Transient analysis of a unified power flow controller and its application to design of the DC-link capacitor

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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. 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 Terms*—DC-link capacitors, dc-voltage regulation, transient analysis, unified power flow controllers.**

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]–[10]. Fig. 1 shows a basic configuration of a UPFC. It 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 the dc-voltage regulation as well as reactive power control. Currently, American Electric Power (AEP) has installed a 160-MVA UPFC at the Inez substation in eastern Kentucky, which is the first practical implementation in the world [10], [11].

Most researches have emphasized the effect of UPFCs on power flow control and stability improvement. However, a little literature has been published on dynamic performance and transient behavior of UPFCs. The authors have presented a transient analysis of power-flow control and proposed a new dynamic control method capable of achieving a power-flow response as fast as 3 ms without any power fluctuation [12].

Fast power-flow control in a UPFC causes fluctuation of the dc-link voltage because the voltage injected by the series device and the current of the transmission line form an amount of active power, which flows into the dc-link capacitor in transient states.

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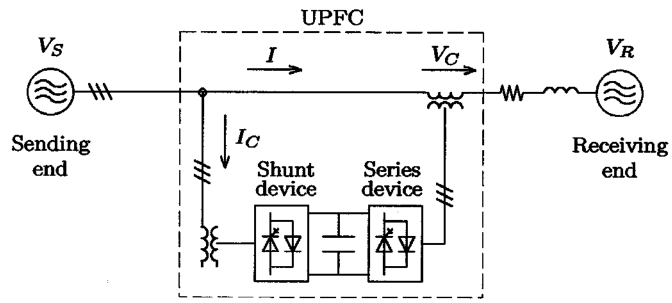

Fig. 1. Basic configuration of a UPFC.

If a nonnegligible active power flows into the dc-link capacitor, the dc-link voltage would rapidly rise up, and overvoltage would appear across the dc-link capacitor. The required capacitance of the dc-link capacitor, along with the transient response of the shunt device for the purpose of controlling the dc-link voltage, should be appropriately designed to avoid the overvoltage.

The purpose of this paper is to perform a transient analysis of power flow in a UPFC. Active power flowing into, or out of, the series device is theoretically discussed, based on instantaneous voltage and current vectors rather than phasors. The analysis reveals that the active power flowing out of the series device is transmitted to the line inductance in transient states. It concludes that the electrical energy released from the dc-link capacitor is equal to the magnetic energy stored in the line inductance during transient states. Design of the dc-link capacitor and transient response of the shunt device are presented along with the theoretical analysis. Experimental results obtained from a 10-kVA laboratory setup agree with 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 experiment and simulation. The circuit parameters 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. The purpose of the installing UPFC is to control the power flow between v_S and v_R. An inductor L and a resistor R represent inductance and resistance existing in the transmission line.

The main circuit of the series device is composed of three H-bridge voltage-fed PWM inverters with a switching frequency of 1 kHz. The ac terminals in each H-bridge inverter are connected in series to the transmission line through a

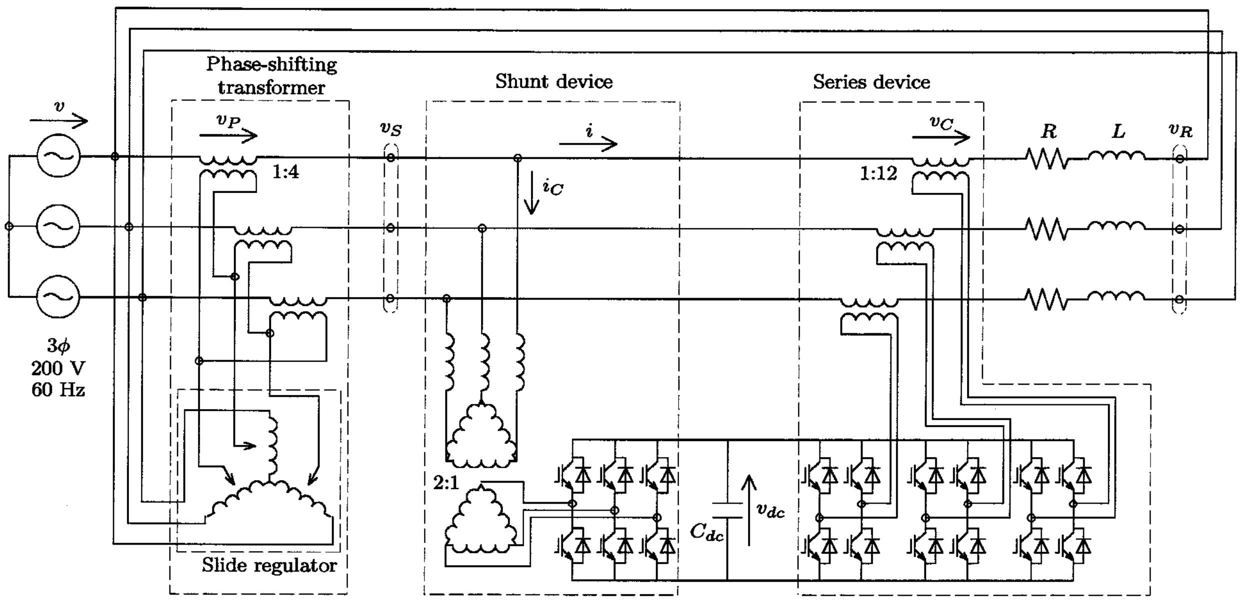

Fig. 2. Experimental system configuration.

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**
Inductance of inductor	L	**1.0 mH (=10%)**
Resistance of inductor	R	**0.04 Ω (=1%)**
Series device capacity	P_C	**1.0 kVA (=10%)**
RMS phase voltage of v_C	V_C	**12 V (=10%)**
Capacitance of dc-link capacitor	C_{dc}	**200** μ**F**
DC-link voltage	V_{dc}	**200 V**
Unit capacitance constant	**UCC**	4×10^{-3} **J/VA**

(3ϕ, 200-V, 10-kVA, 60-Hz base)

single-phase transformer with a turns ratio of 1 : 12. The kVA rating of the series device is given by

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

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

The shunt device consists 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 $V_{\mathrm{dc}} = 200$ V. For the sake of simplicity, the experimental setup has no capability of controlling reactive power.

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) introduced in [13] is

$$\mathrm{UCC} = \tfrac{1}{2} C_{\mathrm{dc}} V_{\mathrm{dc}}^2 / P_C = 4 \times 10^{-3}\ \mathrm{J/VA}.$$

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

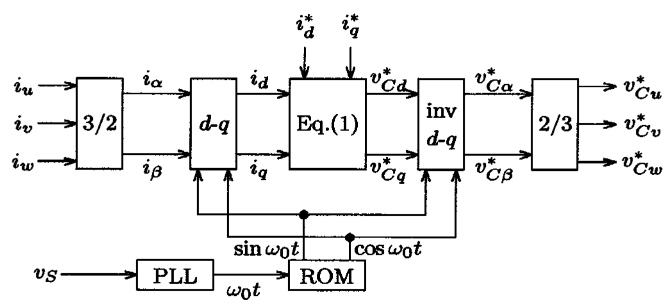

Fig. 3. Control circuit of the series device.

III. CONTROL SCHEME

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

The "advanced control" proposed in [12] is applied to the series device, which has the capability of damping out power fluctuations in transient states. The voltage reference v_{Cd}^* and v_{Cq}^* are given by

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

where K_p and K_q are active- and reactive-power feedback gains, respectively, and K_r is a control gain capable of damping out power fluctuations. Integral gains are added to K_p and K_q to eliminate steady-state errors from the active and reactive powers. 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 power fluctuations, and improves the stability of the power flow in transient states [12]. The gain K_r is set to 1.2 V/A in order to achieve a damping factor of $\zeta = 0.8$. These gain settings allow a response time as fast as 3 ms without any power fluctuations.

On the other hand, the shunt device regulates the dc-link voltage by using a feedback controller with a proportional plus integral gain. The dc-link voltage reference is set to 200 V in the experiments and simulations. The gains are intentionally adjusted to provide a response time as slow as 50 ms in this experiment in order to verify the theory developed in this paper. Fast regulation of the dc-link voltage makes it difficult to measure the energy absorbed or released by the dc-link capacitor, because it is calculated from the dc-link voltage variations in the following experiment. It is possible to introduce fast voltage regulation to practical use.

IV. Power Flow Analysis

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.

At first, the following equation is obtained from the system configuration shown in Fig. 2

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

Applying the d–q transformation to (2) produces

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

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

$$p_C = v_{Cd} i_d + v_{Cq} i_q. \tag{4}$$

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

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

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 resistor R, and the inductor L. The first term in (5) is equal to the dissipated power in the line resistor R. The second term represents active power transmitted to the receiving ends, which depends on the amplitude and phase angle difference between v_S and v_R. Usually, the reactive power component i_q has to be controlled as zero, and $(v_{Sd} - v_{Rd})$ in the second term depends on the phase angle because the amplitude of v_S and v_R are almost the same.

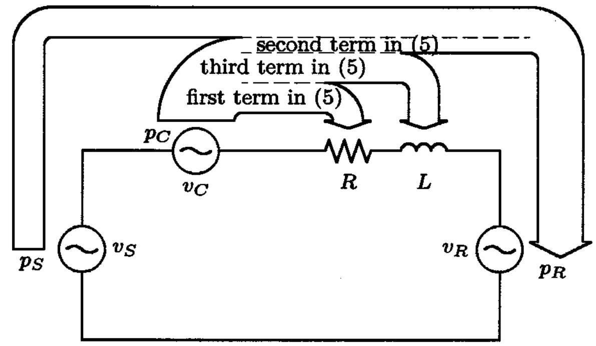

Fig. 4. Power flow of the UPFC in transient states.

The most interesting component in (5) is the third term which means that the active power flows into the inductor L. In other words, the electrical energy stored in the dc-link capacitor is transmitted and stored in the inductor as magnetic energy. This term includes the differentials of i_d and i_q, so that it appears only in transient states, but it does not exist in steady states. Any conventional power flow analysis based on the phasor theory can not predict the existence of the third term, because the phasor theory is applicable only to steady-states analysis.

Usually, the phase angle between v_S and v_R is in a range from 20° to 30° at the rated line current (1 pu) under normal operating conditions in a power system. Then $(v_{Sd} - v_{Rd})$ in the second term is 0.14 pu, and thus the second term is $0.14 \times 1.0 = 0.14$ pu. In this case, the line reactance is about 0.5 pu. If the power flow is change from 0.5 to 1 pu in 3 ms linearly, Then the third term is

$$L\frac{di_d}{dt}i_d = \frac{Z}{\omega}\frac{\Delta I}{\Delta T}I = \frac{0.5}{2\pi \times 60}\frac{0.5}{3 \times 10^{-3}} \times 1.0 = 0.22 \text{ pu}$$

where I is the rms value of each line current. Accordingly, the third term, that is more dominant than the second term, is not negligible when quick change happens in power flow.

B. Energy Transmitted From the Series Device to the Line Inductor

This section discusses how much electrical energy is transmitted from the series device to the line inductor. Here, it is assumed that a transient state starts at $t = 0$ and ends at $t = T$. During the transient state, 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}.

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

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

The energy ΔW is equal to the difference of the stored energy in the inductor between $t = 0$ and $t = T$. Moreover, ΔW depends on the amplitude change of the line current.

Assuming a set of three-phase balanced sinusoidal currents, the line currents i_u, i_v, and i_w are given by

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

Applying the d–q transformation to (7) yields

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sqrt{3}I \\ 0 \end{bmatrix}. \tag{8}$$

Substituting (8) to (6) leads to

$$\begin{aligned} \Delta W &= \tfrac{1}{2}L\left(\sqrt{3}I_1\right)^2 - \tfrac{1}{2}L\left(\sqrt{3}I_0\right)^2 \\ &= \tfrac{3}{2}L(I_1^2 - I_0^2). \end{aligned} \tag{9}$$

Equation (9) concludes that the transmitted power can be determined by the rms values of each line current before and after the transient state. The simple equation is useful 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 inductor has to be released from the dc-link capacitor and/or supplied by the shunt device. If the shunt device supplies all of the energy to the inductor through the series device, no fluctuation occurs in the dc-link voltage. In this case, the kVA rating required for the shunt device is equal to or larger than that of the series device, although the shunt device supplies a small amount of steady-state active power, which corresponds to the first and second terms in (5).

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

The following discussion is based on the assumption that the dc-link capacitor releases the transient-state active power, while the shunt device supplies only the steady-state active power. When the dc voltage changes from V_{dc0} to V_{dc1}, the energy released from the dc-link capacitor, ΔW_{dc} is given by

$$\Delta W_{\mathrm{dc}} = \tfrac{1}{2}C_{\mathrm{dc}}\left(V_{\mathrm{dc0}}^2 - V_{\mathrm{dc1}}^2\right) \tag{10}$$

where C_{dc} is the capacitance of the dc-link capacitor. The released energy ΔW_{dc} is equal to the transmitted energy ΔW, given by (9). Here, the ratio of the dc voltage change, ε is defined as

$$\varepsilon = \frac{V_{\mathrm{dc0}} - V_{\mathrm{dc1}}}{V_{\mathrm{dc0}}}. \tag{11}$$

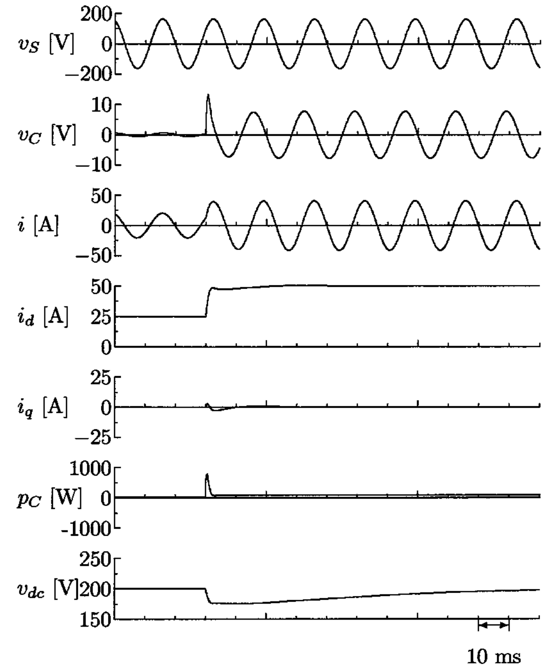

Fig. 5. Simulated waveforms for the step change in power flow from 5 kW to 10 kW.

Substituting (11) to (10), along with invoking an approximation of $\varepsilon^2 \ll 2\varepsilon$, yields the required capacitance of the dc-link capacitor as follows:

$$C_{\mathrm{dc}} = \frac{3L\left(I_1^2 - I_0^2\right)}{2\varepsilon V_{\mathrm{dc0}}^2}. \tag{12}$$

The required capacitance 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 of the dc capacitor 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 the transient state, the required capacitance is given by

$$C_{\mathrm{dc}} = \frac{3 \times 0.001 \times \left(29^2 - 14^2\right)}{2 \times 0.1 \times 200^2} = 240\ \mu\,\mathrm{F}.$$

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 in 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, where 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 a step change in active-power flow from 5 kW to 10 kW. Here, the phase angle of v_S with respect to v_R is set to

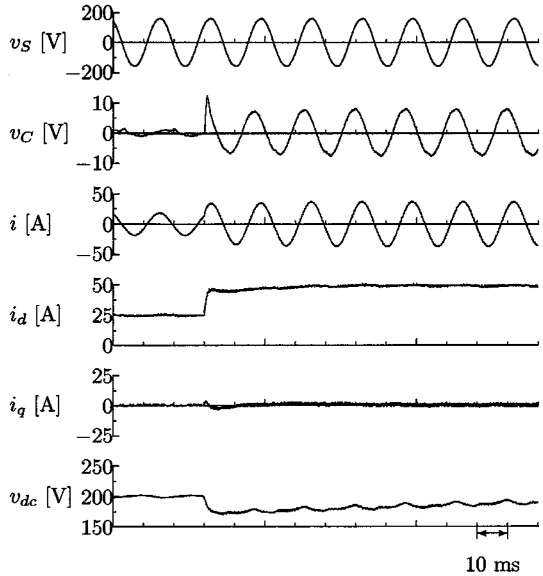

Fig. 6. Experimental waveforms for the step change in power flow from 5 kW to 10 kW.

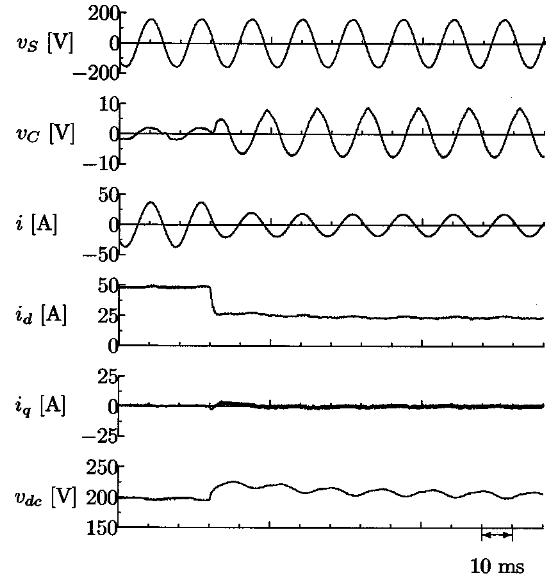

Fig. 8. Experimental waveforms for the step change in power flow from 10 kW to 5 kW.

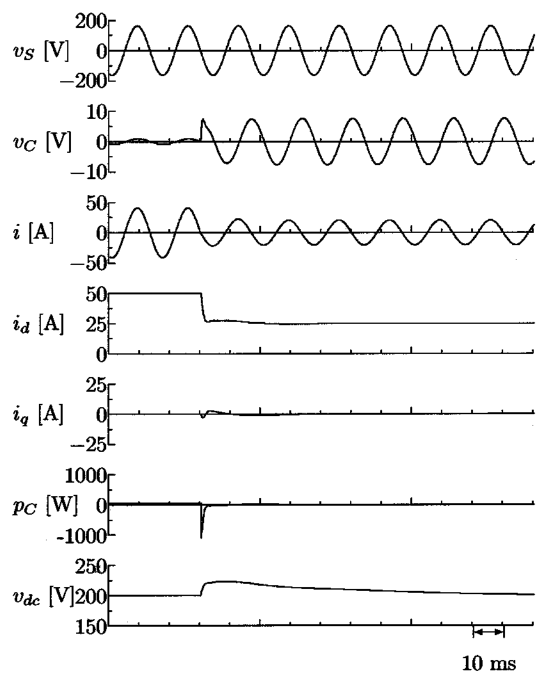

Fig. 7. Simulated waveforms for the step change in power flow from 10 kW to 5 kW.

2.7° to produce the active-power flow of 5 kW before the step change. In this condition, the second term in (5) is as small as 10 W because of the small phase angle. In Fig. 6, i_d starts to rise the instant the current reference i_d^* changes, and reaches 50 A after 3 ms without any power fluctuation.

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

The step change from 5 kW to 10 kW causes decrease of the dc-link voltage v_{dc} from 200 V to 176 V because the dc-link capacitor releases an amount of electric energy. Thereafter, v_{dc} gradually approaches 200 V by the function of the shunt device with a response time of 50 ms. The energy released from the dc-link capacitor, ΔW_{dc} is given by

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

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

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

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

Figs. 7 and 8 show simulated and experimental waveforms for a step change in active-power flow from 10 kW to 5 kW. In this case, v_S leads by 5.4° with respect to v_R. The dc-link voltage rises up from 200 V to 222 V during the transient state, in contrast with Figs. 5 and 6. The energy ΔW_{dc} is -0.88 J, while the energy ΔW is -0.94 J. In this case, the energy is transmitted from the inductor to the dc-link capacitor through the series device.

VII. Conclusion

This paper has theoretically and experimentally discussed transient power flow in a UPFC, based on instantaneous power. The transient analysis performed in this paper reveals that the active power flowing out of the series device is transmitted to the line inductance in transient states. It is experimentally verified that the energy released from the dc-link capacitor is equal to the energy stored in the line inductance at the end of transient states.

Contributions of this paper can be summarized as follows.

- Fast power flow control in transmission line induces a large amount of active-power flow between the series device and the line inductor. The induced active power is in inverse proportion to the response time of the power flow control.
- The required kVA rating of the shunt device is the sum of transient and steady-state power to keep the dc-link voltage constant. When the dc-link capacitor is devoted to releasing or absorbing the transient-state active power, the shunt device has to provide only steady-state power to the series device.

When a UPFC is installed in a long-distance transmission line, it may be impractical for the dc-link capacitor to release or absorb all the transient-state active power through the series device. In this case, the shunt device should share the transient-state active power with the dc-link capacitor, or the series device should impose a limitation on the response time of the power-flow control.

Generally speaking, a response time required for a UPFC seems to be 100 ms in order to damp out power swings in a power transmission system, and therefore the transient-state active power may be negligible. However, line breaking and power change caused by fault conditions induce a faster transition than power swings do. Hence the UPFC should have capability of achieving response time as fast as 3 to 5 ms, in order to overcome the fast transition. In other words, the existence of the transient-state active power has to be considered in the case of coordinating the system operations and designing the hardware implementation of the UPFC.

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