

Non Conventional Transmission Line with FACTS in Electromagnetic Transient Programs

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Abstract—This work presents some procedures to simulate, in an electromagnetic transient program, a non conventional transmission line, that, in the presented example, has 12 conductors per phase, in transmission trunks with an electric length, at power frequency, a little longer than half wavelength ($\lambda/2^+$). This kind of line is indicated to bulk power transmission over very long distances. Although it is not a basically point-to-point transmission system, in a sense similar to HVDC transmission systems, and allows e.g. to connect each “terminal” to a few substations a few hundred kilometers apart, it has some constraints and limitations in power received or supplied at intermediate points and in line operation in separate parts. To overcome this drawback a FACTS device is proposed to drain, or inject, energy from the line without changing its electrical characteristic. The paper also presents some simulation results about FACTS device draining energy from the line.

Keywords—EHV Transmission Lines, UHV Transmission Lines, Power Transmission Lines, FATCS.

I. INTRODUCTION

One of the many upcoming challenge of the Power Industry lies in the transmission of bulk energy over very long distances and/or interconnect large power systems separated by large distances. In many regions throughout the world there are possible candidates for a bulk energy transmission over long distances such as Brazil, Russia or even continents like Africa and Europe. In those sites there are large electric generation potential locate beyond two thousand kilometers from the main load centers. For instance, in the Amazon Basin, in North Region of Brazil, the hydroelectric potential is above 100 GW [1], although the actual used potencial is less than 1% there is a plan to increase the generation up to 18 GW in the next 10 years. In this particular example, the main load centers are located in the Southern Region of Brazil with a distance over 2500 km. Another example is located in Southern Africa, an interconnection from Inga in the Democratic Republic

of Congo to Omega in South Africa and from Kwanza in Angola to Pegasus in South Africa. The objective is to transmit 4 GW over three thousand kilometers [2]. A similar challenge exists in Russia where the main source of energy are concentrated in the Asian part, whereas the load centers are located in the European part. In this case the length of the circuit may exceed three thousand kilometers. With respect of power interconnection there is the tie between Russia and Germany [3], [4] and the interconnections in Northeast Asia that will tie Russia, China, Mongolia, South Korea and Japan [5] [6]. The former is an east-west European power link of 4 GW and circuit length of around 1700 km.

For the challenge of bulk power transmission over very long distances the HVDC transmission system is usually the solution. However, this work shows an option for bulk power transmission, that is an ac transmission system with an equivalent electrical length (at power frequency) a little longer than the half wavelength, i.e. $\lambda/2 \approx 2500$ km (for 60Hz) or ≈ 3000 km (for 50Hz). It uses a non conventional ac overhead circuit lines and ties systems that are a few thousand kilometers apart. This solution can be as competitive as a HVDC system of same circuit length. By non conventional ac transmission system we mean a circuit optimized with robust criteria, with solutions possibly different of “usual”, e.g. in what concerns phase bundle arrangement, choice of conductors, mechanical structures, operation criteria; for instance, the example line is adequate for a transmission, in a single circuit, at a very large distance, of 8 GW, for 1000 kV voltage level [7]–[9].

As the main goal of the non conventional ac system is for very long distance transmission, above 2500 km, in the remaining of this work we call the longer than half wavelength transmission line by $\lambda/2^+$ symbol, to remember that the electrical length is a little longer than half wavelength. It is important to note that such a line cannot operate with an equivalent electrical angle of exactly π (half-wavelength) as this is a singular point and a stable operating point can only be achieved for an electrical length higher than π .

The $\lambda/2^+$ transmission ties two electrical subsystems widely apart, i.e. with a distance of a few thousands kilometers. Thus it shares some similarities with a HVDC transmission systems, although a $\lambda/2^+$ system may have a few substations near the line extremities without any extra equipment. It means that a $\lambda/2^+$ line is not essentially a point-to-point transmission system.

In Section II are presented some conceptions about $\lambda/2^+$

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line, some characteristics and its representation in an EMT type of program. The line modeling is validated against a Frequency Domain Transient Program and results for the line energization is presented. Section III presents the basic structure of the proposed series and shunt HVAC tap. The last Section presents simulation results of some test cases of a HVAC tap inserted along the $\lambda/2^+$ line. Although, there are some issues about line operation in function line loading, e.g. terminal line voltage reduction for minimizing transmission losses, the results presented are valid for any other line operation point.

II. VERY LONG NON CONVENTIONAL TRANSMISSION LINES

Very long transmission line has many aspects that are quite different from what would be expected by simple extrapolation of medium distance transmission line (a few hundred kilometers). For instance [10]:

- It does not need large amount of reactive compensation. It is only needed the compensation required to adjust the electrical length of the line to a little more than half wave length. That decreases (in comparison with “usual” large distance AC transmission trunks) the cost of ac transmission per unit length.
- For several (normal) switching operations the transients are moderate, therefore not imposing a great stress in breakers or other switching equipment and to equipment connected to the transmission trunk.
- For single-phase faults, it is possible to have an high probability of success opening faulted phases at both line terminals and reclosing, after a relatively short time, during which it is assured an high probability or secondary arc interruption. The typical solution, used at traditional transmission systems of a few hundred kilometers, based e.g., in neutral reactors of shunt compensation reactors, is not applicable, but other types of solutions may be used, to very large distance transmission systems.

To explain some basic aspects of very long transmission line consider an ideal line with total length ℓ , longitudinal reactance per unit length X and shunt admittance per unit length Y , both for non-homopolar condition, at power frequency f . The electrical length of the line is defined by:

$$\Theta = \sqrt{XY} \ell \quad \text{or} \quad \Theta = \frac{\omega}{\nu} \ell, \quad (1)$$

being $\omega = 2\pi f$, and ν the phase velocity. For a line without series or shunt compensation and at the power frequency, ν is close to the speed of light, typically around 96% to 99% [11].

The characteristic impedance, (Z_c), and the characteristic power, (P_c), are given by (2).

$$Z_c = \sqrt{\frac{X}{Y}} \quad \text{and} \quad P_c = \frac{U_0^2}{Z_c}, \quad (2)$$

for a reference (line) voltage U_0 .

For the power frequency, the reactive compensation can be “included” in the total series impedance and shunt admittance of the circuit as shown in (3),

$$X = \xi_{se} X_0 \quad \text{and} \quad Y = \xi_{sh} Y_0, \quad (3)$$

being $\xi_{se} = (1 - \eta_{se})$ and $\xi_{sh} = (1 - \eta_{sh})$, where η_{se} is the level of series compensation and η_{sh} is the level of shunt compensation, and X_0 and Y_0 the uncompensated series impedance and shunt admittance per unit length, respectively.

The electric line length, the characteristic impedance and characteristic power are affected by the reactive compensation, respectively as show in (4).

$$\begin{aligned} \Theta &= \sqrt{\xi_{se} \xi_{sh}} \Theta_0 \\ Z_c &= \sqrt{\frac{\xi_{se}}{\xi_{sh}}} Z_{c0} \\ P_c &= \sqrt{\frac{\xi_{sh}}{\xi_{se}}} P_{c0} \end{aligned} \quad (4)$$

For very long transmission distance, conventional ac systems use a large amount of reactive power compensation, both series and shunt. The compensation is needed to reduce the electrical length to much less than a quarter of wavelength which increases substantially the overall cost of the transmission system. Furthermore, a high level of compensation introduces additional resonances which may cause severe switching overvoltages and related problems. For extra long distances (2000 km to 3000 km) this limitation may be overcome with an equivalent electrical length slightly longer than half wavelength, $\lambda/2^+$, (π rad \approx 2500km @ 60Hz or \approx 3000km @ 50Hz) [10]. A $\lambda/2^+$ line has the advantage that it requires little, if any, reactive power compensation. Thus it has the same cost per kilometer as a short line. The main drawback remains in the fact that the transmitted (active) power (P_1) should not exceed the characteristic power of the line (i.e. $-P_c \leq P_1 \leq P_c$) to avoid overvoltages along the line.

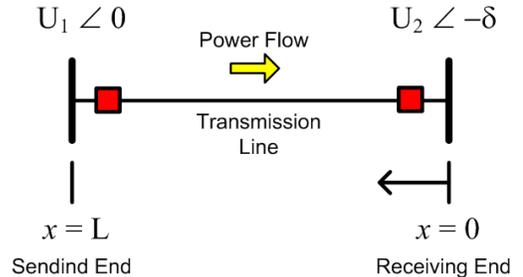


Figure 1: Ideal $\lambda/2^+$ system

To illustrate a little further the basic characteristics of a $\lambda/2^+$ line consider the system shown in Fig. 1. Fig. 2 shows the voltage profile and Fig. 3 shows the current along the line for several loadings on an ideal line with 1.1π rad electrical length. These figures indicate that there are regions along the line where one may find an almost constant

current or an almost constant voltage for a reasonable range of operation conditions.

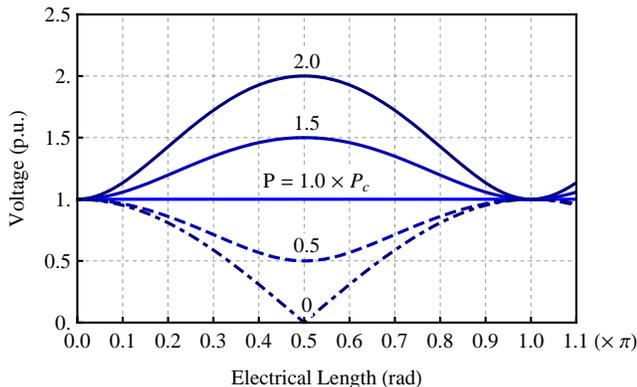


Figure 2: Voltage profile along an ideal line.

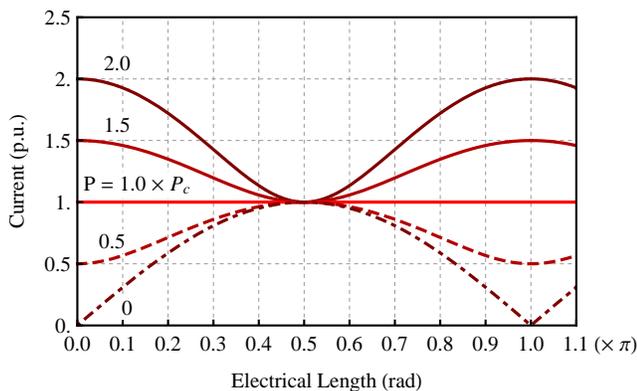


Figure 3: Current profile along an ideal line.

A $\lambda/2^+$ line should be designed for a large capacity of power transmission so an optimization of line geometry is of paramount importance. This optimization can improve the right of way utilization with a minimum cost. Nevertheless, there are several criteria that might be taken into account for reach the minimum total cost (losses, installations, equipment and operational costs). Some parameters have a direct correlation with the total cost, for instance, voltage level, number of phases, conductor type, geometric configuration of the bundle, ground wires, insulating distances, tower profile, foundation type, line route, tower location, tower grounding, circuit breaker, overvoltages limiters, switching overvoltages, environmental issues among others.

All of those parameters have an intrinsic effect on transmission cost and among each other. The great number of parameters presents a limitation to establish a global optimization procedure. Although a global optimization is very hard to reach, partial optimization can be used instead, as it tend to optimize some of the parameters and keep the final cost to reasonable levels. It is important to point out that as a transmission system is in fact a physical system, the minimum cost may not be the best solution.

There are several procedures to optimize transmission line. The applied optimization procedure in this work is based on [12]–[15]. This results in an unconventional bundle arrangements as shown in Fig. 4. For a nominal voltage of 1000 kV, the line presents a characteristic power equal to 8 GW.

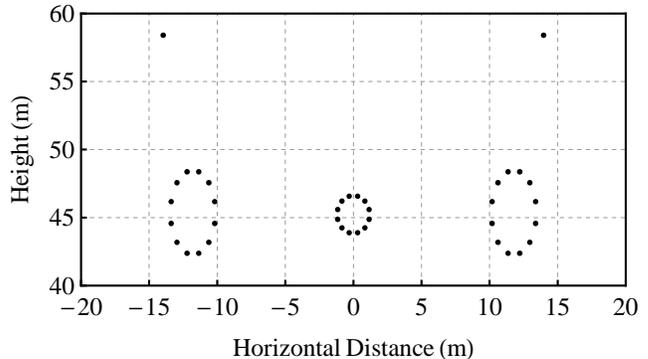


Figure 4: Line spacing and bundle arrangement near the tower.

A. Transmission Line Modeling

Two parallel 2700 kilometer ($\approx 1.1\pi$ rad) $\lambda/2^+$ lines were simulated in electromagnetic transient program PSCAD/EMTDC using a phase-domain model. Due to non conventional bundle arrangement each phase-conductor has to be implemented independently and yet fully coupled line, using a single Line Tower Universal (LTU), as if each phase has a tower, i.e., the line model is equivalent to 3 circuits in the same right of way.

The lines were considered distant from each other so that the magnetic coupling could be considered negligible. In addition, due to very long line length some transposition cycles are necessary. It was considered 9 cycles of 300 km in each line.

In order to verify the adequacy of the implemented model in PSCAD/EMTDC, a comparison with a Frequency Domain Program build in Mathematica using the Numerical Laplace Transform was carried out. It was simulated the energization from an infinite bus bar. Fig. 5 shows the open circuit response at the receiving end (phase a). There is a good agreement between the results.

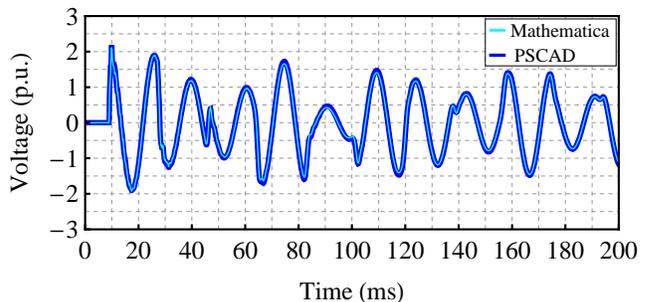


Figure 5: Open circuit output voltage.

B. Line Energization

For the energization tests consider a $\lambda/2^+$ line with a length $\ell=2700$ km and the bundle arrangement shown above. Fig. 7 shows the voltage at the receiving end of the line for an cosine input where phase *a* is closed at the maximum voltage. There are no surge arresters at the receiving end of the line. For this case, the maximum voltage exceeds 2.0 pu. Unlike conventional (medium length) lines where the dominant switching frequencies lie in the range of a few kHz, for a $\lambda/2^+$ line the frequencies are much lower. For instance assuming an ideal $\lambda/2^+$ line, the frequencies for the open circuit voltage f_{oc} are given by

$$f_{oc} \approx \frac{nc}{4\ell} = 28 \cdot n \text{ (Hz)} \quad (5)$$

where c is the speed of light and n is the harmonic number. The low order harmonics cause a modulation at the output voltage and should be avoided to allow an efficient and fast energization. The high frequency components are absent of the output voltage as they are damped along the line.

One possibility to mitigate the transients is to use a controllable switching (point-on-wave closing) with a closing resistor. The point-on-wave closing allows the breaker at the sending end to close near zero voltage for one of the phases while the resistor reduces the line input voltage during the energization. The output voltage for simultaneously switching is shown in Fig. 8. The closing resistor improves the transient damping as can be seen in Fig. 9.

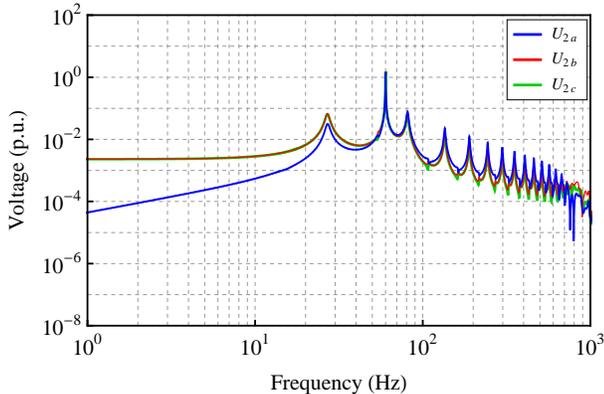


Figure 6: Open circuit output voltage frequency response.

III. HVAC TAP

Several alternatives are usually considered in the studies for the interconnection of two distant subsystems. A $\lambda/2^+$ system can be a feasible solution to high bulk power transmission over extra long distances. However similar to HVDC transmission a $\lambda/2^+$ system is essentially a point-to-point connection. To overcome this limitation, a HVAC Tap can be inserted in the main power line to supply additional loads throughout the circuit length. Although a HVAC Tap may seem an overkill, it should

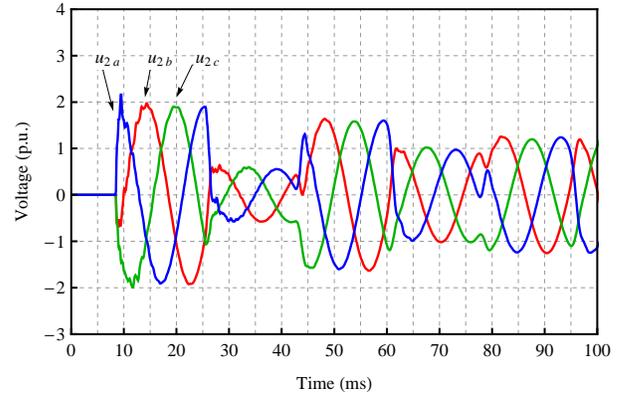


Figure 7: Line energization – phase to ground voltage at receiving end line terminal.

be noticed that a transformer connected to any point in line to drain power from the main circuit, may affects the performance of the whole system. To overcome this limitation a HVAC tap is proposed. The tap is based on a power electronics converter and provides a multi-terminal bi-directional power flow capability. A HVAC tap can be used to connect local loads or generation to a $\lambda/2^+$ line.

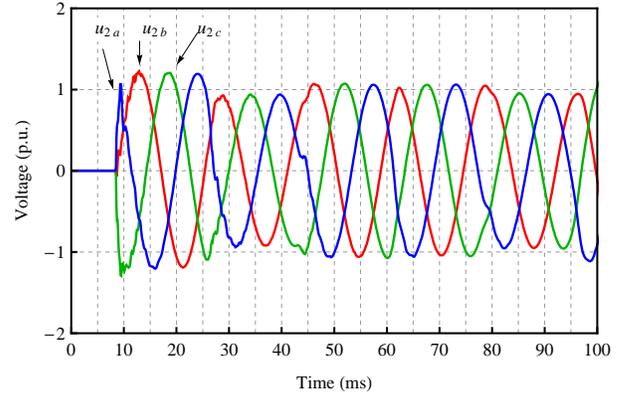


Figure 8: Details of the line output voltage with simultaneously switching – point-on-wave plus closing resistor.

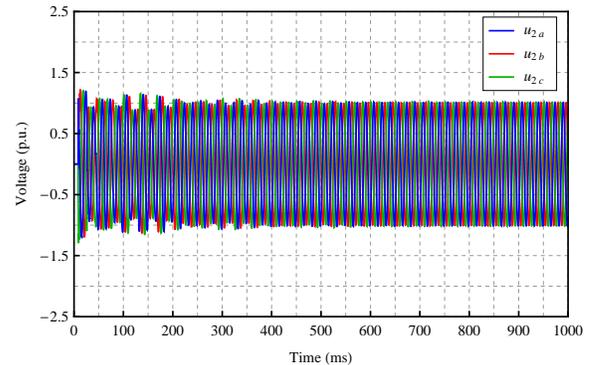


Figure 9: Output voltage with controllable switching – point-on-wave plus closing resistor.

Fig. 10 depicts the general topologies for series and shunt taps. It can be seen that one key difference in power circuits is the connection of the transformer. The remaining circuit is essentially the same: both types consist of two NPC converters [16] linked by DC capacitors in back-to-back configuration. The interface between the converter and the transmission line is done by a connection transformer.

The series taps can be seen as controlled voltage sources that produce a desired power injection (or drain) under the actual line currents. Shunt taps are the dual circuit, i.e. a controlled current source under the actual line voltages. Therefore, for an efficient/effective tap shunt taps should be connected near the line sending (or receiving) end and series tap are more suitable to be connected midway along the line, independently of line voltage operation.

IV. TEST CASES

The single-line diagram for the simulated system is shown in Fig. 12. It is based on the power transmission from the Madeira River either/or Belo Monte complex both in the Amazon Basin to the main load centers in Brazil in the northeast or southeast [17], [18]. The circuit length for this configuration may exceed 2500 km and the generation is over 17 GW, see Fig 11.

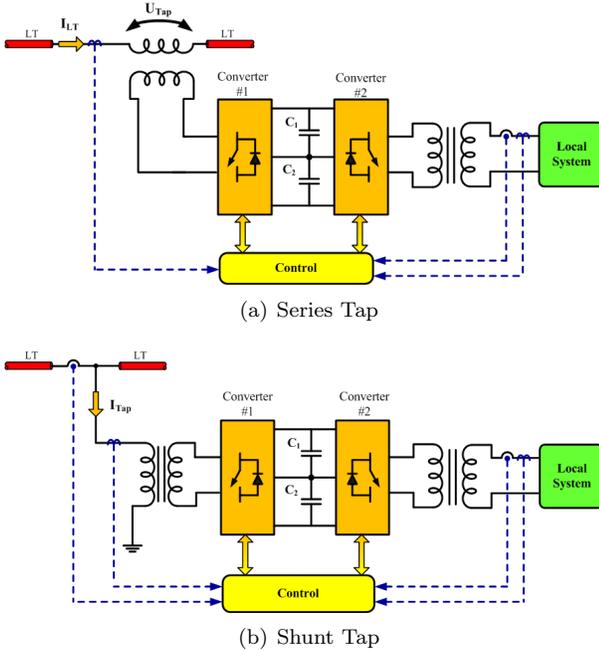


Figure 10: HVAC Tap connection.

The test system has two $\lambda/2^+$ circuit operating at 1000kV. Each overhead line circuit has a characteristic power of 8 GW. The circuit length is 2700 km. The generation is represented by an infinite bus, the load center is represented by an equivalent electrical circuit at power frequency. The HVAC tap connects a local system with generation and load to the main transmission path. The converter series (or shunt) are controlled using the instantaneous active and reactive power theory (pq-theory)

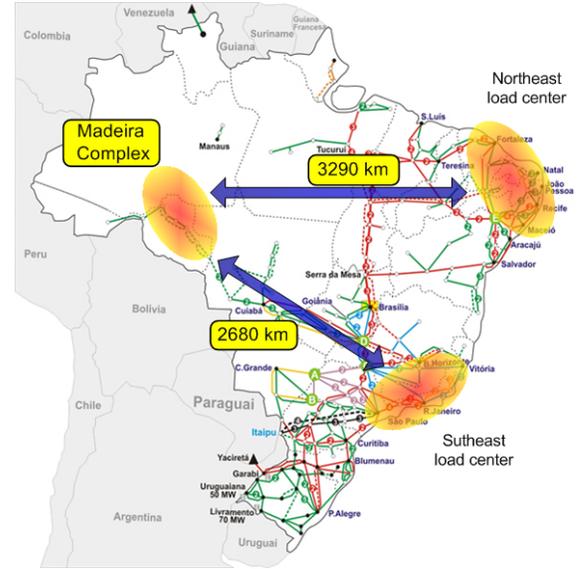


Figure 11: Distances from Madeira river complex to main load centers.

developed in [19]. The controller demands measurements of the line actual voltage and current to transform those data to $\alpha\beta$ frame using Clarke's transformation.

A time-step of $10\mu s$ was considered in all tests and the total simulation time was 5 s. A snapshot of the system (without the converters) at $t = 1$ s was used to initialize all the tests. The chain of effects is as following:

- $t_1 = 1.4$ s \Rightarrow The first converter of the HVAC Tap is connected to the power line to charge the dc-link capacitors.
- $t_2 = 1.7$ s \Rightarrow The second converter of the HVAC Tap which was blocked is now connected to the dc-link, the power order is null, i.e. the HVAC Tap is now fully connected but without any power drain $P_{ref} = 0$.
- $t_3 = 2.0$ s \Rightarrow The HVAC Tap starts to drain 1 GW from one of the $\lambda/2^+$ overhead lines. The load reactive power is supplied by the Local Generation.
- $t_4 = 3.0$ s \Rightarrow Now the HVAC Tap starts to inject 1 GW in the main transmission system, i.e., there is a total power flow inversion.
- $t_5 = 4$ s \Rightarrow the reference power of the HVAC Tap is changed to $P_{ref} = 0.5$ GW.

The same chain of events was considered for the series and shunt HVAC tap. Fig. 13 depicts the variation of instantaneous reactive and active power at the connection of HVAC Tap and the Local Generation at 230 kV. A series HVAC Tap was used in this test. The power consumption at the load remains unaffected independently of the power supply source. At first, the Local Generation is responsible for the load ($P_G > 0$), then the HVAC Tap supplies the load ($P_{tap} > 0$) and finally both the HVAC Tap and the Local Generation share the power demand. It should be pointed out that although not shown here, identical results for the instantaneous active and reactive power are obtained in the case of a shunt HVAC Tap.

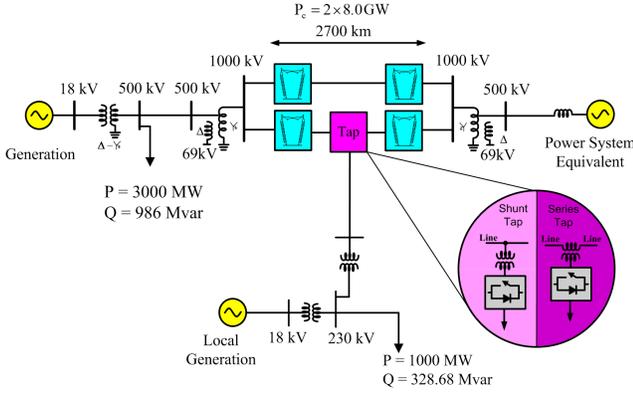
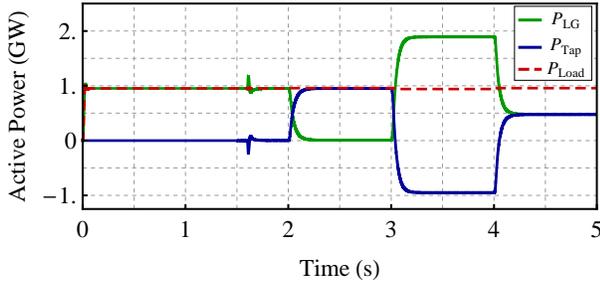
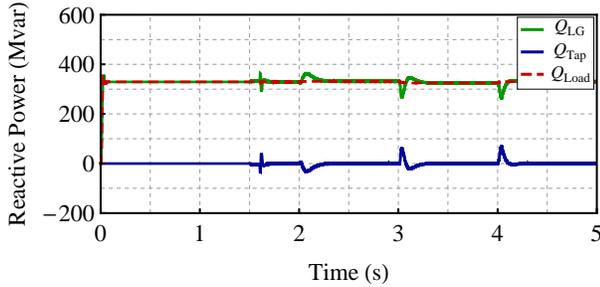


Figure 12: Single Line Diagram of the simulated system.



(a) Active Power



(b) Reactive Power

Figure 13: Interchange of power between HVAC tap and local system (in Fig. 12).

In the following figures i_{tap} stands for the HVAC tap current and u_{tap} is the voltage across the HVAC tap terminals. For a series tap, $u_{tap} = U_{P1} - U_{P2}$. Fig. V shows the waveforms for HVAC Tap connected halfway across the transmission line. At this particular point, the current in the $\lambda/2^+$ line is essentially constant, thus the power flow through the tap heavily depends on the HVAC tap voltage. No significant overvoltage was found. Fig. 15 depicts u_{tap} and i_{tap} during the power flow inversion, as it can be seen, no overvoltages or overcurrents occurred. Fig. 16 shows the rms values for U_{P1} and U_{P2} obtained using measurements from all phases. The shunt HVAC tap was connected at 450 km from the Generation bus. Fig. 17 shows i_{tap} and u_{tap} . Again, no severe overvoltage or overcurrents were found during the tap operation. Fig. 18 shows i_{tap} and u_{tap} during the power flow inversion. It is worth to mention, that the performance of the shunt HVAC tap is dual to its

series counterpart.

V. CONCLUSION

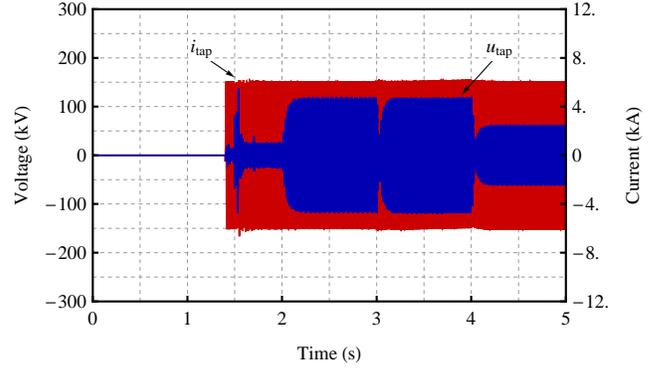


Figure 14: Voltage and current waveforms at tap terminals.

This work presents some aspects of an alternative for bulk ac power transmission over very large distances. It is based on a non conventional ac overhead line with an electrical length a little higher than half wave length (at power frequency), called here $\lambda/2^+$.

As example, we considered a 2700 km three-phase line with transmission capacity 8 GW, at 1000 kV. This example transmission system is of the type of transmission systems adequate for power transmission from the Amazon Basin (in which there important hydro-electric resources not yet used) to main electricity consumer regions of Brazil.

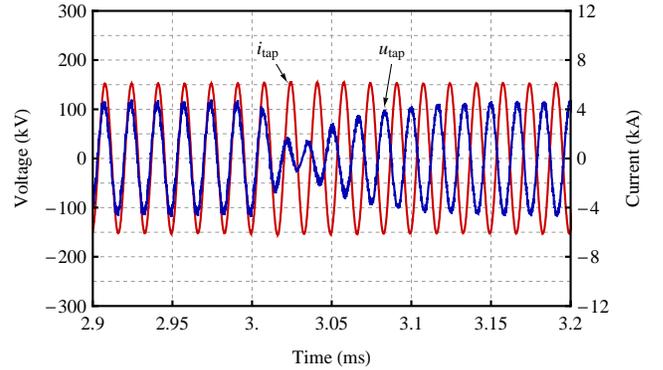


Figure 15: Voltage and current at tap terminals- (detail).

Although the considered alternative is not a basically point-to-point transmission system, in a sense similar to HVDC transmission systems, and allows e.g. to connect each “terminal” to a few substations a few hundred kilometers apart, it has some constraints and limitations in power received or supplied at intermediate points and in line operation in separate parts. As a solution to overcome this limitation, this work presents a HVAC tap, that uses a back-to-back self-commutated converters and can be connected in series or shunt with a $\lambda/2^+$ line. The HVAC tap is used to connect the “main” power circuit to a subsystem with a 1 GW load.

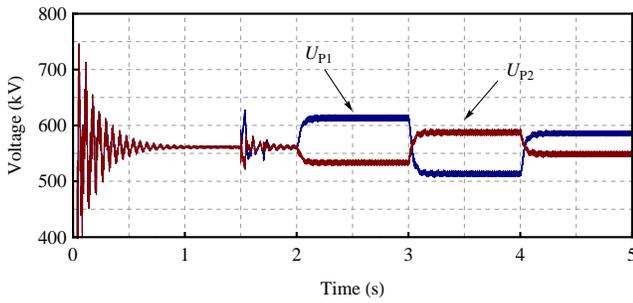


Figure 16: Voltage at tap terminals.

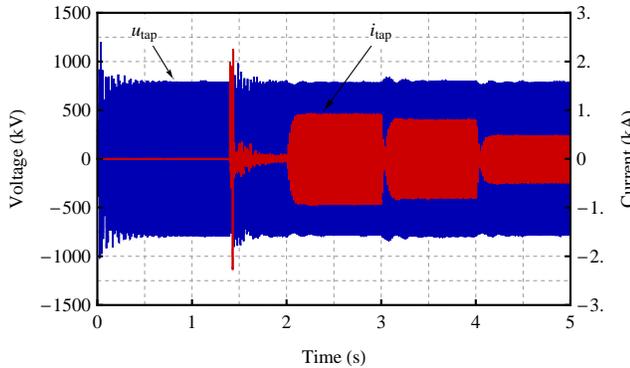


Figure 17: Voltage and current waveforms at shunt tap terminals.

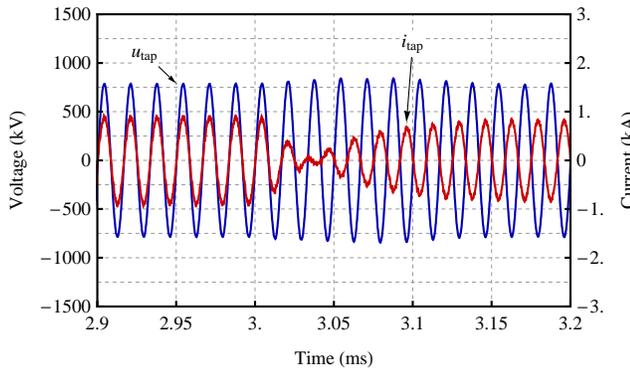


Figure 18: Voltage and current waveforms at shunt tap terminals.

The test indicated that the HVAC tap can inject or drain power from the $\lambda/2^+$ line without affecting the performance of the bulk power transmission.

It is important to notice that many studies have been done to overcome these challenges of electric power transmission at very large distances, and most of them have pointed to the HVDC transmission systems as the most attractive solution. Nevertheless, almost all of such studies have been done without regard to non-conventional ac transmission lines and transmission trunks with an electrical length a little higher than half-wave length (at power frequency). This alternative was carefully studied, e.g. in references indicated in this article. The obtained results show that such alternative has many interesting characteristics and, in several conditions, may have significant economical

and technical advantages, e.g. in comparison with HVDC, for transmission at very large distances.

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