FACTS for Tapping and Power Flow Control in Half-Wavelength Transmission Lines

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***Abstract*—This paper presents a solution for transmission of bulk power over long distances. It allows the interconnection between remote power plants and power grids, which is a common situation in countries with continental dimensions, such as China, Russia, Brazil, and Canada, and also special projects like supergrids in Europe and Asia. This paper also presents an analytical analysis of series and shunt FACTS applications for tapping and power flow control in half-wavelength transmission lines. The proposed FACTS devices are able to drain or inject fractional active power in the half-wavelength line and simultaneously to control the main power flow through the line by means of reactive power compensation, without mischaracterizing its particular principle of half-wavelength operation. Simulation results from a frequency-dependent model of transmission line and the complete models of the series and the shunt FACTS devices were obtained in the PSCAD/EMTDC to demonstrate the feasibility of the proposed systems.**

***Index Terms*—Flexible ac transmission systems, load flow control, reactive power control, transmission lines, voltage control.**

I. Introduction

THE half-wavelength transmission line is a very long ac transmission line with a total equivalent electrical length a little longer than half the wavelength at the power frequency. Hereafter, the symbol $\lambda/2^+$ will be used to refer to this particular type of very long transmission line. If an ideal and uncompensated line is considered, this should mean a line that is a little longer than 2500 km at 60 Hz or 3000 km at 50 Hz. This type of line has some particular characteristics and behaviors, which cannot be treated simply as an extrapolation of a long line [1]–[3].

A great advantage of interconnecting large ac power systems is the possibility of optimizing the costs of electricity production. The seasonal nature of loads and renewable energy resources, where the costs of energy production are lower, can be better managed by means of transporting large amount of energy over long distances [4]. Although the $\lambda/2^+$ line is not intrinsically a point-to-point transmission system like an HVDC system [5], it has some restrictions regarding power derivation and interconnections with local power grids along the line [6]. This line cannot be sectionalized by switching substations and must be energized at once [7].

Power converters (VSC converters) connected back-to-back and in series to—in the case of series HVAC tapping—or in parallel to—in the case of shunt HVAC tapping—the $\lambda/2^+$ line have been developed, to derive fractional power from the line, at unit power factor. This is made without mischaracterizing its half-wavelength transmission principle [8], [9]. Differently from conventional ac transmission systems, the arbitrary connection of loads along the $\lambda/2^+$ line can mischaracterize its half-wavelength property.

On the other hand, the traditional concepts of FACTS are related to reactive power compensation to improve power system performance. The application of a series FACTS device—the GTO-controlled series capacitor (GCSC)—to control the power flow through a $\lambda/2^+$ line was investigated successfully [10]–[12]. All of these applications improve the competitiveness of the $\lambda/2^+$ line as a solution for bulk power transmission over long distances [13].

The novelty in this paper is on the implementation of both functionalities, i.e., FACTS and HVAC tap, into a single device. This new approach still utilizes the same configuration of the previous HVAC tap but now with independent controls for the active and the reactive power interchanges between the $\lambda/2^+$ line and the "compensator." Thus, the new approach will allow interchanging fractional power between the $\lambda/2^+$ line and a local power system, and simultaneous control of the main power flow through the $\lambda/2^+$ line.

Initially, analytical analysis using the exact π model of the $\lambda/2^+$ line and ideal models of a series compensator and a shunt compensator is presented to demonstrate the feasibility of both. It is useful to visualize where they are more effective in performing FACTS functionality together with HVAC tap, as a function of the compensator's position along the $\lambda/2^+$ line. Although they are new devices, for simplicity, here they will be called as just *shunt FACTS* or *series FACTS*. "Shunt FACTS" means that the power transformer of one side connects its power converter in parallel (shunt) to the $\lambda/2^+$ line, whereas in the "series FACTS" configuration, single-phase transformers are used to connect it in series with the line. The converter connected to the $\lambda/2^+$ line behaves as a controlled *current* source in the shunt FACTS configuration, whereas it behaves as a controlled *voltage* source in the series FACTS. In both configurations, the second converter is connected to a local power system. For instance, this analytical analysis indicates that the series FACTS is very effective in acting as an HVAC tap when connected in the central section of the line. Moreover, in this position, it cannot vary significantly the main power flow

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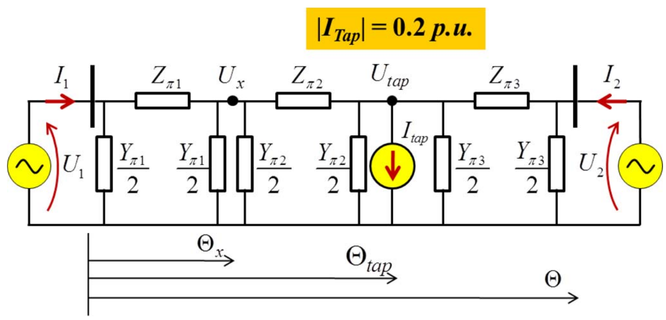

Fig. 1. Analytical model of the $\lambda^{+}/2$ line and the shunt FACTS positioned at Θ_{tap}.

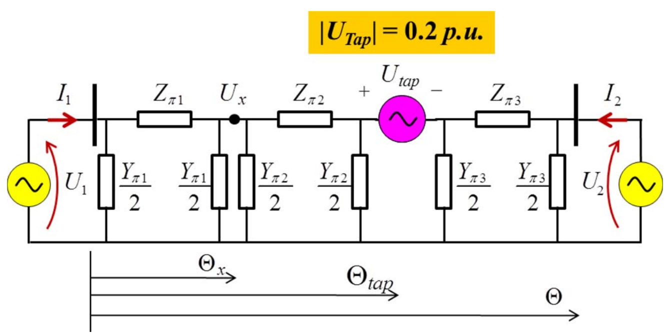

Fig. 2. Analytical model of the $\lambda/2^{+}$ line and the series FACTS positioned at Θ_{tap}.

through the $\lambda/2^{+}$ line. Contrarily, the main power flow of the line is very sensitive to shunt FACTS when connected in the central section, and for most line operation conditions, it can also provide simultaneous HVAC tapping in the same position.

Afterward, controllers for the shunt FACTS and series FACTS devices are designed to make them capable of acting simultaneously as an HVAC tap, as well as FACTS for controlling the main power flow through the $\lambda/2^{+}$ line.

This paper is a modified version of [6], in which all issues regarding the tapping of HVDC systems (dc transmission lines) where suppressed for now, giving focus only on tapping and power flow control in half-wavelength transmission systems.

This paper is organized as follows. Section II presents an analytical analysis of the shunt and series FACTS connected to a $\lambda/2^{+}$ line. Sections III and IV detail the shunt and series FACTS devices, respectively. Section V reports the main simulation results obtained using PSCAD/EMTDC. Section VI concludes this paper.

II. Analytical Models of the Half-Wavelength Line Compensated by FACTS Devices

This section presents an analytical analysis to investigate the feasibility of connecting series and shunt FACTS devices to $\lambda/2^{+}$ lines. For this analysis, a $\lambda/2^{+}$ line of 2722 km, $U_0 = 1000$ kV, and $P_C = 8.0$ GW is considered. It is divided in three exact π sections, with varying lengths, in order to calculate the voltage profile at different points Θ_x along the line and the transmitted active power as a function of the FACTS position Θ_{tap}, as shown in Fig. 1 for a shunt FACTS and in Fig. 2 for a series FACTS.

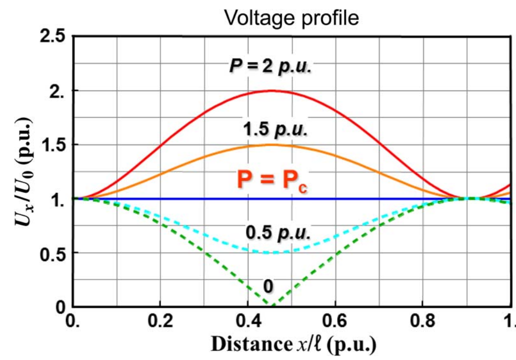

Fig. 3. Voltage profile along the $\lambda/2^{+}$ line as a function of the transmitted power.

The $\lambda/2^{+}$ line is not strictly a point-to-point transmission system, in a sense similar to HVDC transmission systems [13]. It allows the connection of few substations, few hundred kilometers apart from each other, at each "terminal" of the line. However, it has some constraints regarding fractional power derivation at intermediate points, as well as restrictions in operating the line in separated parts. A simple connection of a passive load through a transformer can cause severe overvoltage along the line, and it also can mischaracterize the half-wavelength properties and case instability to the system. To overcome these limitations, series and shunt HVAC taps have been investigated to derive fractional power along the $\lambda/2^{+}$ line in controlled way, i.e., the drained power should have a specific power factor. The HVAC tap provides bidirectional power exchange capability between the line and the local power system.

First, a remarkable characteristic of the voltage and current profile along an ideal $\lambda/2^{+}$ line, without any FACTS, is shown in Figs. 3 and 4 for five different values of line loading. Fig. 3 shows five curves of voltage profiles U_x along the line, as function of the transmitted power. The sending-end voltage $\boldsymbol{U_1}$ is at $\Theta_x/\Theta = x/\ell = 0$ p.u., and the receiving-end voltage $\boldsymbol{U_2}$ is at $\Theta_x/\Theta = x/\ell = 1$ p.u.. Fig. 3 shows that the voltage in the central section of the line varies proportionally with the transmitted power. At the limit, for an open-end line, i.e., $P = 0$, the voltage amplitude in the central section of the line becomes almost zero. In this situation, it would be impractical to apply a shunt HVAC tap to drain active power from the line. The voltage profile is flat when the transmitted power is equal to the line characteristic power P_C. In order to avoid overvoltage, the transmitted power should not exceed the characteristic power of the line.

On the other hand, the current in the central section is almost constant and equal to the nominal value I_0 for all line loading conditions, as shown in Fig. 4. Clearly, just for HVAC tapping in the central section, the series FACTS would be the best solution.

The following analysis shows the influence on the transmitted power through the $\lambda/2^{+}$ line by inserting a series or a shunt FACTS device, as a function of its position along the line, and for inductive or capacitive reactive power compensation.

A. Shunt FACTS Analysis

The insertion of a shunt FACTS device in the $\lambda/2^{+}$ line is investigated regarding the possibility of draining fractional

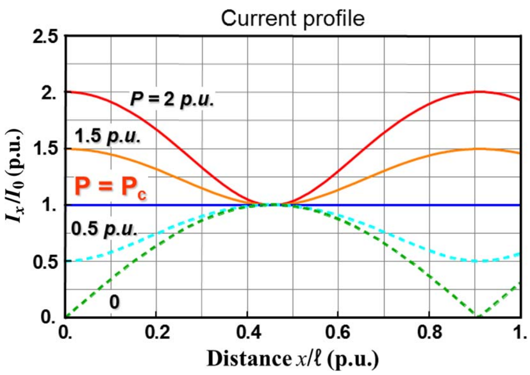

Fig. 4. Current profile along the $\lambda/2^+$ line as function of the transmitted power.

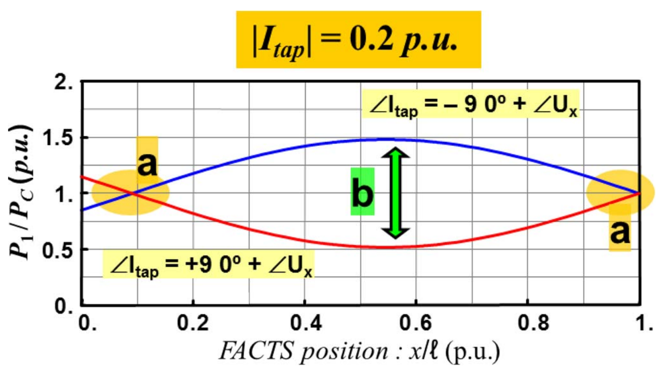

Fig. 5. Transmitted power through the $\lambda/2^+$ line as a function of the shunt FACTS position along the line and for a pure capacitive or pure inductive current with constant magnitude.

active power, as well as the possibility of controlling the main power flow through the line by means of varying shunt reactive power compensation. To accomplish both functionalities, the power converter associated to the shunt transformer directly connected to the $\lambda/2^+$ line should be a self-commutated converter type, provided with a current PWM minor control loop. In other words, it behaves as a controlled current source, where the amplitude and phase angle of the current drawn out from the $\lambda/2^+$ line can be controlled independently from the point of coupling to the line or voltage profile along the line.

Fig. 1 shows the analytical model used in this feasibility study. The current amplitude of the shunt FACTS is fixed at 0.2 p.u. of the nominal line current that transmits the characteristic power. Two curves as function of the shunt FACTS position are shown in Fig. 5: one for a pure inductive current and the other for a pure capacitive current drained by the shunt FACTS. As a conclusion, a shunt FACTS is very effective in controlling the main power flow through the $\lambda/2^+$ line when it is connected in the central section of the line, just by varying the reactive current component drained from the line. Shunt inductive current increases the power flow through the line, whereas capacitive current reduces the transmitted active power. Note that 0.2 p.u. of current in the shunt FACTS can vary the transmitted power in the range of 1.0 ± 0.5 p.u. if it connected in the central section of the line.

Fig. 6 shows the voltage profile along the line when the shunt FACTS is drawing a constant current magnitude of 0.2 p.u. and connected at the middle of the line ($\Theta_{\rm tap}/\Theta = x_{\rm tap}/\ell =$

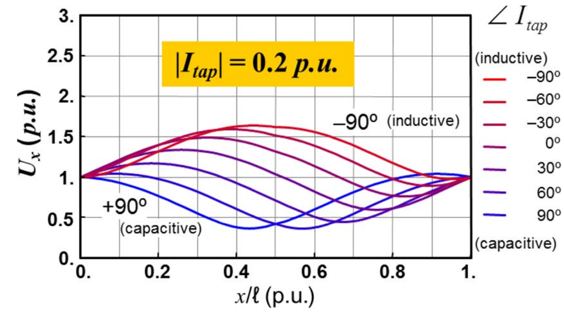

Fig. 6. Voltage profile along the $\lambda/2^+$ line as a function of the phase angle of the current drawn by the shunt FACTS positioned at the middle of the line.

0.5 p.u.), for different power factors, including curves for a pure capacitive, a pure resistive, and a pure inductive current. Later, simulation results will be presented to show that it is possible to drain or inject active power into the $\lambda/2^+$ line by means of a shunt FACTS device, without mischaracterizing its half-wavelength behavior.

In summary, the voltage profile of a $\lambda/2^+$ line is very sensitive to a shunt FACTS device located at the central section of the line. Although it presents some restrictions, it is possible to draw current with varying power factor. In fact, the concepts of instantaneous real and imaginary powers—the *pq theory*—are used to design the controller of the shunt FACTS to generate current references composed of active (real) and reactive (imaginary) current components. These components are used to determine the current reference accordingly to the desired active power to be drawn from the line and the desired active power flow through the line, respectively.

B. Series FACTS Analysis

As a dual case of the previous shunt FACTS, this section demonstrates the feasibility of draining fractional active power from the $\lambda/2^+$ line and the possibility of controlling its transmitted active power by means of inserting a series FACTS device.

Fig. 2 shows the analytical model used in this feasibility study. The voltage amplitude of the series FACTS is fixed at 0.2 p.u. of the nominal line-to-ground voltage that transmits the characteristic power. Two curves as function of the series FACTS position are shown in Fig. 7: one for a pure inductive voltage and the other for a pure capacitive voltage inserted in series with the $\lambda/2^+$ line. As a conclusion, a series FACTS is very effective in controlling the main power flow through the $\lambda/2^+$ line when it is connected at the ends of the line, just by varying the reactive voltage component inserted in series with the line. Series capacitive voltage increases the power flow through the line, whereas series inductive voltage reduces the transmitted active power. Note that 0.2 p.u. of voltage in series with the line can vary the transmitted power in a range wider than 0.5–1.5 p.u. if the series FACTS is connected at the terminal sections of the line.

For a series FACTS fixed at the middle of the line ($\Theta_{\rm tap}/\Theta = x_{\rm tap}/\ell = 0.5$ p.u.), Fig. 8 shows the voltage profile along the line when the series FACTS is inserting a constant voltage magnitude of 0.2 p.u. but with varying power factor, including curves for a pure capacitive, a pure resistive, and a pure

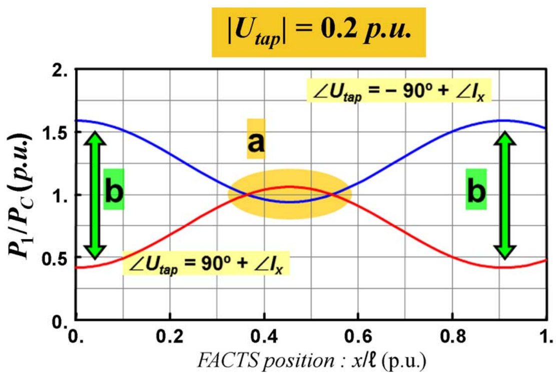

Fig. 7. Transmitted power through the $\lambda/2^+$ line as a function of the series FACTS position along the line and for a pure capacitive or pure inductive voltage with constant magnitude.

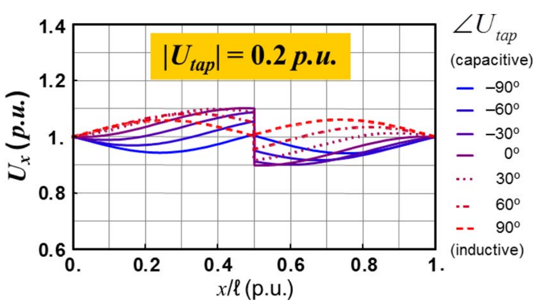

Fig. 8. Voltage profile along the $\lambda/2^+$ line as a function of the phase angle of the voltage inserted by the series FACTS positioned at the middle of the line.

inductive voltage. Later, simulation results will be presented to show that it is possible to drain or inject active power into the $\lambda/2^+$ line by means of a series FACTS device located in the central section of the line, without mischaracterizing its half-wavelength behavior. However, in this position, the series FACTS is not effective in controlling the transmitted active power, as indicated by region "a" in Fig. 7.

III. Shunt FACTS Device

The power circuit of the shunt FACTS is composed of two three-level converters (NPC converters) connected in back to back, as shown in Fig. 9. One advantage of using this converter topology is the possibility to double the total dc-link voltage $(V_{\rm dc} = V_{C1} + V_{C2})$ still using IGBTs and diodes having $V_{\rm dc}/2$ of rated voltage. The midpoint of the dc bus can be grounded. Two power transformers are employed to connect the shunt FACTS: one to connect to the $\lambda/2^+$ line and another to the local power system. Nominal values for the system will be given later in the simulation section.

In order to avoid disturbance in the main power flow and to mitigate severe overvoltage, the exchanged power between the line-side converter and the $\lambda/2^+$ line should be at a unity power factor [9]. However, it has also showed that the main power flow could be controlled by varying reactive power line compensation if the shunt FACTS is connected in the central section of the line. Thus, it is possible to combine both functionalities in the same shunt device.

The shunt FACTS controller provides *current* references for the current PWM controls of converters #1 and #2, as shown in Fig. 9. Self-commutated converters can control independently the active (real) and reactive (imaginary) power. Converter #2 supplies controlled active and reactive power to the local power system following their active $(P_{\rm ref})$ and reactive $(Q_{\rm ref})$ power orders. On the other hand, converter #1 draws variable *reactive* current from the line to control its main power flow (instantaneous active power), which is set up by the power order $P_{\rm ORDER}$. This FACTS functionality is similar to that of a conventional STATCOM. Additionally, converter #1 drains from, or injects to, the $\lambda/2^+$ line the corresponding active power being supplied by converter #2 to the local system, in order to keep the dc-link voltage regulated, around its nominal value $(V_{\rm dc.ref})$, which is the HVAC tap functionality that permits us to interconnect local power systems to the line without mischaracterizing the $\lambda/2^+$ line. Thus, the dc-voltage regulator in the FACTS controller determines the active-current component of converter #1. Therefore, the inputs to calculate the current reference I_C^* for converter #1 are the following: $P_{\rm ORDER}$, $\lambda/2^+$ line voltage V_1 and current I_1, and dc-capacitor voltages $V_{\rm dc1}$ and $V_{\rm dc2}$. Moreover, there are current measurements for the minor control loops in the current PWM controls, as shown in Fig. 9.

The power flow through the shunt FACTS can be in both directions, just by setting positive or negative values for the active power order $P_{\rm ref}$ of converter #2. Moreover, the reactive current component generated by converter #2 that is set up by the reactive power order $Q_{\rm ref}$ can be calculated conveniently by an additional control aiming to provide reactive power support for the local power system, in a similar way as made by a STATCOM. Therefore, the inputs to calculate the current reference $I_{\rm tap}^*$ for converter #2 are the following: $P_{\rm ref}$, $Q_{\rm ref}$, $V_{\rm tap}$, and $I_{\rm tap}$ from the local power system.

A. Shunt FACTS Controller

Fig. 10 shows the part of the shunt FACTS controller that is responsible for calculating the current reference $I_{\rm tap}^*$ of converter #2. This converter supplies active and reactive power to the local power system, according to their power orders $P_{\rm ref}$ and $Q_{\rm ref}$. The output voltage $(V_{\rm tap})$ and current $(I_{\rm tap})$ form two feedback control loops, which, together with $P_{\rm ref}$ and $Q_{\rm ref}$, dictates how converter #2 interacts with the local power system. In this way, the power flow and the power factor of converter #2 are fixed, and the local power generation has to handle variations in the local load. The output signals of this part of the controller are the following: 1) the phase angle of the fundamental positive-sequence voltage (ωt); 2) the current references $i_{\rm tap.\alpha}^*$ and $i_{\rm tap.\beta}^*$; and 3) the measured currents $i_{\rm tap.\alpha}$ and $i_{\rm tap.\beta}$. These output signals are passed to the current PWM control of converter #2, as shown in Fig. 11.

In order to guarantee zero error in steady state, the $\alpha\beta$ variables are transformed to dq variables (Park's transformation), and the current errors are passed through PI controllers. Then, the inverse Park's and Clarke's transformations are applied to determine the abc references, to be compared with the triangular carrier wave to determine the switching pulses for the NPC converter. Note that the controller of converter #2 cares about neither the total dc-link voltage nor the dc-capacitor voltage

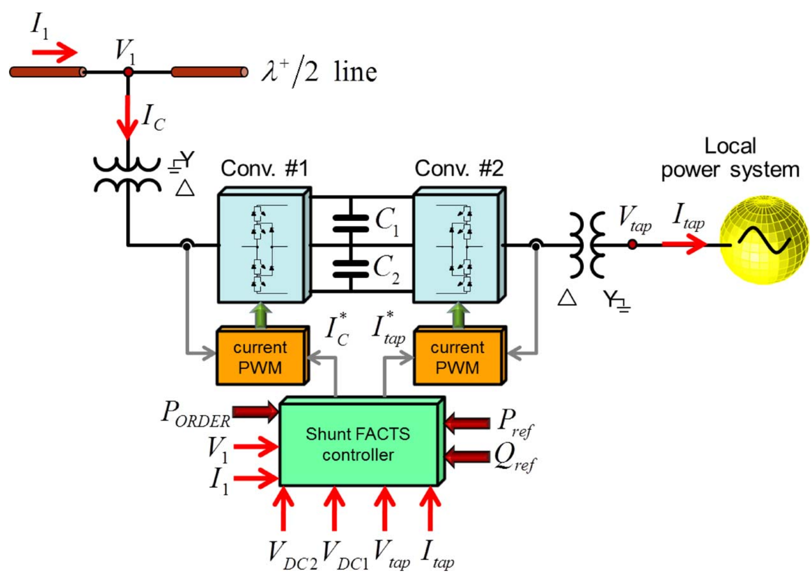

Fig. 9. Shunt FACTS.

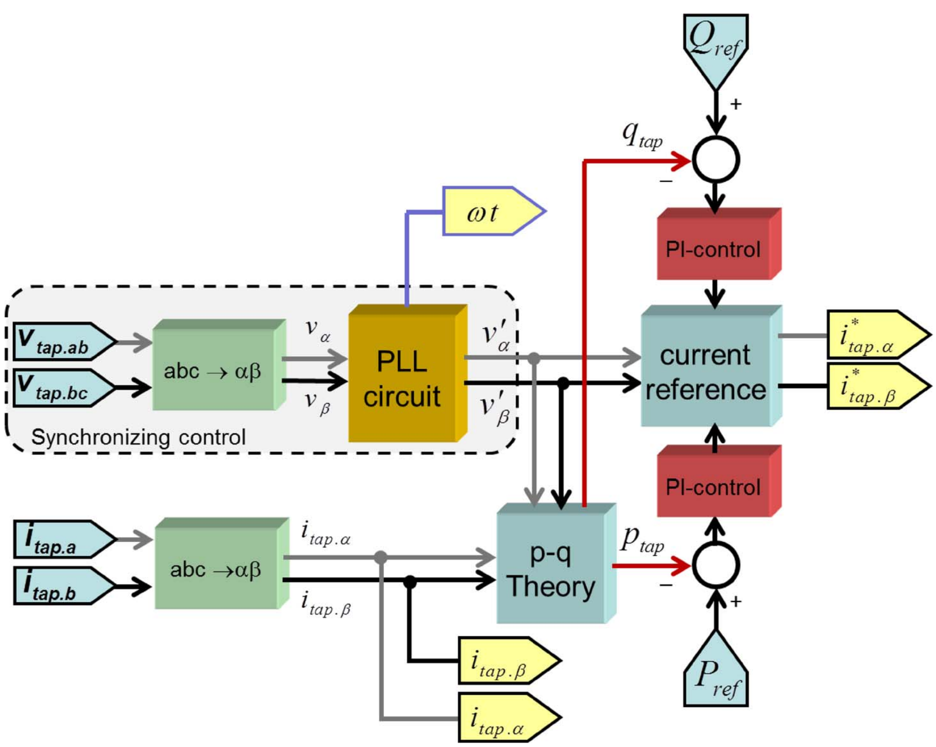

Fig. 10. Current controller of converter #2 of the shunt FACTS.

equalization. These controls are implemented in the control part of converter #1 as follows.

Fig. 12 shows the control part of converter #1 that is directly connected to the $\lambda/2^+$ line. This part is responsible for controlling the power exchange between the local power system and the half-wavelength line, which passes through the shunt FACTS, as well as for controlling main power flow through the $\lambda/2^+$ line. In fact, the power through the shunt FACTS is controlled indirectly, by sensing the total dc-voltage variations. The total dc voltage $V_{\rm dc} = V_{\rm dc1} + V_{\rm dc2}$ is compared with its reference value $V_{\rm dc.ref}$, and the error is passed through a PI controller to determine the instantaneous real power reference p^*. This is used to calculate the active-current component of current I_C of converter #1.

Additionally, the controller of converter #1 also calculates the main power flow through the $\lambda/2^+$ line to generate the reactive-current component of current I_C that is drained by the shunt FACTS in order to control the transmitted power through the $\lambda/2^+$ line. The instantaneous real power p_{TL1} shown in Fig. 12 is determined by the product of voltage V_1 and current I_1 of the line (Fig. 9). This power signal is compared with the active power order $P_{\rm ORDER}$ for the $\lambda/2^+$ line, and the error is passed through a PI controller. The analytical analysis described before establishes that a shunt reactive compensation

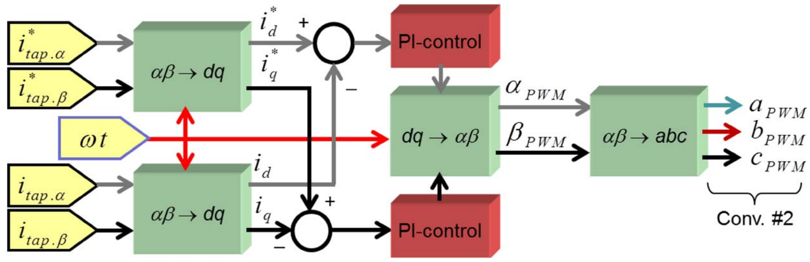

Fig. 11. Current PWM control of converter #2.

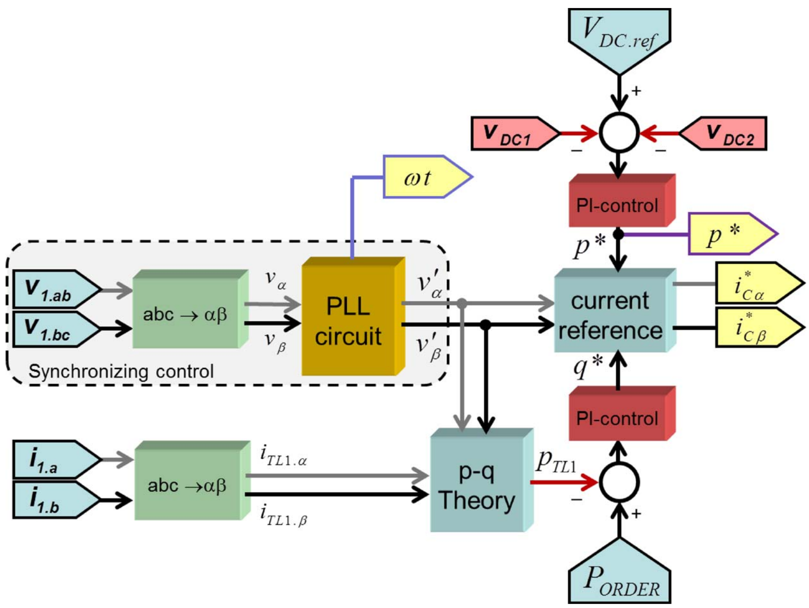

Fig. 12. Current controller of converter #1 of the shunt FACTS device.

located in the central section of the $\lambda/2^+$ line is very effective in varying the transmitted active power. Shunt inductive compensation increases the active power, whereas shunt capacitive decreases it. Thus, the output of the PI controller generates an imaginary power reference q^* that is used to calculate the reactive (imaginary) current component of current reference I^*_C for converter #1.

Fig. 13 shows the current PWM control of converter #1. It differs from the current PWM control of converter #2 (Fig. 11) due to its additional functionality for equalizing the dc-capacitor voltages V_{dc1} and V_{dc2}. The additional control loop that generates the signal ε can be understood as an "offset" that is simultaneously subtracted from all abc references that are compared with the triangular carriers to generate the pulses for the power switches of the NPC converter. The equalizing loop is a simple and efficient way adopted to balance the capacitors' voltages, and it permits the HVAC tap functionality to be implemented in an arrangement of back-to-back three-level converters. As an example, if the instantaneous real power reference p^* is positive, this means that the dc power in the dc link should be flowing from converter #1 to converter #2. In this situation, if the voltage of capacitor C_1 is higher than that of capacitor C_2, then the product of error Δ and p^* is positive, and the PI controller starts to increase the signal ε. Consequently, the references a_{PWM}, b_{PWM}, and c_{PWM} will receive greater negative "offset," which causes a transitory reduction of the current flowing into capacitor C_1, allowing capacitor C_2 to charge faster than C_1. The opposite occurs when $V_{\mathrm{dc1}} < V_{\mathrm{dc2}}$ or when p^* is negative.

IV. Series FACTS Device

The results from the analytical model for a series FACTS demonstrated that series reactive compensation in $\lambda/2^+$ line is more effective when it is applied at the ends of the line (see Fig. 7). Some previous works have shown the application of a GTO-based series compensator, denominated as *GCSC* (gate-controlled series capacitor), connected at the receiving end of a $\lambda/2^+$ line, for controlling the power flow through the line [10]–[12]. In fact, series reactive compensation in the central section of a $\lambda/2^+$ line has an adverse behavior. On the other hand, series FACTS in the central section is very effective for tapping the $\lambda/2^+$ line. The following series FACTS controller will be simplified to adequate the series FACTS to be applicable in the central section of the $\lambda/2^+$ line. In other words, the reactive power component generated by converter #1 in Fig. 14 will be set to zero. In this case, the device is working only as an HVAC tap, and the FACT functionality is disabled since the main power flow is not being controlled by injection of reactive power.

If compared with the previous shunt FACTS, another fundamental difference in the series approach is that now converter

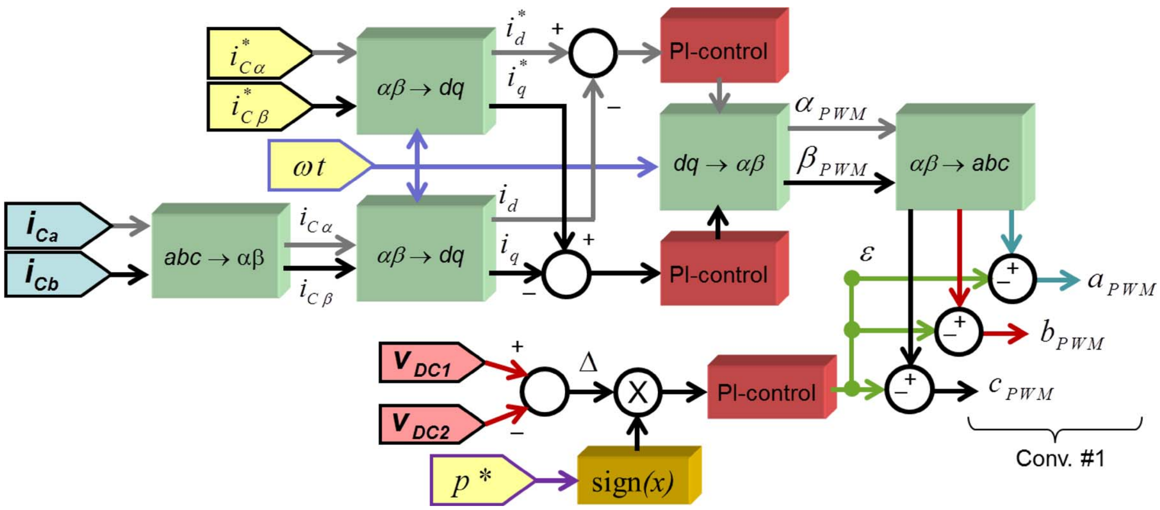

Fig. 13. PWM control of converter #1.

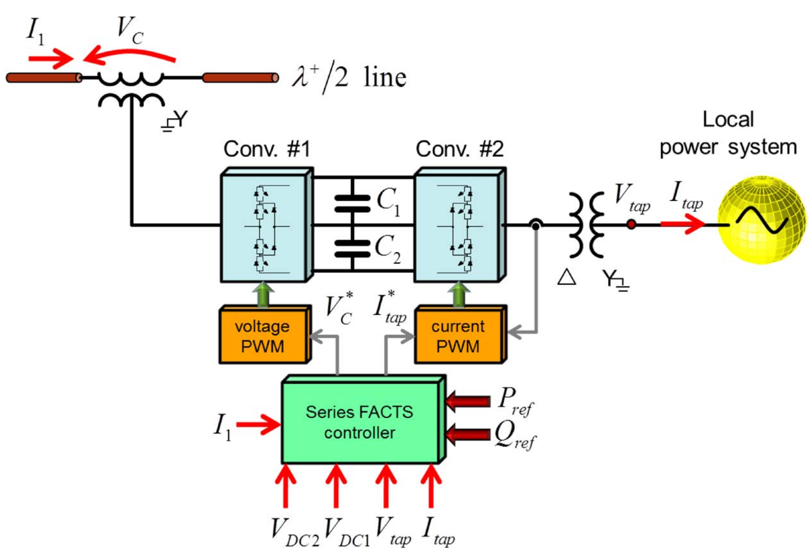

Fig. 14. Series FACTS device.

#1 act as a controlled voltage source inserted in series with the $\lambda/2^+$ line. Converter #2 of the series FACTS is connected to the local power system, and it has the same functionalities as those in the shunt FACTS. Thus, its controller is the same as that described before and shown in Figs. 10 and 11.

The voltage reference V_C^* of converter #1 is determined as shown in Fig. 15. The current of the $\lambda/2^+$ line is used in the synchronizing control (PLL), which extracts the fundamental component of the line current. Recalling that the current in the central section of a $\lambda/2^+$ line is almost constant, from zero to full loading conditions, choosing the line current as input for the PLL is the best option for series FACTS applications in the central section of the line. Together with the p^* signal from the dc-voltage regulator, the fundamental voltage references $v_{C\alpha}^*$ and $v_{C\beta}^*$ are directly determined using the fundaments of the *pq theory*.

Finally, $v_{C\alpha}^*$ and $v_{C\beta}^*$ are transformed back to the abc variables by means of Clarke's inverse transformation, which are added to an "offset" signal ε to provide dc-capacitor voltage equalization, as shown in Fig. 16, in a similar way as made

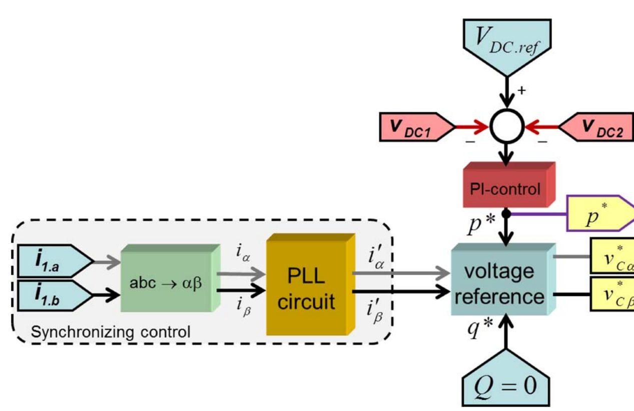

Fig. 15. Voltage controller of converter #1 of the series FACTS device.

in the previous current PWM control (Fig. 13) of the shunt FACTS.

It should be remarked that the aforementioned series FACTS controller is adequate for applications in the central section of a $\lambda/2^+$ line. Contrarily, if applied near to the ends of the line, the

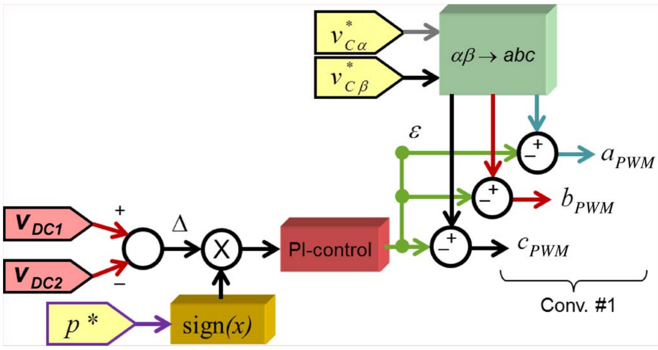

Fig. 16. Voltage PWM control of converter #1.

line voltage, instead of the line current, should be selected as input of the PLL. In this case, together with the line current, the instantaneous active power p_{TL1} can be calculated, in a similar way as made in the shunt FACTS, as shown in Fig. 12. An extra PI controller could be implemented in Fig. 15 to dynamically generate the reactive-voltage component, instead of $Q = 0$, for converter #1 of the series FACTS, which now rehabilitates the series FACTS to control the main power flow through the $\lambda/2^+$ line.

V. Test Case for Simulations

The half-wavelength ac-transmission principle is an attractive solution for bulk power transmission over extra-long distances, around 2000–3000 km. In order to provide higher power transmission capability to the $\lambda/2^+$ line, nonconventional designs of conductor bundles should be considered to minimize the characteristic impedance of the line. Studies on line optimization were presented in [8] and [9]. One of those optimized designs of line will be used as a test case for evaluating the shunt FACTS and the series FACTS described before. In each simulation case, both FACTS devices are connected in the central section of the $\lambda/2^+$ line.

Fig. 17 shows the complete system adapted to evaluate the performance of the series and shunt FACTS. Two $\lambda/2^+$ lines of 2700 km are connected in parallel, with right of ways sufficiently away from each other, which allows disregarding the electromagnetic coupling between the lines. The phase-domain model in the PSCAD/EMTDC simulator was used for calculating the frequency-dependent parameters of the lines. Considering nominal voltage U_0 equal to 1000 kV, the $\lambda/2^+$ lines present a characteristic power of 8.0 GW [9]. No electromechanical equivalents were used for representing the power generators. The phase angles of the voltage sources included in the equivalents at both sides of the $\lambda/2^+$ lines were adjusted to initiate the simulation with about 7.0 GW of transmitted power through each $\lambda/2^+$ line. At the beginning of both simulations, the 230-kV local power system is supplying the isolated local load, and the FACTS devices are not connected to the $\lambda/2^+$ line, i.e., the shunt FACTS is disconnected from the line, and the series FACTS is bypassed. The shunt FACTS is located at 1200 km far from the sending end (generation side) of line #1, whereas the series FACTS is connected at the midpoint of this line.

The total simulation time is 10.0 s for the shunt FACTS and 5.0 s for the series FACTS case. There are some circuit breakers in the system, as well as some step functions, which were programmed to perform a sequence of events during the simulations.

A. Shunt FACTS Simulation Case

The $\lambda/2^+$ line is energized from the sending end with opened receiving end and with circuit breakers equipped with preinsertion resistors. This happens at once and smoothly. No severe overvoltage occurs. Fig. 18 shows the a-phase voltages of the 1000-kV buses at the sending and receiving ends of the $\lambda/2^+$ line, V_{1a} and V_{2a}, respectively.

The complete sequence of events for the shunt FACTS simulation case is shown in Fig. 19. Clearly, this sequence is impracticable in a real power system. It is applied here only to show all transients in a single simulation within a short simulation time interval. The simulation starts with the following setup:

1) $V_{\mathrm{dc.ref}} = 100$ kV and $P_{\mathrm{ORDER}} = 7.0$ GW for converter #1;
2) $P_{\mathrm{ref}} = 0.0$ MW and $Q_{\mathrm{ref}} = 0.0$ Mvar for converter #2.

Fig. 20 shows the transmitted active powers through $\lambda/2^+$ lines #1 and #2, measured at both sending and receiving ends of the lines. The transients in the transmitted powers between $1.5\ \mathrm{s} < t < 2.5\ \mathrm{s}$ are related to the startup sequence of the shunt FACTS, as shown in Fig. 19. After that, at $t = 3.0$ s, a step change in P_{ref} to +500 MW is applied, and converter #2 starts to supply active power to the local power system. A full power reversion from $+500$ to -500 MW is applied at $t = 5.0$ s, which alters significantly the active power at the receiving end of line #1 (see curve labeled as P_{TL1_REC}). In between, a step change in P_{ORDER} to 8.0 GW occurs at $t = 4.0$ s. This forces raising the active power at the sending end of line #1 (P_{TL1_SEND} curve) and keeping it at 8.0 GW, until $t = 8.0$ s, when another step-change is applied to push it down to 6.0 GW.

Fig. 21 shows the active powers of the local power system, where all step changes in P_{ref} as shown in Fig. 19 can be verified. The half-wavelength behavior remained stable during all the time, which proves that a shunt FACTS device may be applied in a $\lambda/2^+$ line to provide simultaneous power flow control in the line together with tapping fractional power from/to it. The authors believe that this achievement can be very important in the future, when the $\lambda/2^+$ line will become competitive for bulk power transmission over very long distances.

An important remark is that a relatively small shunt reactive compensation can vary significantly the transmitted power through the line if the shunt FACTS is located in the central section of the line. Fig. 22 shows the instantaneous real and imaginary powers of converter #1, calculated by the products of voltage V_1 and current I_C as shown in Fig. 9. Note that, after $t = 4.0$ s, the shunt FACTS is raising the transmitted power of line #1 to 8.0 GW, whereas it is drawing 500 MW from it. In summary, Figs. 20–22 show that a relatively small shunt reactive power compensation of about 600 Mvai can vary the transmitted power in the range of 7.0 ± 1.0 GW.

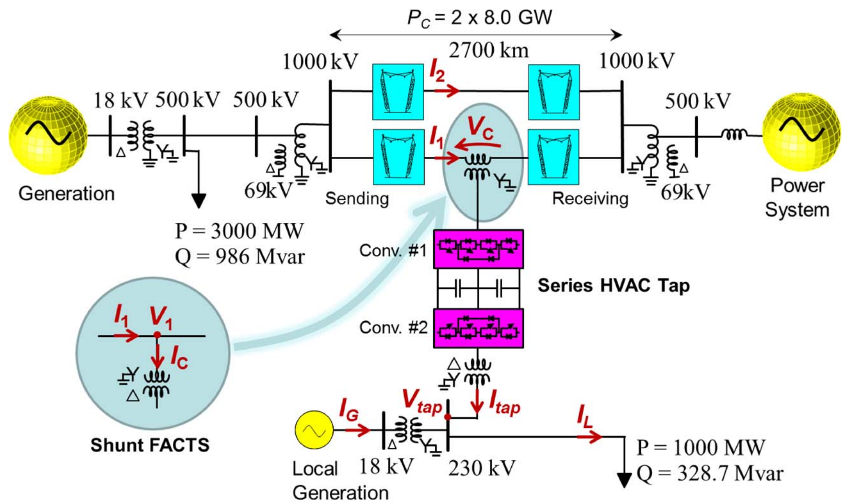

Fig. 17. Test case for simulations.

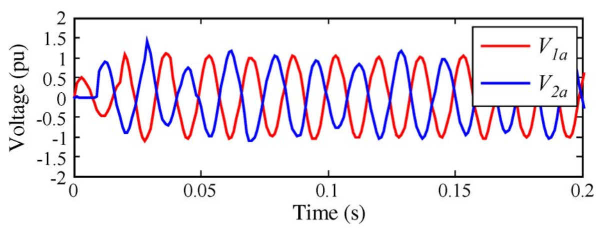

Fig. 18. Simultaneous energization of the $\lambda/2^+$ lines: a-phase voltages of the 1000-kV bus bars at the sending (V_{1a}) and receiving (V_{2a}) ends.

Finally, Fig. 23 shows the dc-capacitor voltages V_{dc1} and V_{dc2} of the back-to-back NPC converters applied in the shunt FACTS device. Both curves are coincident, proving that the auxiliary control loop for voltage equalization is very effective in maintaining both capacitors equally charged.

B. Series FACTS Simulation Case

As mentioned before, the following simulation results from the series FACTS were obtained by applying it in the midpoint of line #1 in the power system shown in Fig. 17. Due to the reasons explained in the analytical analysis, the controller of this series FACTS, as shown in Figs. 15 and 16, was implemented without reactive power compensation. In other words, the series FACTS does not realize power flow control in the $\lambda/2^+$ line and acts only as an HVAC tap. Thus, converter #1 of the series FACTS does not generate reactive power and always drains or injects power at unity power factor. Due to this reason, it was possible to use NPC converters with the same nominal power as that in the shunt FACTS, but now, the series FACTS can increase its tapping capability up to ± 1 GW, as it will be shown in the following results.

After the line energization, the following events occur, during the startup of the series FACTS.

1) Closing of the circuit breakers at the primaries of the series transformers at $t = 1.0$ s and opening the bypass breakers at $t = 1.05$ s. During this operation, three circuit breakers are closed, acting as a three-phase short circuit at the secondary of the series transformers.

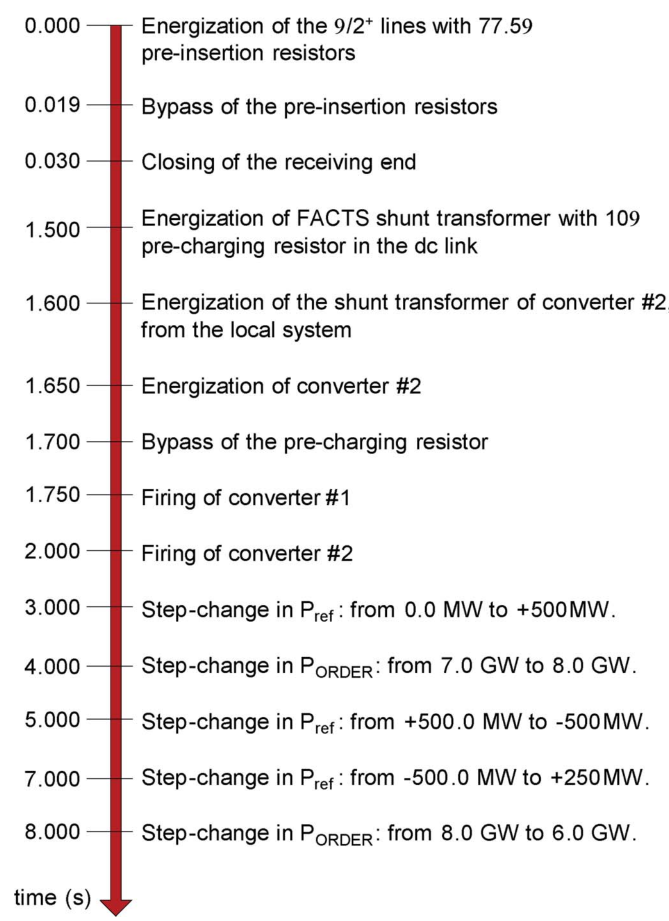

Fig. 19. Sequence of events of the shunt FACTS simulation case.

2) The PWM firing of converter #1 starts at $t = 1.1$ s, and the short-circuit breakers open at $t = 1.15$ s.
3) Closing of the circuit breakers between the local power system and the primary of the shunt transformer of converter #2 at $t = 1.0$ s. The circuit breakers that energize converter #2 are closed at $t = 1.15$ s.
4) The dc-link breaker is closed at $t = 1.2$ s, and the PWM firing of converter #2 starts at $t = 1.3$ s.

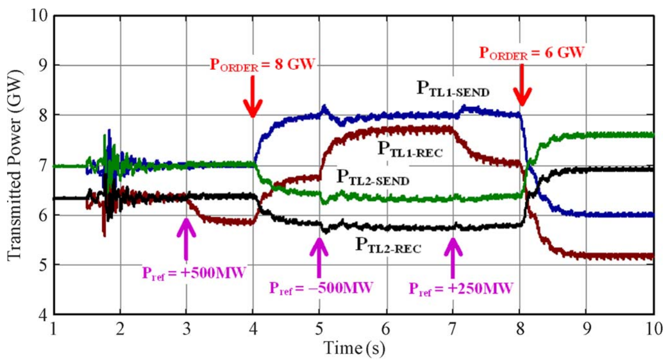

Fig. 20. Transmitted active powers through $\lambda/2^+$ lines #1 and #2, measured at both sending and receiving ends of the lines.

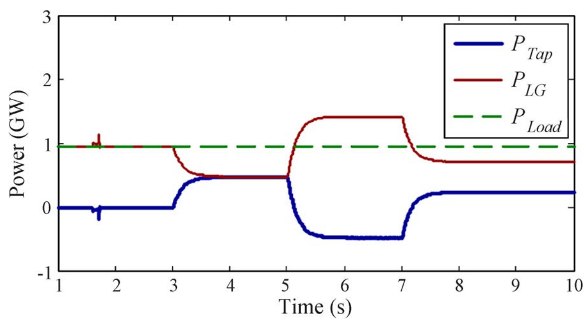

Fig. 21. Active powers of the local power system: P_{Tap} is the power from/to converter #2, P_{LG} is the local power generation, and P_{Load} is the local load power.

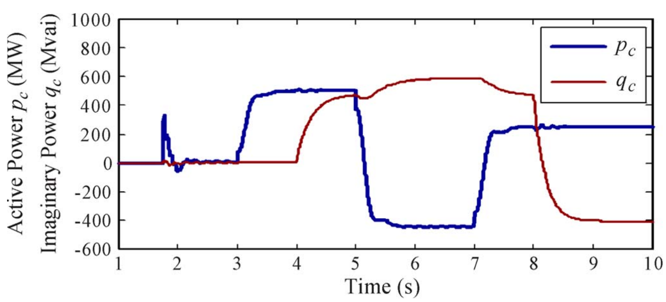

Fig. 22. Instantaneous real and imaginary powers of converter #1 of the shunt FACTS realizing dc-voltage regulation and power flow control in line #1.

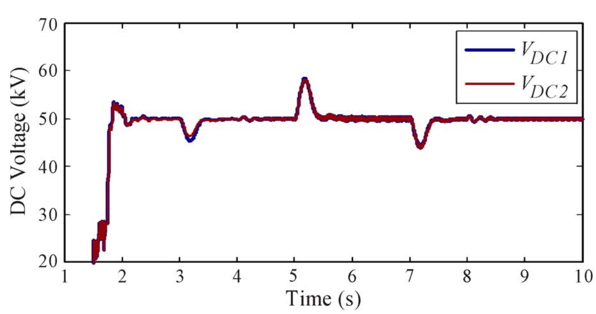

Fig. 23. dc-capacitor voltages V_{dc1} and V_{dc2} of the back-to-back NPC converters applied in the shunt FACTS device.

After the complete start of the series FACTS, the following step changes were applied to the power order.

- P_{ref} starts at 0.0 MW and then jumps to -1.0 GW at $t = 2.0$ s and then to $+1.0$ GW at $t = 4.0$ s. Q_{ref} remains equal to zero all the time (Fig. 10). $V_{\mathrm{dc.ref}}$ remains equal to 100 kV all the time (see Fig. 15).

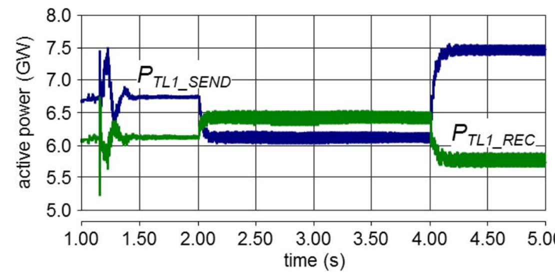

Fig. 24. Transmitted active powers through $\lambda/2^+$ line #1, measured at both sending and receiving ends of the line.

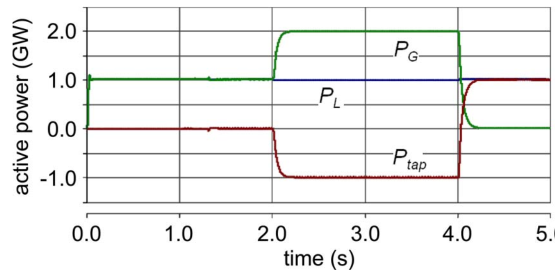

Fig. 25. Active powers of the local power system: P_{tap} is the power from/to converter #2, P_G is the local power generation, and P_L is the local load power.

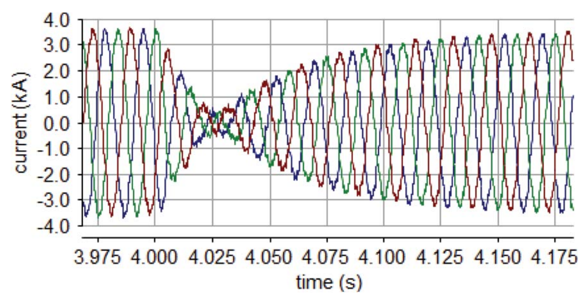

Fig. 26. Instantaneous currents of converter #2 of the series FACTS.

Fig. 24 shows the transmitted active powers through $\lambda/2^+$ line #1, and Fig. 25 shows the active powers of the local power system, where the step changes in P_{ref} as listed previously can be verified. If compared with the previous results from the shunt FACTS, the gains of the series FACTS controller were increased, and a faster response was achieved, even now handling the double of power (± 1.0 GW). Fig. 26 shows the three-phase current of converter #2 during the full power reversion. Such a fast response is not practical in real power systems. This transient was imposed to demonstrate that the half-wavelength behavior can sustain a relatively high amount of power exchange with local power systems along the power trunk. Finally, Fig. 27 shows a well-controlled dc-capacitor voltage regulation and equalization.

In general, all simulation results obtained from the series FACTS acting as an HVAC tap in the midpoint of the $\lambda/2^+$ line confirm its feasibility. The authors are now working on the investigation of the use of series FACTS located outside the central section of the $\lambda/2^+$ line to simultaneously control the power flow of the line and tapping of fractional power.

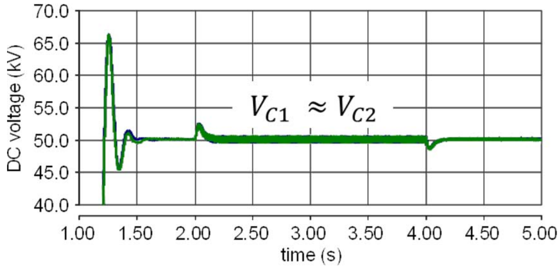

Fig. 27. dc-capacitor voltages V_{dc1} and V_{dc2} of the back-to-back NPC converters applied in the series FACTS.

VI. Conclusion

A new controller for a shunt FACTS has been developed, which combines conventional FACT functionalities and an HVAC tap functionality to be applied to a $\lambda/2^+$ transmission line. Two NPC converters connected back to back were used as power circuit of the shunt FACTS. The shunt FACTS realizes simultaneously two principal functions: 1) power flow control through the half-wavelength line (FACTS functionality) and 2) power exchange between the line and a local power system (HVAC tap functionality). Both functionalities were successfully implemented in the shunt FACTS, without mischaracterizing the half-wavelength nature of the very long line. It was demonstrated that a relatively small shunt reactive power compensation realized by the shunt FACTS is capable of varying the transmitted power in the range of 7.0 ± 1.0 GW. The controller of the shunt FACTS allows bidirectional power flow between the $\lambda/2^+$ line and the local power system. A full power reversion, from $+500$ to -500 MW was applied while keeping constant at 8.0 MW the transmitted power through the $\lambda/2^+$ line.

The application of series FACTS when inserted at the central section of the $\lambda/2^+$ line, just to derive power to a local power system (HVAC Tap), has proved be very effective, and it allowed a faster response and did not cause any power oscillations in the $\lambda/2^+$ line. However, the series FACTS is not suitable for power flow control when connected at the central section of the line. All modifications in the series FACTS controller were indicated, which are necessary to adapt it to be applicable outside the central section of the $\lambda/2^+$ line and to allow it to perform simultaneous power flow control and HVAC tapping functionalities in the $\lambda/2^+$ line.

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