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Transient Analysis of a Unified Power Flow Controller, and its Application to Design of the DC-Link Capacitor

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Abstract— **This paper presents a transient analysis of a unified power flow controller (UPFC), and design of capacitance of the dc-link capacitor based on that analysis. Active power flowing out of the series device in transient states is theoretically discussed to derive what amount of electric energy the dc link capacitor absorbs or releases through the series device. As a result, it is clarified that the active power flowing out of the series device is stored in the line inductance as magnetic energy during transient states. Design of capacitance of the dc-link capacitor is also presented in this paper, based on the theoretical analysis. Experimental results obtained from a 10-kVA laboratory setup are shown to verify the analytical results.**

Index term— unified power flow controller, transient analysis, dc-link capacitor, dc voltage regulation.

I. Introduction

A unified power flow controller (UPFC), which is one of the most promising devices proposed in the FACTS concept, has the potential of controlling power flow and improving stability in transmission lines [1]-[9]. Fig. 1 shows a basic configuration of a UPFC. The UPFC consists of a combination of series and shunt devices, the dc terminals of which are connected to a common dc-link capacitor. The series device controls power flow between the sending end V_S and the receiving end V_R by means of adjusting the phase angle of its output voltage V_C. On the other hand, the shunt device performs regulation of the dc-link voltage as well as control of reactive power. Currently, American Electric Power (AEP) is planning to install a 160-MVA UPFC at the Inez substation in eastern Kentucky, which will be the first implementation of a practical UPFC [9].

Reserch on UPFCs has emphasized effect of the power flow control, improvement of stability, and performance of power-swing damping. However, a small amount of literature has been published on dynamic performance and transient behavior of UPFCs. The authors have performed a transient analysis of power-flow control and proposed a new dynamic control achieving a power-flow response as fast as 3 ms without any fluctuation in power flow [10].

Fast power-flow control causes fluctuation of the dc-link voltage because active power is produced between the output voltage of the series device and the current of the transmission line and flows into the dc-link capacitor in transient states. If a large amount of active power flows into the series device, the dc-link voltage rapidly rises up, and overvoltage may be applied not only to the dc-link capacitor but also to series and shunt devices. The capacitance of the dc-link capacitor and response time of the shunt device should be appropriately designed to avoid such a condition.

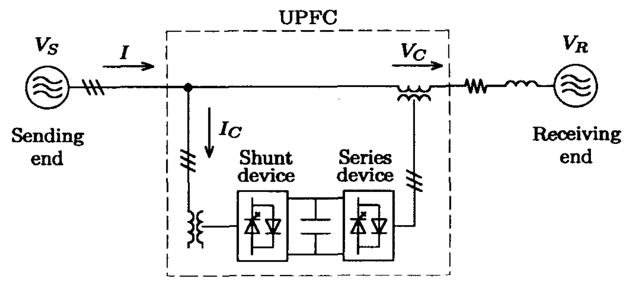

Fig. 1. Basic configuration of a UPFC.

The purpose of this paper is to perform a transient analysis of power flow inside the UPFC. Active power flowing into, or out of, the series device is theoretically discussed, based on instantaneous voltage and current vectors, rather than phasor. The analysis reveals that the active power flowing out of the series device is transmitted to the line inductance in transient states. Therefore, the electrical energy released from the dc-link capacitor is equal to the magnetic energy stored in the line inductance during transient states. The fluctuation of the dc-link voltage caused by the power-flow control and design of the dc-link capacitor are presented along with the theoretical analysis. Experimental results obtained from a 10-kVA laboratory setup agree with the analytical results as well as simulated results.

II. Experimental System Configuration

Fig. 2 shows the 10-kVA laboratory setup of the UPFC used in the following experiments and simulations. The circuit parameters of the UPFC are shown in Table I. In the experiment, v_S and v_R are assumed to be sending and receiving ends of the transmission line, respectively, and the UPFC controls the power flow between v_S and v_R. The reactors L and resistor R represent inductance and resistance existing in the transmission line.

The main circuit of the series device consists of three H-bridge PWM inverters, the switching frequency of which is 1 kHz. The ac terminals in each H-bridge inverter are connected in series to the transmission line through a single-phase transformer with a turns ratio of 1:12. The kVA rating of the series device is given by

$$3 \times 12^{\mathrm{V}} \times 29^{\mathrm{A}} = 1.0\,\mathrm{kVA},$$

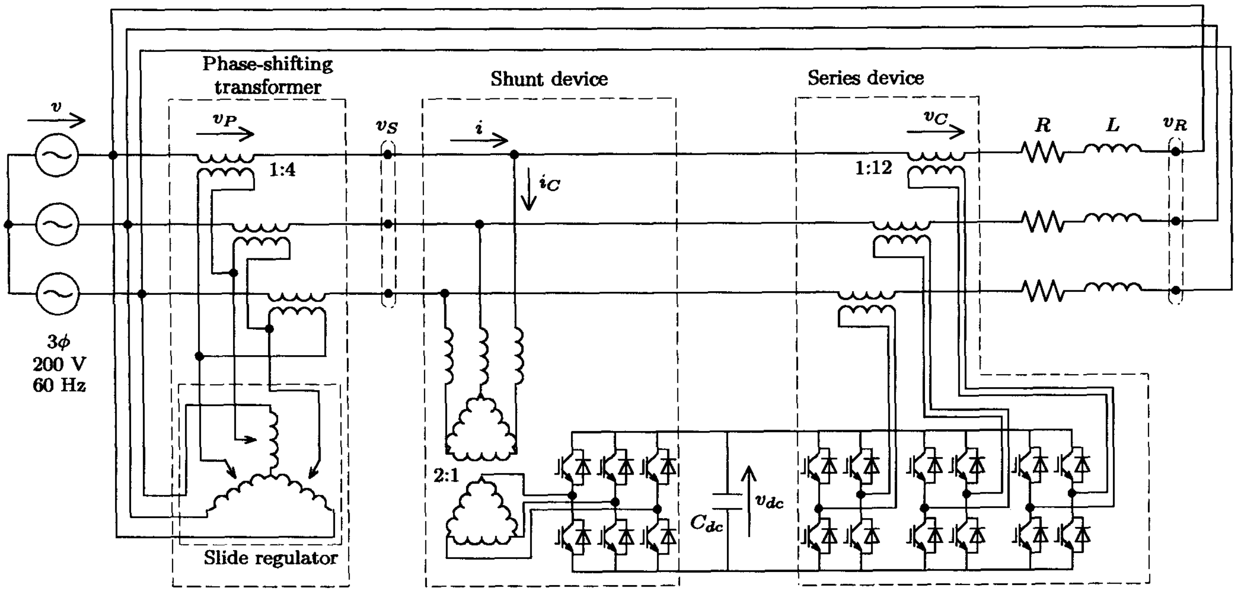

Fig. 2. Experimental system configuration.

TABLE I
EXPERIMENTAL SYSTEM PARAMETERS.

Transmission rating	P	10 kVA
Utility line-to-line voltage	V_S	200 V
Utility angular frequency	ω_0	$2\pi \times 60$ rad/s
Line inductance	L	1.0 mH (=10%)
Line resistance	R	0.04 Ω (=1%)
Series device capacity	P_{INV}	1.0 kVA (=10%)
RMS voltage of v_C	V_C	12 V (=10%)
Dc link capacitor capacity	C_{dc}	200 μF
Dc link voltage	V_{dc}	200 V
Unit capacitance constant	UCC	4×10^{-3} J/VA

(3φ, 200-V, 10-kVA, 60-Hz base)

which is 10% of the rated power in the transmission line between v_S and v_R.

The shunt device is composed of a three-phase PWM inverter, and its ac terminals are connected in parallel with the transmission line via a three-phase transformer with a turns ratio of 2:1. The shunt device regulates the dc-link voltage as $V_{dc} = 200$ V. For the sake of simplicity, reactive power control is not implemented in the experimental setup.

The dc terminals of both series and shunt devices are connected to a common dc capacitor of $C_{dc} = 200\ \mu$F. The UCC (unit capacitance constant)[11] of the experimental system is

$$\text{UCC} = \frac{1}{2}C_{dc}V_{dc}^2/P = 4 \times 10^{-3}\ \text{[J/VA]}.$$

A phase-shifting transformer is employed to simulate a difference in phase angle between the sending and receiving ends, which consists of three single-phase transformers and a three-phase slide regulator. The phase-shifting transformer injects a 90°-leading or lagging voltage, and then allows to adjust the phase angle of v_S.

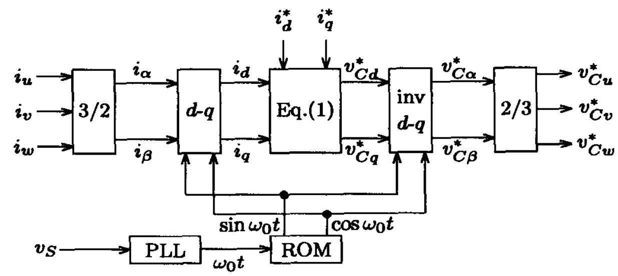

Fig. 3. Control circuit of the series device.

III. CONTROL SCHEME

Fig. 3 shows a block diagram of the control circuit. The three- to two-phase transformation obtains i_α and i_β from the three-phase currents i_u, i_v and i_w. The d-q transformation gets i_d and i_q with the help of sinusoidal signals of $\sin\omega_0 t$ and $\cos\omega_0 t$ taken from a read only memory (ROM). The phase information $\omega_0 t$ is generated by a phase-lock-loop (PLL) circuit.

"Advanced control" [10] is applied to the series device, which has the capability of damping the power swings in transient states. The voltage reference v_{Cd}^* and v_{Cq}^* are given by the following equation:

$$\begin{bmatrix} v_{Cd}^* \\ v_{Cq}^* \end{bmatrix} = \begin{bmatrix} K_r & -K_q \\ K_p & K_r \end{bmatrix} \begin{bmatrix} i_d^* - i_d \\ i_q^* - i_q \end{bmatrix}, \tag{1}$$

where K_p and K_q are active and reactive power feedback gains, respectively, and K_r is a control gain capable of damping the power swings. Integral gains are added to K_p and K_q to reduce steady-state error in the active and reactive power feedback loops. The control gains K_p and K_q are set to 0.5 V/A, and the time constant of the integral gain is set to 5 ms. The gain K_r acts as a resistor for the power swings, and improves the stability of the power flow in transient states [10]. The gain K_r is set to 1.2 V/A in order to achieve the damping factor of $\zeta = 0.8$. These settings allow a response time as fast as 3 ms without any power swings.

On the other hand, the shunt device regulates the dc-link voltage by using a feedback control with a proportional and integral gain. The dc-link voltage reference is set to 200 V in the experiments and simulations. The gains are adjusted to enable a response time as slow as 50 ms in the experiments in order to verify the theory on the power flow through the series device. Since measurement of active power through the series device is based on the dc-link voltage variations, fast regulation of the dc-link voltage makes the measurement difficult. It is possible to introduce fast voltage regulation to practical use.

IV. Theoretical Analysis of Power Flow

A. *Active power flowing out of the series device*

To design the dc capacitor and the shunt device, it is necessary to know the active power flowing out of the series device. The following assumptions are made in the theoretical analysis:

- The current of the shunt device, i_C is much smaller than the line current i, when the reactive power control is not implemented.
- No power loss occurs in the series device.

The following equation is obtained from the system configuration shown in Fig. 2.

$$\left(R + L\frac{d}{dt}\right)\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \begin{bmatrix} v_{Cu} + v_{Su} - v_{Ru} \\ v_{Cv} + v_{Sv} - v_{Rv} \\ v_{Cw} + v_{Sw} - v_{Rw} \end{bmatrix} \quad (2)$$

Applying the d-q transformation to (2) produces

$$\begin{bmatrix} R + L\frac{d}{dt} & -\omega_0 L \\ \omega_0 L & R + L\frac{d}{dt} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_{Cd} + v_{Sd} - v_{Rd} \\ v_{Cq} + v_{Sq} - v_{Rq} \end{bmatrix}, \quad (3)$$

where ω_0 is the angular frequency of the transmission system. The active power flowing out of the series device, p_C is given by

$$p_C = v_{Cd} i_d + v_{Cq} i_q. \quad (4)$$

Substituting v_{Cd} and v_{Cq} in (3) for (4), the active power p_C is represented as follows:

$$p_C = R({i_d}^2 + {i_q}^2) - [(v_{Sd} - v_{Rd})i_d + (v_{Sq} - v_{Rq})i_q] + L\left(i_d\frac{di_d}{dt} + i_q\frac{di_q}{dt}\right). \quad (5)$$

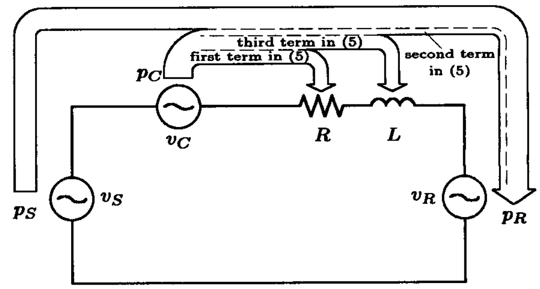

Fig. 4. Power flow of the UPFC in transient states.

Equation (5) tells us the power flow in the transmission line equipped with the UPFC in transient states as shown in Fig. 4. The active power flowing out of the series device, p_C is drawn into the receiving end v_R, the line resistance R, and the line inductance L. The first term in (5) is equal to the dissipated power in the line resistance R. The second term represents the difference of active power between the sending and receiving ends, which depends on the amplitude and phase angle of v_S and v_R. Usually, the amplitude of v_S and v_R are almost the same, so that $(v_{Sd} - v_{Rd})$ in the second term is almost zero. A small difference exists in the phase angle between v_S and v_R, but the reactive power component i_q has to be controlled as zero. Therefore, the second term may be quite small in normal operating conditions.

The most interesting component in (5) is the third term, which means the active power of the line inductance L. In other words, the electrical energy stored in the dc-link capacitor is transmitted and converted to magnetic energy in the line inductance. The term includes the differentials of i_d and i_q, so that it appears only in transient states, but does not exist in steady states. However, the third term can not be negligible when the power flow is quickly changed, because the differential values are in inverse proportion to the transient time. The third term can not be explained by any conventional analysis based on phasor vector, because phasor can essentially be applicable only in steady states.

B. *Energy transmitted from the series device to line inductance*

How much electrical energy is transmitted from the series device to the line inductance is discussed in this section. Here, it is assumed that a transient state starts at $t = 0$ and finishes at $t = T$, and then the d-axis current i_d changes from I_{d0} to I_{d1} and the q-axis current i_q from I_{q0} to I_{q1} during the transient state.

Integrating the third term in (5) from $t = 0$ to $t = T$ derives the electrical energy transmitted from the series device to the line inductance in the transient state. The transmitted energy ΔW is given by

$$\Delta W = \int_0^T \left(i_d(t) L \frac{di_d(t)}{dt} + i_q(t) L \frac{di_q(t)}{dt} \right) dt$$
$$= \frac{1}{2} L \left({I_{d1}}^2 + {I_{q1}}^2 \right) - \frac{1}{2} L \left({I_{d0}}^2 + {i_{q0}}^2 \right). \quad (6)$$

The transmitted energy ΔW is equal to the difference of the stored energy in the line inductor between $t = 0$ and $t = T$. Moreover, ΔW is independent of phase angle of the line current before and after the transient state, but depends on the amplitude change of the line current.

Accordingly, the transmitted energy is represented by rms currents before and after the transient state. Assuming a three-phase balanced sinusoidal current, the line currents i_u, i_v, and i_w are given by the following equation:

$$\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \sqrt{2} I \begin{bmatrix} \cos \omega_0 t \\ \cos(\omega_0 t - 2\pi/3) \\ \cos(\omega_0 t + 2\pi/3) \end{bmatrix}, \quad (7)$$

where I is rms value of the line current. Applying d-q transformation to (7) yields $[\, i_d \,,\, i_q \,] = [\, \sqrt{3} I,\, 0 \,]$. Applying this relation for (6) leads to the following equation:

$$\Delta W = \frac{1}{2} L (\sqrt{3} I_1)^2 - \frac{1}{2} L (\sqrt{3} I_0)^2$$
$$= \frac{3}{2} L (I_1^2 - I_0^2). \quad (8)$$

As shown in (8), the transmitted power can be represented by using only the rms values of the line currents before and after the transient state. The simple equation is utilized for designing the capacity of the dc-link capacitor.

V. Designing the dc-link capacitor

Based on the analysis of power flow in the previous section, designing the capacity of the dc-link capacitor is performed in this section. The electrical energy transmitted to the line inductance has to be provided by the dc-link capacitor and the shunt device during transient states. If the shunt device provides all of the transmitted energy to the series device, no fluctuation occurs in the dc-link voltage. Then the required kVA rating for the shunt device is the same or larger than the series device, although the shunt device provides a small amount of power in steady states, that is, the first and second terms in (5).

On the other hand, when the dc-link capacitor provides the transmitted energy to the series device in transient states, a small kVA rating is required for the shunt device, which is slightly larger than the steady-state power. The dc-link voltage, however, fluctuates in transient states, according to releasing or absorbing the energy. Then the dc-link capacitor has to be designed to regulate the fluctuation of the dc-link voltage.

The following discussion is based on the assumption that the dc-link capacitor provides the energy transmitted to the line inductance, while the steady-state power is provided by the shunt device. When the dc voltage changes from V_{dc0} to V_{dc1}, the energy released from the dc-link capacitor, ΔW_{dc} is given by

$$\Delta W_{dc} = \frac{1}{2} C_{dc} (V_{dc0}^2 - V_{dc1}^2), \quad (9)$$

where C_{dc} is the capacitance of the dc-link capacitor. Then the released energy ΔW_{dc} is equal to the transmitted energy ΔW, as assumed above. Here, the ratio of the dc voltage fluctuation, ε is defined as

$$\varepsilon = \frac{V_{dc0} - V_{dc1}}{V_{dc0}}. \quad (10)$$

Substituting (10) to (9) and applying an approximation of $\varepsilon^2 \ll 2\varepsilon$ yields the following relation of the required capacitance of the dc-link capacitor:

$$C_{dc} = \frac{3L(I_1^2 - I_0^2)}{2\varepsilon V_{dc0}^2}. \quad (11)$$

The required capacity of the dc capacitor is proportional to the line inductance, so that a large capacitor is required for long-distance transmission systems.

For example, the capacitance in the experimental setup is designed here. It is assumed that the power flow increases from 5 kW to 10 kW (50% to 100%), that is, the line current changes from 14 A to 29 A. In order to reduce the fluctuation of the dc-link voltage to 10% in a transient state, the required capacitance is given by

$$C_{dc} = \frac{3 \cdot 0.001 \cdot (29^2 - 14^2)}{2 \cdot 0.1 \cdot 200^2} = 240\ \mu\text{F}.$$

In the following experiment, a 200-μF capacitor is employed.

VI. Simulated and experimental Results

Figs. 5-8 show simulated and experimental waveforms for a step change of active power flow. The output voltage of the series device, v_C is measured by using a 400-Hz low-pass filter to remove switching ripples of 1 kHz in the experiments. The transient analysis program EMTDC is used for the following simulations, and then the series device is assumed to be an ideal controllable voltage source disregarding switching operation.

The simulated and experimental waveforms agree well with each other not only in the steady state but also in the transient state. Figs. 5 and 6 show simulated and experimental waveforms in the case of power flow change from 5 kW to 10 kW. Then the phase angle of v_S with respect to v_R is set to 2.7° to produce the active power flow of 5 kW before the step change. The i_d starts to rise the instant the current reference i_d^* changes, and reaches 50 A after 3 ms without any power swings.

The active power flowing out of the series device, p_C reaches 800 W in the transient state, while it is less than 100 W after the transient state. The required power rating

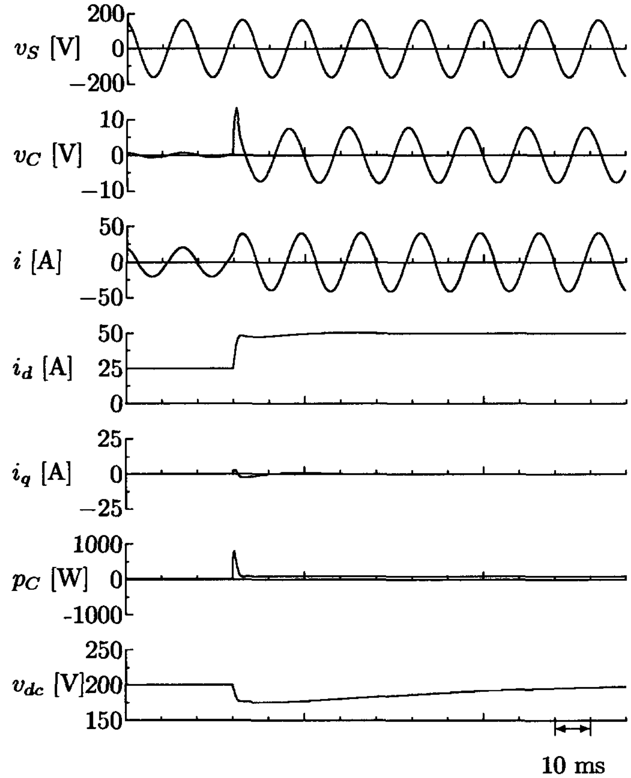

Fig. 5. Simulated waveforms for the step change of power flow from 5 kW to 10 kW.

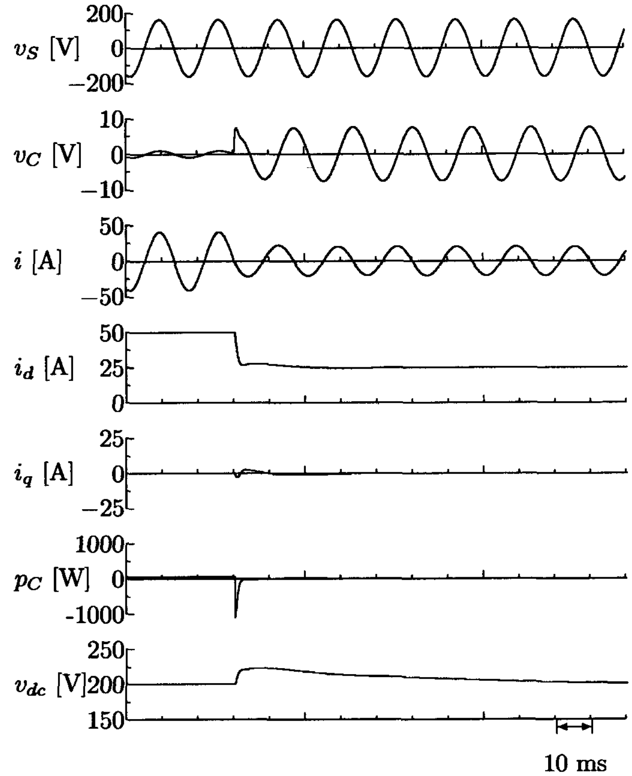

Fig. 7. Simulated waveforms for the step change of power flow from 10 kW to 5 kW.

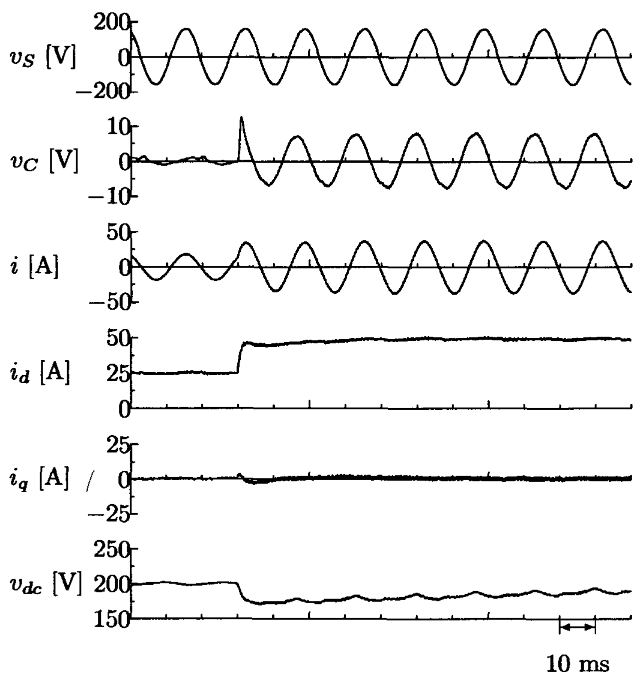

Fig. 6. Experimental waveforms for the step change of power flow from 5 kW to 10 kW.

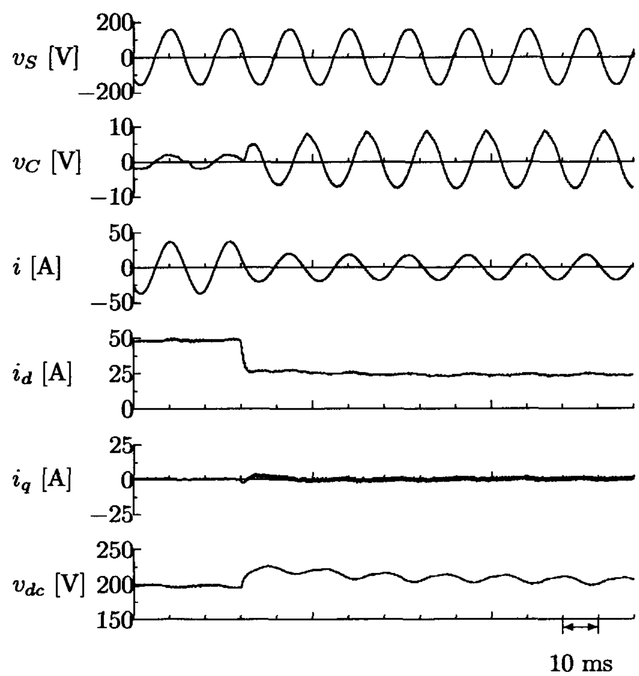

Fig. 8. Experimental waveforms for the step change of power flow from 10 kW to 5 kW.

of the shunt device is about 100 W in the case of this experiment because the dc-link capacitor provides the active power in the transient state. If the shunt device provides the active power, the dc-link voltage can be maintained as a constant level. However, a shunt device rated at 800 W is required for maintaining the dc-link voltage, accompanied by increasing losses and costs.

In consequence of the step change, the dc-link voltage v_{dc} decreases from 200 V to 176 V because the dc-link capacitor releases an amount of electric energy. Thereafter, v_{dc} gradually approaches 200 V due to the dc-link voltage regulation of the shunt device with a response time of 50 ms. The energy released from the dc-link capacitor, ΔW_{dc} is given by

$$\Delta W_{dc} = \frac{1}{2} \cdot 200 \times 10^{-6} \cdot (200^2 - 176^2) = 0.90\,\text{J}.$$

While the increase of electromagnetic energy stored in the line inductor, ΔW is obtained from (6) as

$$\Delta W = \frac{1}{2} \cdot 0.001 \cdot (50^2 - 25^2) = 0.94\,\text{J}.$$

Note that ΔW_{dc} almost equals ΔW. This means that the series device transmits the energy from the dc-link capacitor to the line inductance during the transient state.

Figs. 7 and 8 show simulated and experimental waveforms for a step change of power flow from 10 kW to 5 kW. Then the phase angle of v_S leads by 5.4° to v_R. The dc-link voltage increases from 200 V to 222 V during the transient state, as contrasted to Figs. 5 and 6. Then the energy ΔW_{dc} is −0.88 J, while the energy ΔW is −0.94 J. and thus, the electromagnetic energy stored in the line inductor is drawn into the dc-link capacitor. These results show that active power is transmitted from the dc-link capacitor to the line inductance.

VII. Conclusion

Transient power flow inside the UPFC has been theoretically and experimentally discussed in this paper, based on instantaneous power theory. The transient analysis performed in this paper reveals that the active power flowing out of the series device is drawn into the line inductance in transient states. And it is experimentally verified that the energy released from the dc-link capacitor is equal to the energy stored in the line inductance during transient states.

The theoretical and experimental discussion in this paper can be summarized as follows:

- Fast power flow control needs a large amount of active power in transient states. The required active power is in inverse proportion to the response time of the power flow control.
- The kVA rating required for the shunt device is about 1/10 of that for the series device when the dc-link capacitor can provide the active power in transient states.

When a UPFC is installed in a long-distance transmission line, it may be difficult for the dc-link capacitor to provide all the active power flow out of the series device because of the size and cost of the dc-link capacitor. Then it is required for the shunt device to provide the active power in transient states, or for the series device to limit the response time of the power flow control. A method of assigning the active power from the dc-link capacitor and the shunt device, and limiting the response time for the series device, should be designed taking into account cost effectiveness and space utilization.

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