible compared with the line reactance (see (a)(b)(e)(f)), the actual instantaneous power flow p completely agrees with the theoretical power p(theory). If the line resistance is rather large (see (c)(d)(g)(h)), then the actual instantaneous power flow has transient oscillations. However, this oscillations are not so large even if the line resistance is about one third of the line reactance. If the slope of the inductance change dL_v/dt is small, the transient oscillations do not appear (see (d)(h)). Because the circuit becomes only RL passive circuit once VAPAR becomes constant inductance, thus the controlled power never becomes unstable. This is one of the important advantages of the proposed method.

The power flow of this line without VAPAR is about 406W. In (e)-(h), VAPAR works as a negative inductance so that the instantaneous power flow can be quickly increased without any unstable phenomenon.

In every simulations, i_u suddenly varies at the moment when the inductance changes. These results verify the theory as described in the section 3.1.

5.2 Experiments The experiments were carried out to verify the performance of the proposed method. Fig.7 shows the experimental system. Each phase VAPAR is composed as shown in Fig.7 with a single phase voltage source inverter controlled by a DSP(TI TMS320C31)-based digital controller. Instantaneous power flow is also calculated by the DSP system. Parameters used in the experiments are the same as those used in the simulations. However, experiments were done only with $R_l = 2.3\Omega$ because of the limitation of the actual experimental circuit. Fig.8 show the experimental results. Fig.8(a)(b)(c)(d) correspond to Fig.6(c)(d)(g)(h) in simulations, respectively. The experimental results well agree with theory and simulations in each case.

6. Conclusion

In this paper, a new instantaneous power flow control method using variable inductance realized by the Variable Active-Passive Reactance (VAPAR) is proposed. The results are summarized as follows

(1) The concept of the proposed power flow method was introduced.

(2) The theoretical analysis of the proposed method was completed when line resistance is negligible. From the analysis, the instantaneous power flow of the power line can be controlled by changing the line inductance without any unstable oscillations.

(3) The effectiveness of the proposed method are verified by simulations and experiments.

(4) From simulations and experiments, if the line resistance is rather large, the actual instantaneous power flow has transient oscillations. However, this oscillations are not so large even if the line resistance is about one third of the line reactance.

7. Acknowledgments

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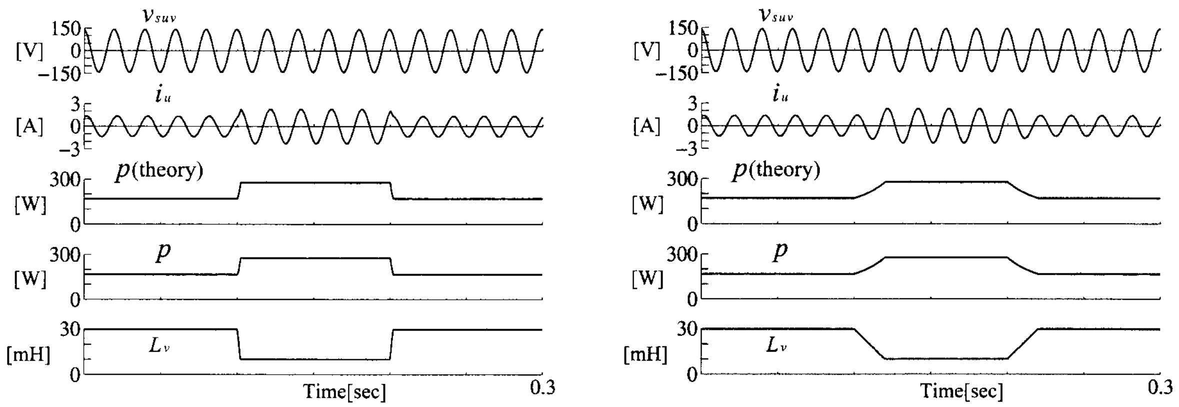
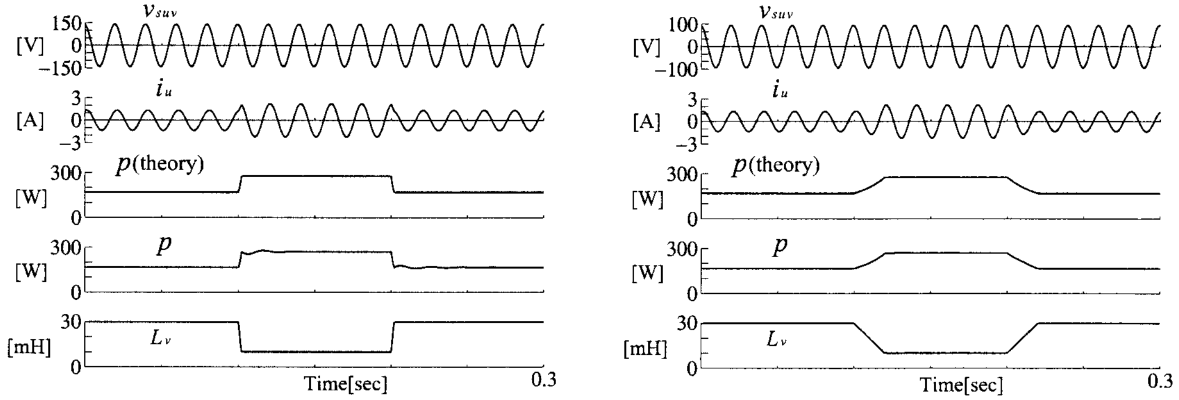


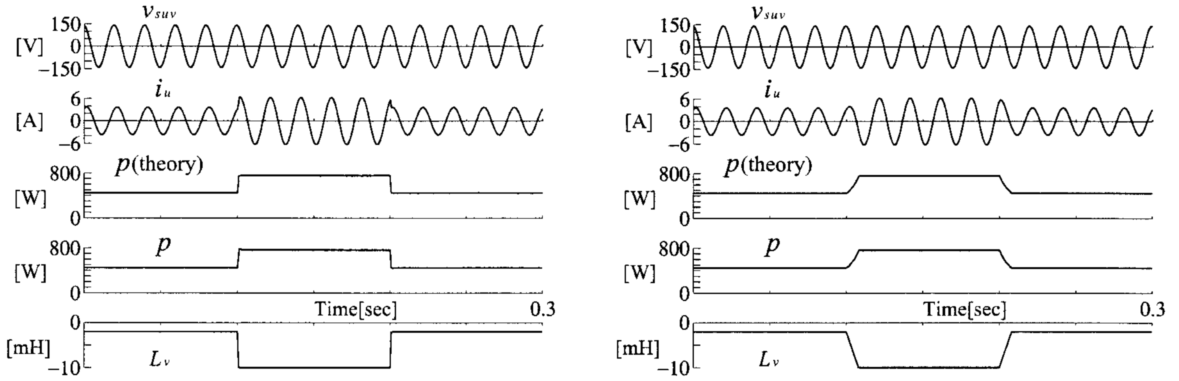
(a)L_v : 10mH⇔ 30mH,R_l = 0.01Ω,dLv/dt = ±10H/sec

(b)L_v : 10mH⇔ 30mH,R_l = 0.01Ω,dLv/dt = ±1H/sec



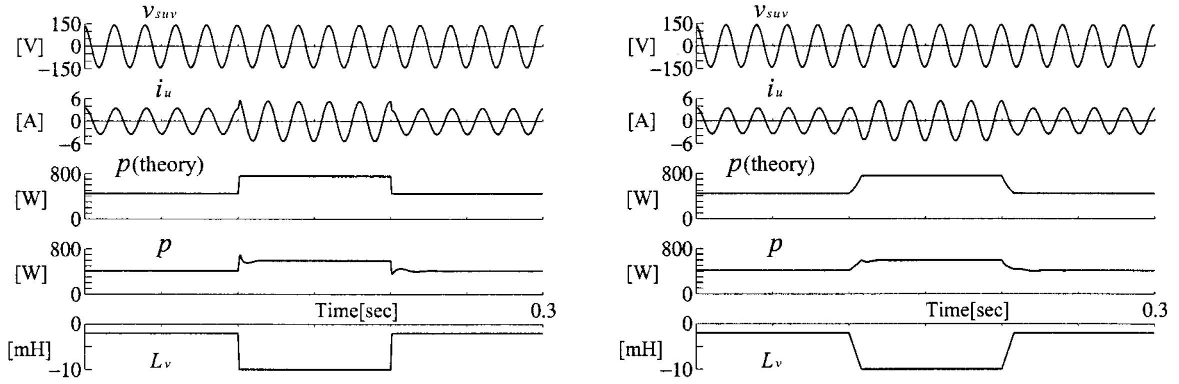
(c)L_v : 10mH⇔ 30mH,R_l = 2.3Ω,dLv/dt = ±10H/sec

(d)L_v : 10mH⇔ 30mH,R_l = 2.3Ω,dLv/dt = ±1H/sec



(e)L_v : −10mH⇔ −2mH,R_l = 0.01Ω,dLv/dt = ±10H/sec

(f)L_v : −10mH⇔ −2mH,R_l = 0.01Ω,dLv/dt = ±1H/sec



(g)L_v : −10mH⇔ −2mH,R_l = 2.3Ω,dLv/dt = ±10H/sec

(h)L_v : −10mH⇔ −2mH,R_l = 2.3Ω,dLv/dt = ±1H/sec

Fig. 6. Simulation results

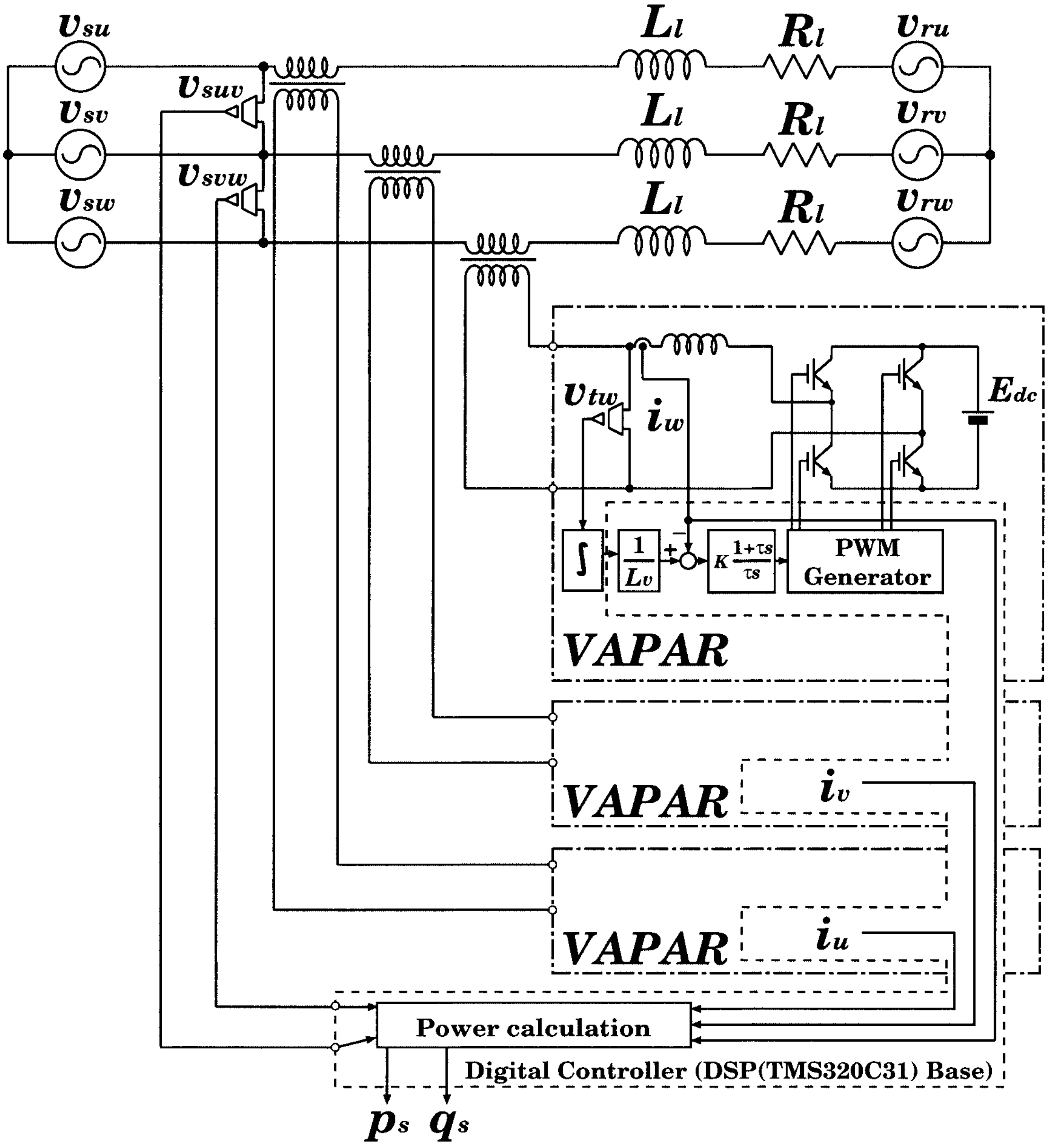


Fig. 7. Experimental system

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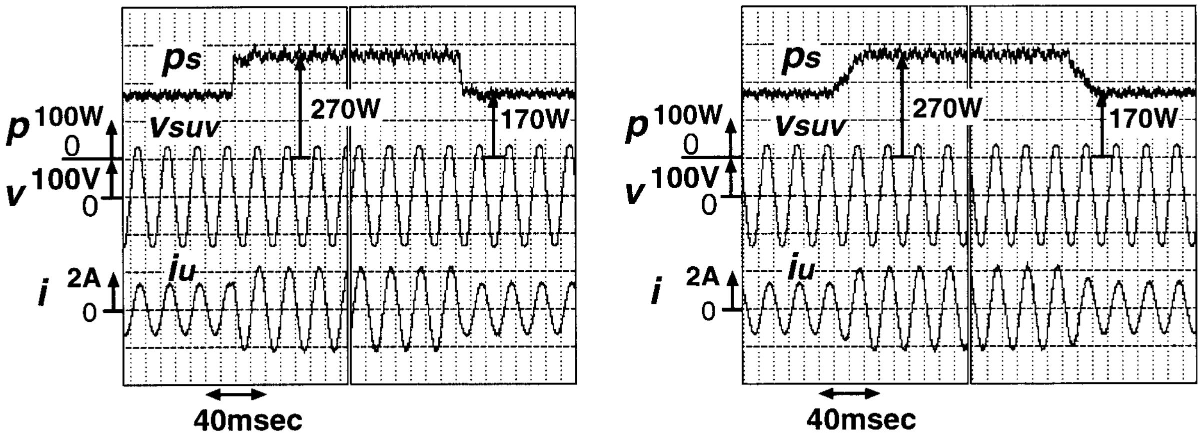
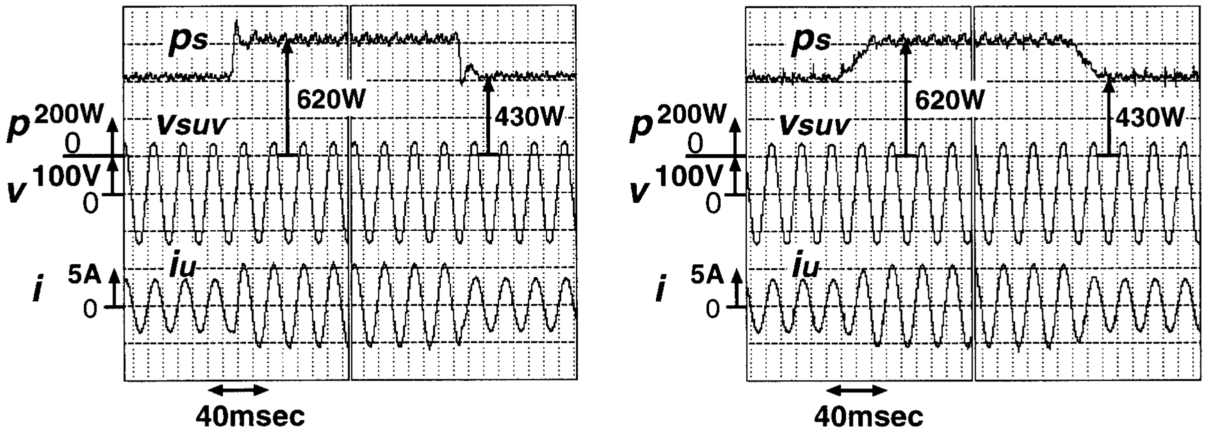


(a)L_v : 30mH$\Longleftrightarrow$ 10mH, $s_{Lv} = \pm 10$H/sec

(b)L_v : 30mH$\Longleftrightarrow$ 10mH, $s_{Lv} = \pm 1$H/sec



(c)L_v : -2mH$\Longleftrightarrow$ -10mH, $s_{Lv} = \pm 10$H/sec

(d)L_v : -2mH$\Longleftrightarrow$ -10mH, $s_{Lv} = \pm 1$H/sec

Fig. 8. Experimental results

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