COMPENSATION REQUIREMENTS FOR HVAC TAPS IN HALF-WAVELENGTH TRANSMISSION LINES

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Abstract – **This paper intends to study some compensation requirements for HVAC taps in a half-wavelength transmission line. This type of long transmission is known for its similarity, in many aspects, with conventional short distance transmission. However, HVAC taps to feed intermediary loads may cause changes in line quantities such as power and voltage profile, leading to the use of some compensation techniques. Shunt and series taps topologies are analyzed and compared, to point out their advantages and disadvantages.**

Keywords – **Compensation, converters, half-wavelength, HVAC taps, power electronics, transmission lines.**

I. INTRODUCTION

Electric transmission requirements in Brazil may be quite different from many other countries, since most available energy potential sources are located in the North and Northeast regions, far away from the southern load centers. Interconnection of local and distant subsystems has lead to a large transmission grid, including lines more than 1000 km long.

While the grid keeps growing, new hydroelectric plants are also being built, as well as new lines are being planned. As an example, Pará's Belo Monte Hydro Power Plant, expected to begin its operation in 2008, is about 2500 km far from many southern cities, and a half-wavelength line should be one of the alternatives studied for AC transmission.

However, political and economical issues are likely to arise about point-to-point transmission type, as such a long line would cross several important cities, and line derivations (taps) to feed them should be seriously considered. In this case, power electronics devices such as FACTS, active filters [1] and converters can be used instead of intermediary stations, but the consequences to voltage profile and power transfer capability should be investigated.

In this paper, HVAC taps in half-wavelength transmission are analyzed, in what concerns to modifications in voltage profile and active and reactive power. A comparison with a point-to-point line is also carried out, to clarify the compensation requirements of the tapped line.

II. HALF-WAVELENGTH TRANSMISSION

Transmission lines in electrical systems are usually less than 300 km long, being a common practice to use series/shunt compensation to reduce the electrical angle of the line in cases where two distant subsystems are to be interconnected.

However, as the distance between them increases, compensation levels may turn to be excessive, raising transmission costs and causing great sensibility to transient phenomena [1]. Intermediary substations are also frequently needed.

If the subsystems are separated by 2500-2700 km (near half-wavelength at 60 Hz), an interesting solution consisting of a single line (with small or no compensation) has already been proposed [2]. This line is often called a half-wavelength transmission line [3].

In most aspects, its electrical behavior is much like a conventional short line rather than a very long one, which can be partially explained with a fast look at the series parameter of the π-equivalent circuit, shown in Fig. 1. It should be noted that the electrical angle θ of a line equals π when its length is a half of the wavelength.

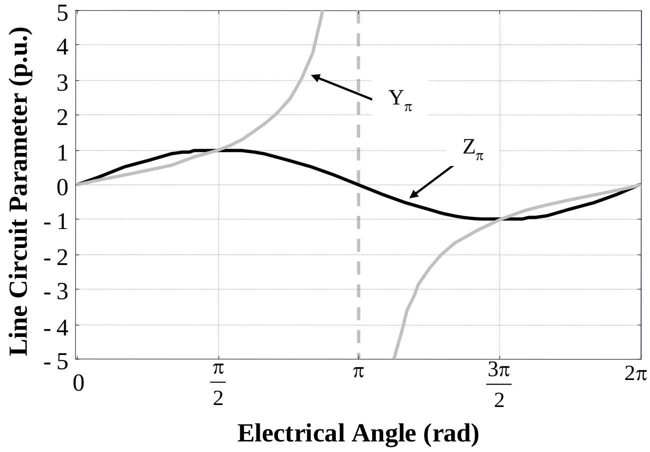

Fig. 1. Equivalent circuit parameters (of a lossless line).

Half-wavelength lines have an electrical angle slightly greater than π, typically in the vicinity of 1.05π. In this region, $\dot{Z}_\pi$ has the same absolute value of that in the region of $\theta = 0$, but with an opposite sign.

A different behavior is found when comparing the values of the shunt parameter $\dot{Y}_\pi$. Short transmission corresponds to a low and positive value, while a half-wavelength line has a negative and high one.

Furthermore, a somewhat deeper investigation of line quantities shows that the region where θ is a little higher than π correspond to a stable operation, as long as terminal voltages phase difference is also near π.

Figure 2 presents voltage and current profiles along the line for three different situations – P = 0, P = Pc and P = 1,5·Pc.

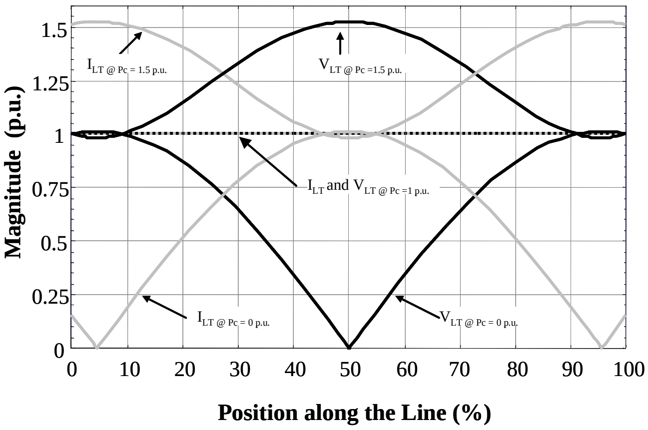

Fig. 2. Voltage and current profiles.

The transmission of more than the characteristic power is usually avoided due to the overvoltages (and other stability-related problems) that may occur. These problems are also present in conventional long lines (but not short ones) and are one of the reasons why half-wavelength lines should be hi-SIL-type.

On the other hand, voltages and currents along the line go from zero to 1 p.u., provided that the SIL is not exceeded. It is also note-worthy that an open line has zero voltage and nominal current in its middle point.

Some previous works [1] have considered the region where $1{,}05\pi \le \theta \le 1{,}1\pi$ as a reasonable approach for the ideal operating point. In practice, a FACTS device can be used as a slight series compensation, since the actual distance between substations may not result in a value of θ in this region.

III. HVAC TAPS

Several alternatives are usually considered in the studies for the interconnection of two distant subsystems. Depending on factors like distance and frequency, they often include type of transmission (AC/DC), converters/substations location and half-wavelength transmission.

In Brazil, interconnection lines are usually HVAC and 800-1200 km long, with nominal voltages of 500 and 765 kV. They are commonly segmented between three or four intermediary substations. There is also one HVDC 800 km transmission line, ±600 kV, for a point-to-point transmission from Itaipu power plant.

Due to the huge dimensions of the country and its northern hydroelectric unexplored potential (located far from main load centers), some studies have been conducted about HVAC half-wavelength transmission. Actually building and operating such a line, however, depends on several political and economical aspects, like whether or not it could deliver power to crossed regions and cities, which should be a disadvantage for HVDC transmission as well.

In general, it seems to be reasonable the use of interconnection lines just to connect two subsystems at the terminals, leaving the task of feeding intermediary loads to some other local lines. However, sometimes either the local system cannot afford that or it becomes difficult to overcome legal issues.

For these cases, HVDC taps have already been suggested and analyzed [4][5]. Since the discussion in the previous section was based on the π-equivalent circuit of the line considering its full length, electrical behavior with derivations along a HVAC line has not been analyzed yet. Similarly to what happens to the DC case, HVAC taps can be designed based on present power electronics devices, such as converters and active filters [6].

Changes in both voltage and power are to be expected, and this section presents a quantitative (yet theoretical) discussion about it. Digital simulation with some realistic Brazilian parameters can be found in the next section.

Figures 3 and 4 present the general topology for shunt and series HVAC taps, respectively.

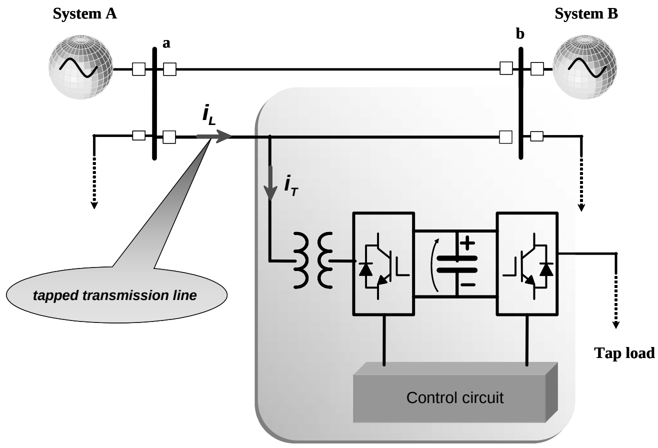

Fig. 3. Shunt HVAC tap topology.

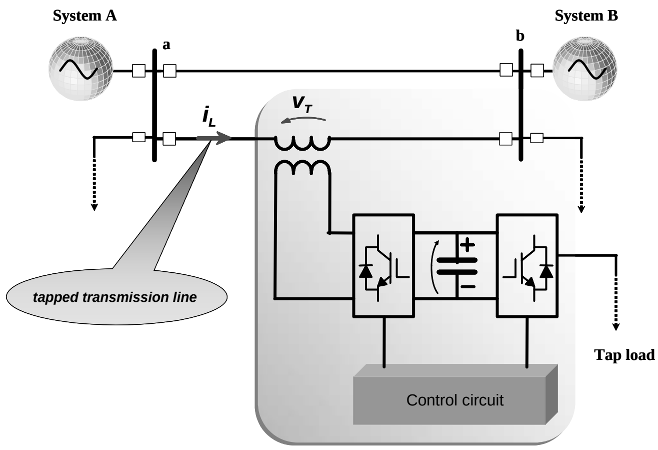

Fig. 4. Series HVAC tap topology.

The key difference is the series/shunt converter transformer. Both topologies have two converters linked by a DC capacitor in a back-to-back configuration.

A. Operation and Control

The control strategies for the taps presented in this paper are designed with basis on the instantaneous active and reactive power theory (pq-theory) concepts, first proposed by Akagi [7].

The main idea is that the converters drain only the mean value of the instantaneous active power, therefore representing unity power factor loads for the line. Many taps can be distributed along line length, independently feeding different regions.

While shunt taps can be seen as controlled current sources that produce the desired power under the actual line voltages, series taps are the dual circuit, representing a controlled voltage source under the actual line currents.

One important point is that shunt taps must contain a converter transformer to reduce the voltage applied to the switches. However, since line currents are of an order of magnitude that can be handled by present switches, it is possible that some configurations of series taps do without it. Although the subject needs a further investigation, this would be an advantage of the series tap if it were the case.

The basic generation of the controlled voltage or current is achieved with the pq-theory-based control circuit shown in Figs. 5 and 6.

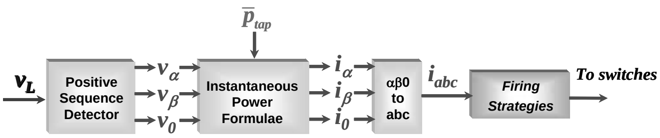

Fig. 5. Shunt HVAC tap control.

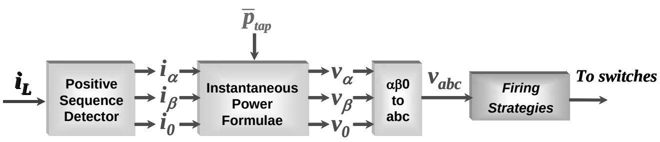

Fig. 6. Series HVAC tap control.

Measurement of line voltages (currents) values is needed, as well as some calculation in Clarke's αβ frame. Common PWM firing strategies like vector or space vector control can be used.

B. Voltage Profile Analysis

It was mentioned before that the most important analyses to be done in what concerns to taps in a half-wavelength transmission are on voltage profile and power transfer and balance. This item focuses on voltage profile while next is about real and imaginary power.

It was previously shown (Fig. 2) that voltage and current profiles are flat when the line transmits characteristic power. Also, when the line is open, voltage varies from zero (in the middle-point) to 1 p.u. (in both ends) as well as the current, which is zero in the terminals and 1 p.u. in the middle-point.

This should be considered when defining the location of the taps – a shunt tap cannot operate where voltages are zero, as well as series taps do not operate with zero current.

Either type of HVAC taps does modify voltage profile. Figure 7 shows the voltage profile of a SIL-loaded half-wavelength line with a 20% shunt/series tap in its middle-point.

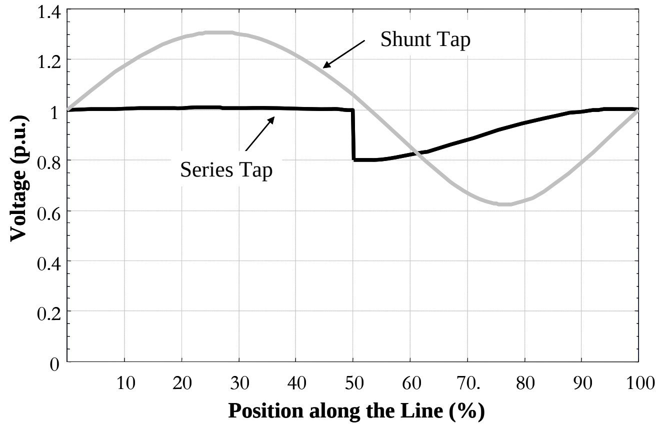

Fig. 7. Changes in voltage profile.

It can be pointed out that the shunt tap leads to an overvoltage of about 1.3 p.u., while the series tap causes almost no overvoltage, which is a quite interesting point. The voltage-step shown is caused by the voltage generated by the converter to drain the active power of 20%.

A further investigation of the series tap location is shown in Fig. 8. Since the line is SIL-loaded with little current variation, tap voltage is almost constant, wherever it is located.

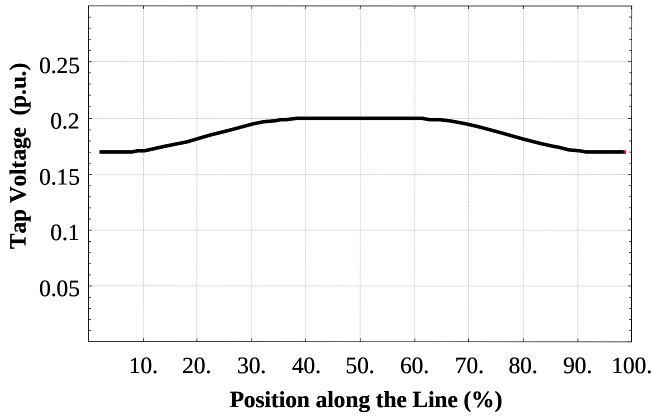

Fig. 8. Tap voltage along a SIL-loaded line (drained power of 0.2 p.u.).

Considering just the behaviors presented in Figs. 7 and 8, voltage profile tends to be a critical issue with shunt taps, probably leading to the use of capacitive series compensation to reduce overvoltages when a high amount of power is to be drained.

C. Real and Imaginary Power Analysis

Considering again a lossless line to allow analytical computation, the active power transmitted and the reactive power balance in a half-wavelength transmission line is given by [8]:

$$\frac{P}{SIL} = \frac{\sin(\delta)}{\sin(\theta)} \tag{1}$$

$$\frac{\Delta Q}{SIL} = 2 \cdot \left(\cot(\theta) - \frac{\cos(\delta)}{\sin(\theta)} \right) \tag{2}$$

Figure 9 shows the relations between these two variables and the terminal voltages phase difference δ in an untapped half-wavelength line with θ = 1.1π:

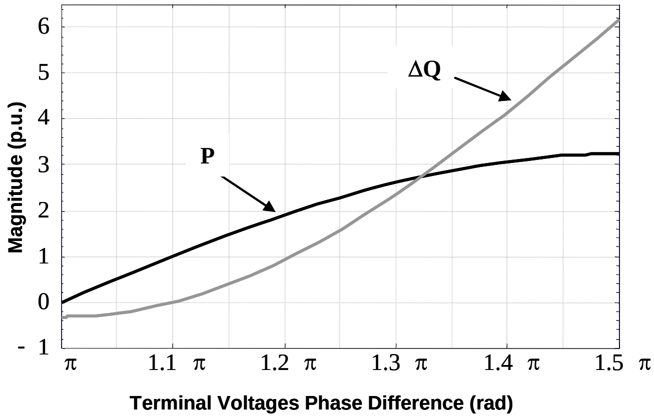

Fig. 9. Active and reactive power in a half-wavelength line.

The point where the relation δ = θ holds is an interesting point, since the active power is in its nominal value (SIL) while reactive power balance is null.

Here again, both shunt or series taps modify the relations presented in (1) and (2). Keeping terminal voltages constant, a shunt tap reduces the power transferred by a line, while a series tap increases it (see Fig. 10).

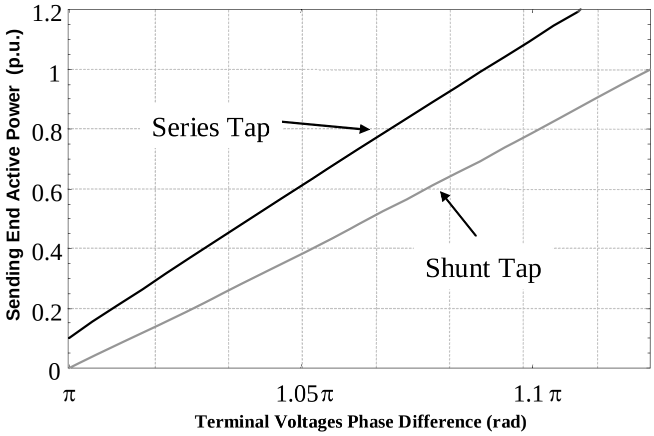

Fig. 10. Changes in active power.

The previous figure is again about a 20% tap and shows that, keeping voltages constant, nominal power (SIL) is reached with δ < θ in a series tap.

In a shunt tap, however, it is just the other way around – δ must increase to keep nominal power at the sending end of the line. It should be clear that active power at the receiving end cannot be the same because of the power drained by the tap.

Figure 11 presents the modifications in the reactive power balance in the line, that is, the difference between reactive powers at both line ends. Just as in the case of the active power, 20% taps causes no significant changes.

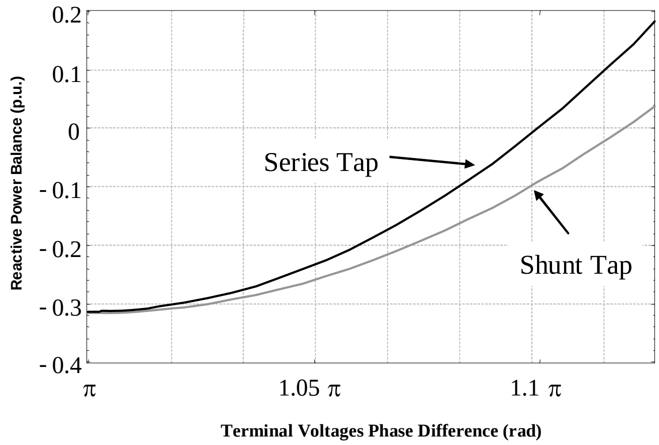

Fig. 11. Changes in reactive power balance.

As it has happened with the voltage profile, the shunt tap is responsible for the major changes. The series tap caused practically no modifications in the balance, while the shunt one lead to a 0.1 p.u. unbalance between sending and receiving ends.

The results discussed in this last two items show that some half-wavelength lines features remain, even considering heavy tapping. Typically, although both have to be carefully verified, greater attention is to be given to voltage profiles rather than to power issues.

IV. SIMULATION AND RESULTS

A. Subsystem set-up

An electromagnetic transients program has been used to provide further insight into the HVAC taps. The subsystem represented is shown in Fig. 12 and contains parameters typically found on the Brazilian electrical system.

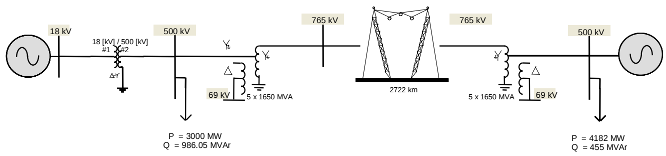

Fig. 12. Subsystem for electromagnetic transient simulation.

According to preliminary studies, Belo Monte power plant will deliver 11,000 MW by means of 20 generators of 550 MW (18 kV) each. 3,000 MW shall feed North and Northeast regions, while the remaining power may be transferred to southern load centers.

Although the subsystem considered is hypothetical, its data have been taken from actual elements of the Brazilian system. The generators are connected to the EHV system by means of 20 Δ-Y, 18:500 kV transformers.

Belo Monte’s 765 kV sector is reached with 5 x 1650 MVA transformers, similar to the ones found in Itaipu system.

Two 765 kV half-wavelength transmission lines are connected, with a characteristic power of about 3500 MW instead of the conventional value of 2100 MW. This was achieved with some optimization [9], but keeping a regular conductor bundle geometry (7 x ACSR 954 kCM – 45/7, Rail). The transposition cycles are 300 km long.

The chosen point for interconnection was Cachoeira Paulista substation, in Sao Paulo, where an equivalent circuit was used. Depending on the route, the line length may vary from 2600-2700 km, but a value of 2722 km (corresponding to $\theta \cong 1.1\pi$) has been used in these simulations.

B. Taps Locations

Three different situations were investigated: (a) a middle-line series 100 MW tap, (b) a middle-line shunt 100 MW tap, and (c) three series 100 MW taps, located at 30%, 50% and 70% of line length. Figure 13 shows the locations of the taps.

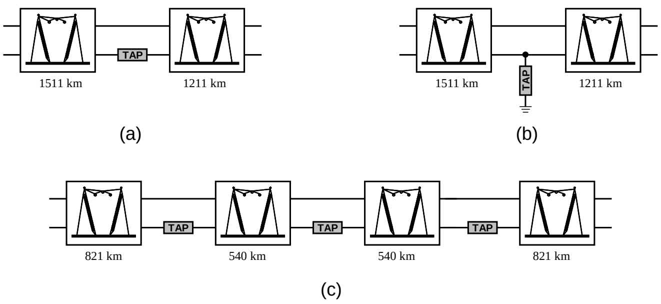

Fig. 13. Subsystem with taps included.

C. Simulation Results

The voltage profile along the untapped line was also analyzed, but the results have not been shown, since no significant modifications were found.

1) Voltage profile

Figure 13 shows the phase voltage profile along the tapped line for the case of a series 100 MW (almost 3% of SIL) HVAC tap. It has few changes and no overvoltages. The voltage-step is proportional to the amount of drained power.

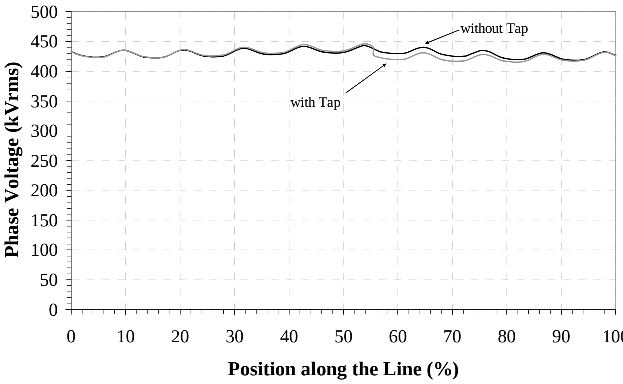

Fig. 13. Voltage profile with a 100 MW series tap.

The profile for the case of a 100 MW shunt tap is presented in Figure 14. Although it drains the same power of the series tap, some overvoltages now appear in the first half of the line, as expected. They are also related to the power drained by the tap.

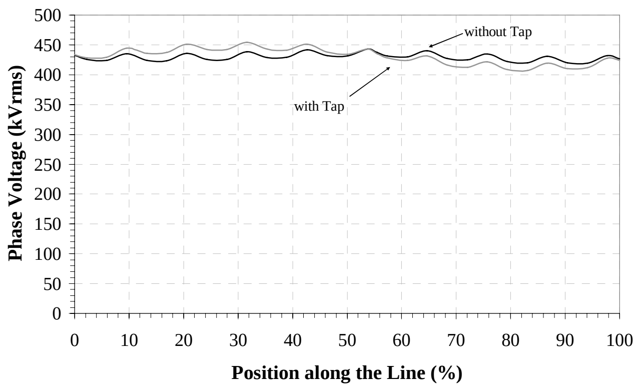

Fig. 14. Voltage profile with a 100 MW shunt tap.

A situation where three 100 MW series taps are inserted at the same time along the line is shown in Fig. 15. A slight overvoltage of about only 3% is present, due to the increase in SIL caused by the series taps, as discussed in the previous sections. It should be noted, however, that this overvoltage can be reduced and even eliminated, with a reduction of the value of δ to keep the line SIL-loaded.

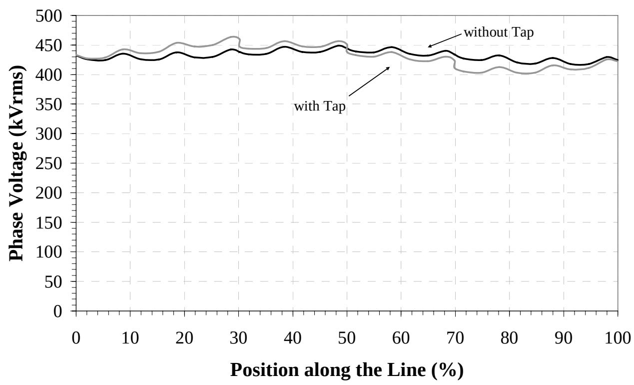

Fig. 15. Voltage profile for three 100 MW series taps.

2) Instantaneous active power

Figure 16 shows the results for the instantaneous active power transmitted by the two transmission lines.

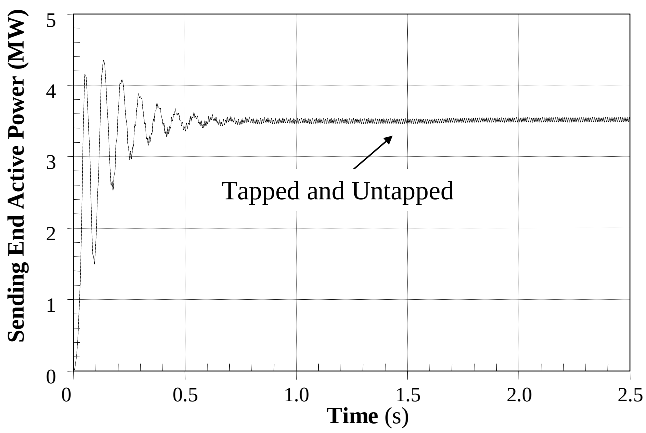

Fig. 16. Active power transmitted with a 100 MW series tap.

Tap operation begins at 1.6 s, which almost went unnoticed. This is in accordance to what was previously pointed out – changes in power transfer are less significant than in voltage profiles.

V. CONCLUSIONS

Some alternatives for feeding intermediary loads with half-wavelength transmission lines have been presented and discussed. Although the main task of these lines is to interconnect two distant subsystems, delivering power to crossed regions may be needed.

In these cases, one possible solution is the use of either shunt or series HVAC taps, designed with present power electronics converters and inserted along the line to drain power.

In what concerns to topology, series taps may have the advantage of a configuration without converter transformers, since typical line currents can be handled by the switches. However, series taps require non-conventional bypass protection, which may be a slight disadvantage.

Aspects like voltage profiles and power balance changes have also been analyzed. Half-wavelength typical power features do not change significantly, and should not represent a problem for tap operation. Shunt taps lead to a decrease in active power transmitted, while series ones increases it. Reactive power balance is not relevantly affected.

If a strict power control is needed, the use of a FACTS device that represents either capacitive or reactive compensation [10] – such as an UPFC or a TCSC – may be considered and studied. The GCSC [11], although providing only controlled capacitive compensation, can be also used.

However, changes in voltage profile are a more critical problem, especially when using shunt taps, since they naturally lead to overvoltages along the line. Series taps, on the other hand, have lead to no overvoltage. It should therefore be expected that shunt taps require more compensation levels to limit overvoltages and avoid insulation-related problems along the line.

It is correct to state that series taps turned out to be a promising solution and a study focusing on transformer-less topologies, converters performance and compensation devices (probably using FACTS) may be among the extensions to what was first presented in this paper.

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