OVERVIEW OF TAPPING METHODS FROM HIGH VOLTAGE TRANSMISSION LINES

D.V. Nicolae[1)], A.A. Jimoh[1)], J.F.J. van Rensburg[2)] and M.J. Case[2)]
[1)] Tshwane University of Technology, Private Bag X017, 0116 Pretoria North, South Africa
[2)] Vaal University of Technology, Private Bag X021, Vanderbijlpark, 1900, South Africa
E-mail: danaurel@yebo.co.za, adisa.jimoh@tut.ac.za, hannesvr@vut.ac.za, mikecase@global.co.za

Abstract. This paper takes an overview of various electric energy tapping methods from the high voltage transmission lines. Some of these have been studied and implemented previously, some of them are in advance stage of implementation and other new methods have just been started and they are at the initial stage of modeling and simulation. This paper briefly covers the tapping methods for ac transmission lines including two new methods that are at the final stage of research. Dc transmission presents a more challenging situation, but this paper manages to present a few new methods for energy tapping.

Keywords: Converter circuits, Distribution of electrical energy, HVDC, Modelling, Modulation strategies, New devices, Power supplies, Power transmission, Transmission of electrical energy

1. INTRODUCTION

In South Africa a problem has arisen in areas that have high voltage networks of high power rating yet do not have the population density which justifies the installation of standard power supply systems. One of the main focus areas of our government is to bring electricity to all people.

Another problem in these areas is the supply of power to the telecommunications installations, a problem that is presently being addressed mainly by means of solar power generation. A power supply of several kW would meet many of these needs.
In recent years, other solutions to address the electric energy supply in remote areas have been approached. The aim of these new energy-tapping solutions is to supply several kW output at 50 Hz 230 V from a high voltage (HV) transmission line, that would meet the needs of the repeater stations as previously stated and also unlock potential for bringing more users into the electric fold which otherwise would not be economically justifiable. These methods of connecting to the high voltage transmission line will eliminate the need for the conventional rural grid from a conventional substation to the rural users.

2. REQUIREMENTS FOR SMALL POWER TAPPING

As presented by other authors [1], [3], [7], the requirements for a small power tapping station should be:

- The power extracted from the transmission line should be less than 10 percent of the main system [3].
- The tap must have a negligible impact on the reliability of the main transmission along either alternating current (HVAC) or direct current HVDC lines [7].
- The tap control should not interfere with the main system control, i.e. the tap control has to be strictly local [1].
- Any fault in the local ac network must not disturb the operation of the main transmission line [7].

Further, tapping methods that are generally complying with the small power tapping will be presented. The methods will be classified into two big groups:

- Tapping methods from High Voltage Alternative Current Transmission Lines (HVAC).
- Tapping methods from High Voltage Direct Current Transmission Lines (HVDC).

Conditions for small power tapping

The electromagnetic field that surrounds the transmission lines carries electric energy. In order to tap small amount of power from this field, the main condition is:

$$p = \frac{\partial}{\partial t}\mathscr{U} > 0 \tag{1}$$

where $\mathscr{U}$ is the energy in electromagnetic filed.

Let us consider a cylindrical conductor (main transmission line) of radius r_o, length L, carrying a current I and the line having a potential/voltage V. After applying Maxwell laws for this situation, then the power density in the magnetic field and electric field respectively for a point at distance r can be written [17] as:

$$p_m = \frac{\partial}{\partial t}\mathscr{U}_m = \frac{\mu I \cdot L}{2\pi}\left(\ln\frac{r}{r_o}\right)\cdot\left|\frac{dI}{dt}\right| \tag{2}$$

$$p_e = \frac{\partial}{\partial t}\mathscr{U}_e = \frac{\pi \cdot \varepsilon_0^3 \cdot L \cdot V}{2 \cdot \ln\left(r / r_o\right)} \cdot \left|\frac{dV}{dt}\right| \tag{3}$$

The conclusion that can be derived from (2) and (3) is that for high voltage ac transmission lines (HVAC) the condition requested by (1) is naturally achievable. The methods to draw energy from HVAC can therefore be achieved and they can be classified into direct contact and non-contact methods.

3. TAPPING METHODS FROM HVAC LINES

The tapping methods from HVAC transmission lines could be classified into capacitive and inductive.

3.1 Capacitive methods for tapping from HVAC

These methods are based on tapping down electric energy via a capacitor that is either a physical one or a coupling one between the line and an auxiliary wire. The auxiliary wire could be obtained either by isolating the existing shield wire or by attaching an extra wire close to line conductors.

3.1.1 Capacitive divider method

The capacitor divider has been known for quite a while but using this technology to transform high voltage to medium voltage for delivering power is more recent [5]. In this method, a bank of capacitors is connected directly to the conductor line via a high voltage protective device as presented in Figure 1.

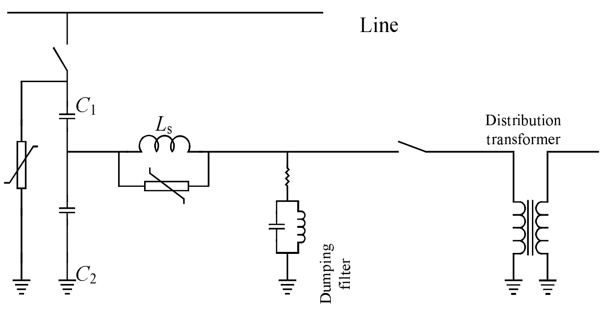

Fig. 1 Capacitive divider

The system is then brought to resonance by inserting an inductor (L_s):

$$L_s = 1 / [\omega^2 (C_1 + C_2)] \tag{4}$$

This system is used on transmission lines from 120 kV up to 345 kV and delivers power between 1,5 MVA and 4 MVA. A 3-phase, 1.5-MW, system has replaced the conventional Rivière-Ste-Anne (see Figure 2) substation of Hydro-Québec in 1994 and has always operated correctly: Gaétan Beaulieu [18] is very satisfied with the technology.

The capacitive solution is also under development in South Africa [13].

Fig. 2 Capacitive divider station at Post Rivière Saint-Anne

3.1.2 Isolated shield-wire method

The method is based on isolating the shield wire for a certain length. Then the capacitance between lines and this isolated shield wire is further used to draw energy from HVAC. Just as for capacitive divider, a series inductance is inserted between coupling capacitor and step - down transformer. The circuit is tuned for the industrial frequency, which could be 50 or 60 Hz depending on the standard frequency.

This method further falls into two categories: passive and active.

3.1.2.1 Passive method

The passive method was firstly studied in South Africa by Leigh Stubbs [15]. The result of this study led to a prototype with a power rating of 17 kVA, which was built near ESKOM's Apollo substation on the Kendal Minerva transmission line in 1992. In this solution, shown in Figure 3, the value of the series inductor and other elements of the system should be implemented very closely to the designed values; else any change in parameters can shift the system from resonance.

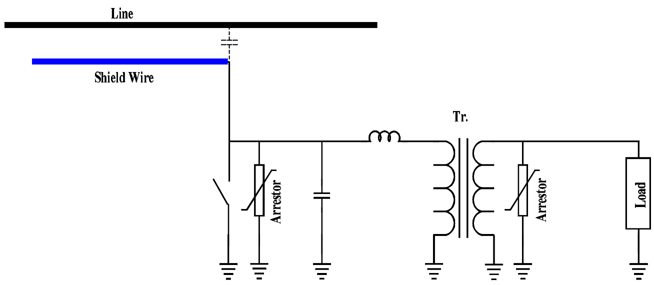

Fig. 3 Isolated shield wire - passive method

This method was further studied and improved upon in a 50 kVA prototype model [11]. Here a three-phase motor was introduced to limit the variation of the load and make the tuning conditions fairly constant.

3.1.2.2 Active method

The passive method presented some problems such as resonant frequency shift, ferroresonant oscillations and voltage regulation. In another method developed at I.R.E.Q.

Canada [18], the initial series inductor plus the transformer was replaced by a “self-regulated reactor with air gap”, presented in Figure 4. The controller keeps the system tuned to the desired frequency (60 Hz in this case) and in this way the output voltage is identical in shape with line voltage and in phase with it.
The power available from the wire is around 6 kW/km if the overhead grounding wire is pushed to around 60 kV. The Canadians have 30 of these systems installed (15 substations with 2 systems, one operating, the other used as a standby) operating this way and feeding 20-35 kW.

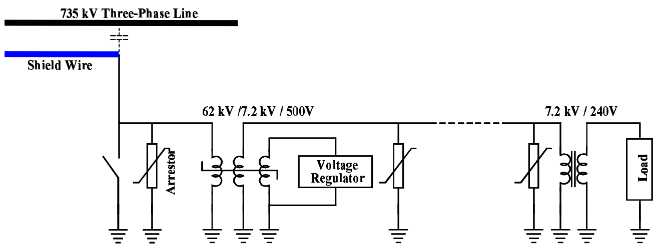

Fig. 4 Isolated shield wire – active method

3.1.3 Antenna method
In this method, an antenna-wire is attached to a live conductor of the line. Using isolation spacers, the wire is fixed at a certain distance. For an example of this: a 16 m long antenna mounted 0,30 m below a 120 kV conductor line can supply a 30 W load [18]. The load could be a radio transmitter, receiver or a neon light. This method is widely used by EDF in France to light transmission lines [18].

3.1.3 General comments about capacitive methods
The capacitive methods represent a big class of solutions of extracting energy from HVAC. They are based on a straightforward principle that allows good design. The range of power extracted could be from tens of watts up to megawatts.
The methods based on an isolated shield wire present the inconvenience of a very long distance in order to get relatively high power.
In the higher range of power is the capacitive divider. But this method requires a direct contact with the conductors of the line which brings serious protection problems. It should be mentioned that this method presents another major advantage: if placed somewhere between two classic inductive substations, the capacitive divider substation serves not only to feed loads but, in addition, acts as a reactive compensator thus improving the voltage regulation of the line.

3.2 Inductive methods for tapping from HVAC

This class of methods is based on the magnetic flux which exists around the transmission lines and that can induce an electromagnetic force (emf) in an inductor.

3.2.1 Current transformer tapping method
A class of inductive methods to extract energy from HVAC is based on the current transformer (CT). Normally, a current transformer is designed to be used for measuring currents.
Basically, however the CT is an iron-core transformer and its function is based on Faraday’s Law. With a different approach to design, a CT can be made to handle a reasonable output power. The basic model is presented in Figure 5.

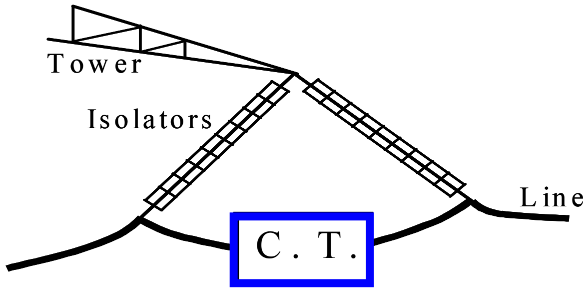

Fig. 5 Current transformer method

3.2.1.1 Current-to-voltage conversion with dc storage
In this method [9], the input current that feeds a CT is converted into voltage via a boost converter and by means of using a PWM switching technique a constant DC voltage is generated. This voltage supplies a single/three-phase inverter to create the 50Hz AC voltage and deliver a power of 1-3 kW. The basic diagram of this method is presented in Figure 6.

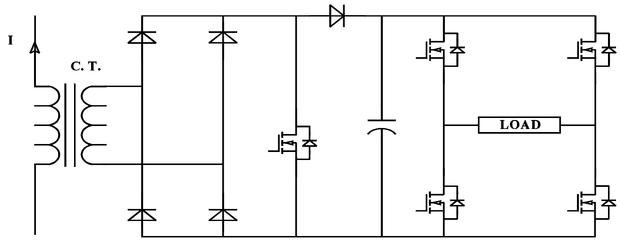

Fig. 6 Basic diagram of current-to-voltage with dc storage – CT-based tapping method

This method has the following advantages:

- It can feed single or three-phase loads.
- It is equivalent to voltage source that is suitable for almost all AC loads.
- It has good control facilities.

3.2.1.2 Direct alternating current to alternating voltage conversion
In this method [19], a new design of the power CT permits a direct conversion of alternating current into alternating voltage using an additional secondary or control winding. This winding, by means of PWM switching, modulates the magnetic flux and thus the output voltage of the main secondary winding, which is connected to the load via a low-pass filter (see Figure 7).
The voltage controller picks up the output voltage, compare with the reference and via a microcontroller provides the control signal for the gate of the bilateral switch. The bilateral switch controls the current into control winding and thus the flux in the current transformer.

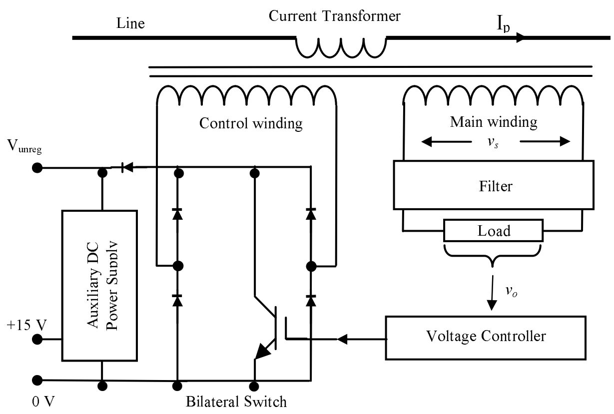

Fig. 7 Direct ac current to ac voltage conversion-basic circuit

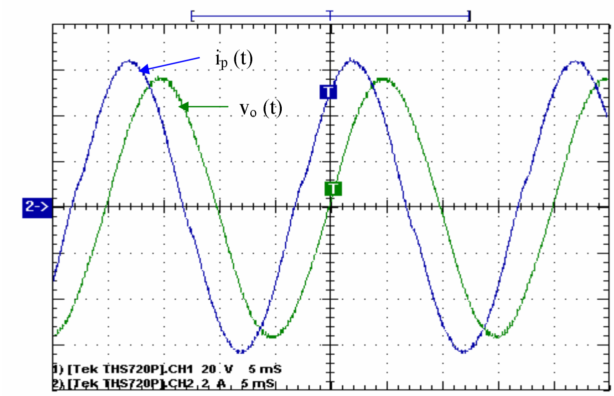

Fig. 8 Input current & output voltage for 30% duty cycle

The load secondary (v_s) is designed for a voltage higher than the required output voltage. According to Faraday's law:

$$v'_s = -\frac{d}{dt}\Phi_p \tag{4}$$

But the primary flux Φ_p is directly dependent on the primary/main current i_p:

$$i_p(t) = I_p \sin \omega_p t \tag{5}$$

$$\Phi_p = C \cdot i_p \tag{6}$$

where C is a constant that depends on the geometry of the current transformer.
Thus:

$$v'_s = -C\omega I_p \cos \omega_p t \tag{7}$$

or

$$v'_s = V_s \sin \omega_p t \tag{8}$$

The control winding is designed such that when it is short-circuited the resulting current saturates the core irrespective of what happens in the load winding. At that moment: $v_s = 0$. When the switch is OFF, the secondary voltage is given by relation (5).

The output signal of the main winding is non-sinusoidal. Hence, assuming its Fourier series components and the harmonic content attenuated [19], the resulting voltage output signal will depend on the duty cycle:

$$v_o = (1-k)V_s \sin \omega_p t \tag{9}$$

One other function of the proposed circuit is recovering the energy passing through the control winding; when the bilateral switch is OFF, a pulse goes to the auxiliary DC power supply. The unregulated voltage will appear from the very beginning, thus eliminating the need of a back-up battery. Although the variation of the unregulated voltage is relatively high, it still can be used to power the associated electronics and some DC loads eventually. Figure 8 shows the output voltage versus input current for a control signal with 30 percent duty cycle.

During experiments in the laboratory a power of 3 W was delivered using a reduced scale model. Based on these results a model of 5-15 kW is under development.

3.2.2 Air-core transformer method

If a loop is placed in the vicinity of a conductor/line carrying a variable current, then according to Faraday's Law, an electromotive force (emf) will be induced in that loop. Based on this principle [12], when a passive/pick up loop is placed below the plane of the transmission line an air-core transformer is created and energy extraction from HVAC is achieved (Figure 9).

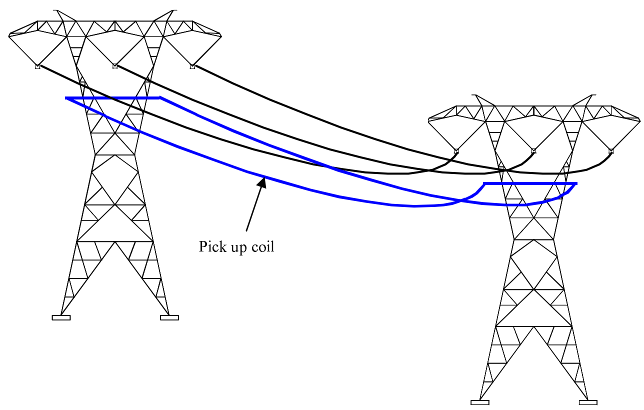

Fig. 9 Air-core transformer method

If a three-phase current system with amplitude I is considered, then the emf induced [19] in the pick up coil is given as:

$$e(t) = \sqrt{3} \cdot E \cdot \sin(\omega t) \tag{10}$$

where:

$$E = k \cdot \ln \frac{(D_L + b/2)^2 + D^2}{(D_L - b/2)^2 + D^2} \tag{11}$$

and

$$k = \omega \cdot I \cdot N \cdot a \cdot 10^{-7} \tag{12}$$

where D_L is the distance between lines, D is the distance between the plan of the lines and the plane of pick up coil, a is the length of the coil b is the width and N is the number of turns.

The method has been validated in the laboratory on a

reduced scale model. Figure 10 shows that emf induced in the pick up coil when a three-phase system is involved is approximately in phase with the reference current; the small difference which can be observed is due to imperfect current balancing and distortions of currents.
Taking into consideration the safety and mechanical constrains of a 440 kV transmission line with D_L = 8.5 m between the lines, the recommended position of the coil is horizontal at D = 3.5 m below the lines plane; the coil is installed between two consecutive towers which gives an approximate coil length of 300 m, and having a width of 9 m. These parameters and considering the amplitude of the line current of 1500 A will be translated in estimated amplitude for emf of E = 45.5 V/turn or E_{rms} = 32.17 V/turn. For 20 turns of 2 mm diameter copper wire a power of 3 kW can be achieved.
At this moment a large scale model is under design using aluminum steel reinforced, the estimated power will go up to 10-15 kW.

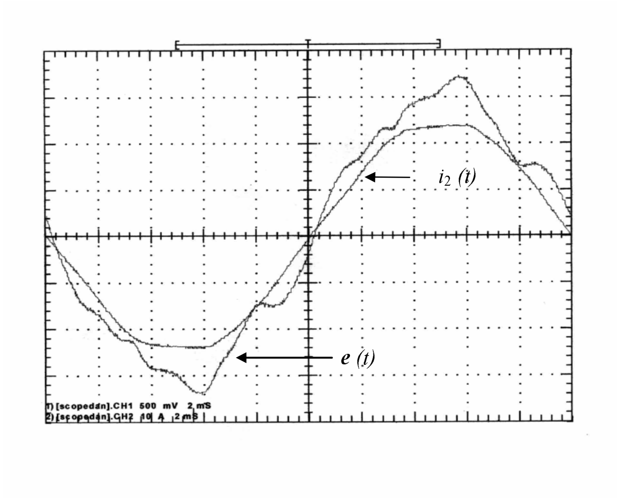

Fig. 10 Output voltage versus input current

3.2.3 General comments about inductive methods
The inductive methods of extracting energy from HVAC transmission lines represent a viable alternative to the capacitive. They are recommended for a power range of several kilowatts. The CT-based method can produce an even higher power when applied on each phase of the transmission lines.
Compared to the isolated shield wire (capacitive) methods, the inductive method does not require a very long distance. For the methods based on CT only one tower is required, while for air-core transformer the coupling device should be installed between two or eventually three towers.
The influence of the CT-based methods on the transmission is dependent on the ratio of the current transformer. If one takes into consideration a ratio of 1:100 and a level of load current of 10 to 30 A, then what is seen in the primary is below 1 A. If this small input current is compared with the main current through the line that very well exceeds 1000 A, then the conclusion is that there is practically no influence. The air-core transformer also exerts a very small influence on the transmission line due to the air-core coupling.

4. TAPPING METHODS FROM HVDC LINES

The classical method to draw energy from high voltage dc transmission lines (HVDC) is a direct contact between the line and tapping devices [1], [2], [3], [6] and [7].
For HVDC the conditions (2) and (3) cannot be satisfied. So, the challenge is obvious. However, if the ripple of the dc voltage and current are considered, then it is possible to use some methods similar to those for ac lines. But the trend for the future HVDC is a ripple that will be reduced more and more.

4.1 Energy stored into electric field

In order to find new developments for tapping energy from HVDC, let us consider the expression of energy in electric field of a capacitor and an inductor respectively:

$$\mathscr{U}_e = \frac{1}{2} C \cdot V^2 \tag{13}$$

$$\mathscr{U}_m = \frac{1}{2} L \cdot I^2 = \frac{\Phi_m^2}{2 \cdot L} \tag{14}$$

If the voltage and current are perfect constant, then the power can be expressed as:

$$p_e(t) = \frac{\partial}{\partial t}\mathscr{U}_e = \frac{V^2}{2} \cdot \frac{\partial C}{\partial t} \tag{15}$$

$$p_m(t) = \frac{\partial}{\partial t}\mathscr{U}_m = \frac{I^2}{2} \cdot \frac{\partial L}{\partial t} = \frac{\Phi_m}{L} \cdot \frac{\partial \Phi_m}{\partial t} \tag{16}$$

The above equations show that a power transfer appears if the capacitance, inductance or the magnetic flux could be modulated.

4.2 Direct contact methods

This class of methods can achieve a relatively high power drawn from the HVDC. There are two possible ways to approach power tapping:

- In series with the line.
- In parallel to the line.

4.2.1 Current fed capacitor-switched converter
The method [1] implies a switching mode converter series connected with HVDC line. The basic diagram is presented in Figure 11.

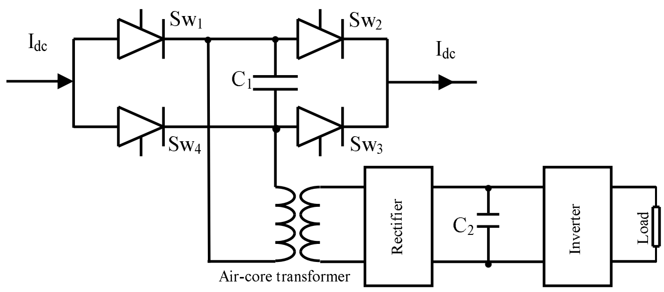

Fig. 11 Current fed capacitor switched converter

When switches Sw_1 and Sw_3 are ON the capacitor C_1 charges to a voltage proportional to the time current is flowing in it. This voltage is directly applied across the non-conducting switches, as well as the primary of the winding of the isolation transformer. When the voltage reaches a set limit, switches Sw_2 and Sw_4 are triggered thereby naturally commutating Sw_1 and Sw_3. Now the capacitor C_1 is discharged and charged further in opposite polarity. Thus an alternative voltage of relatively high frequency is created, which is transformed and further processed to the ground potential.

4.2.2 Soft-switch current fed dc to dc converter

The basic diagram of this tapping method [2] is presented in figure 12. It comprise two self-commutated switches (MCT or IGBT) represented by Sw_1 and Sw_2, two diodes D_1 and D_2 and a snubber capacitor C_H.

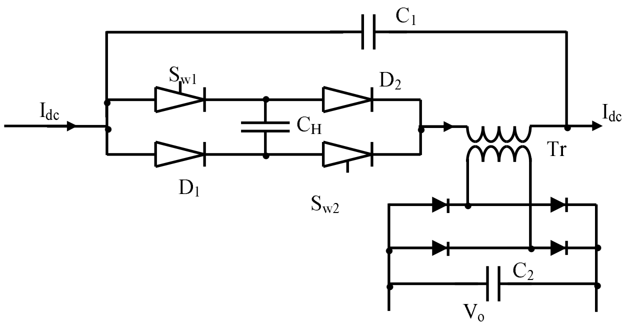

Fig. 12 Soft switch dc to dc converter

The H bridge (Sw_1, Sw_2, D_1 and D_2) turns ON at zero current switching conditions and turns OFF at zero voltage conditions. This could contribute to the use of a switching frequency as high as 5 kHz. The alternating voltage created across the primary of the air-core transformer (Tr) is then stepped down and rectified to provide dc voltage (V_{dc}) which can be further used either to supply a dc load or 50 Hz inverter single or three phase.

4.3.3 Current fed inductor-switched converter

This method [7] basically uses the same configuration as III.B.1 but the switched element is the primary of the isolation transformer (Figure 13). The elements L_1, C_1 and L_2 constitute a filter for the switching frequency.

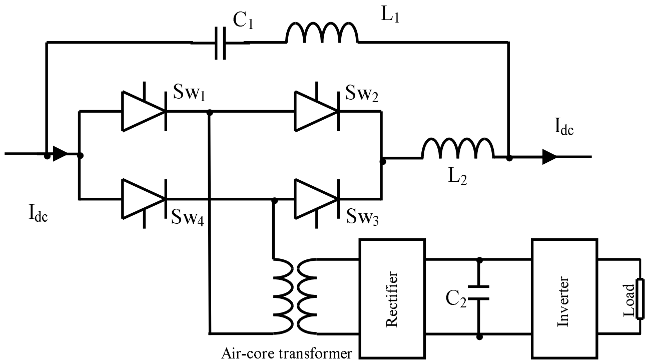

Fig. 13 Current fed inductor switched converter

Thyristors are used as switching element and the control of firing angle is used to control the dc link voltage.

4.2.4 Current fed PWM chopper

This method [3] consist in inserting in series with the line a chopper which, using PWM switching, charges a capacitor bank thus creating the necessary voltage to supply an inverter (Figure 14).

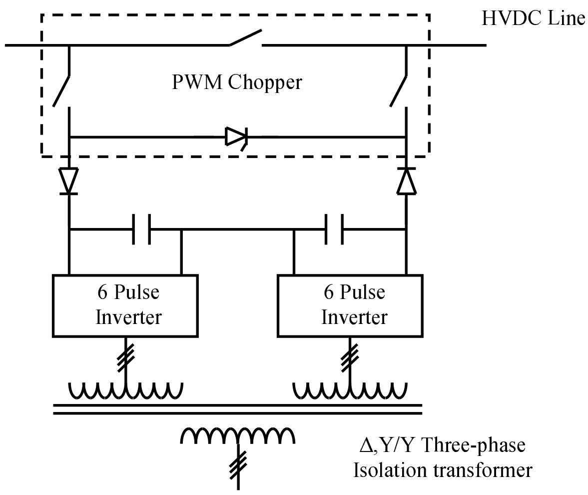

Fig. 14 Current fed PWM chopper

4.2.5 Parallel connected inverter

The series connected tapping station introduces a volt drop on the HVDC line which restricts the number of such stations along the transmission line. By using parallel taping of small amount of energy, the number of tapping stations could be increased [6]. The method is simple (Figure 15) and consists of an inverter (single or three-phase) which via an isolation transformer supplies various ac loads.

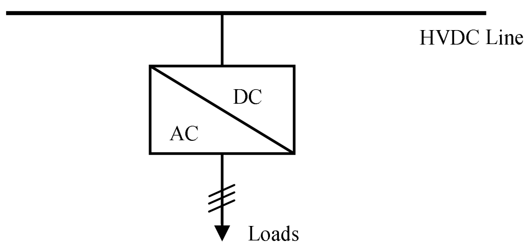

Fig. 15 Parallel taping method

4.3 Non-contact methods: capacitive coupling

This method [17] is based on harmonic content of the dc voltage. If an auxiliary wire is connected in parallel to the main line, a capacitor is created and the harmonic content of the voltage can be transferred to an ac circuit which will recover the harmonics' energy (Figures 16 and 17).

Let us consider the case of Cahora-Bassa-Apolo HVDC transmission system which is a classical twelve pulse converter; the voltage is 500 kV and the load current is 1800

A. To simplify the situation, let us consider a zero degree firing angel. Let us also consider the auxiliary wire is L = 1000 m long situated at D = 4 m away of the main line. The capacitance between two parallel wires is given by:

$$C_c = \frac{2 \cdot \pi \cdot L}{4 \cdot \pi \cdot 9 \cdot 10^9 \ln \frac{D^2}{r_1 \cdot r_2}} \qquad (17)$$

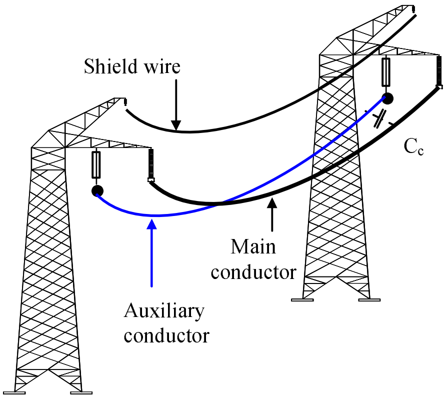

Fig. 16 Capacitive method: basic model illustration

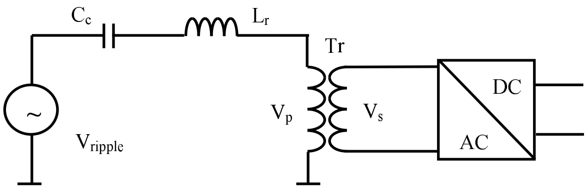

Fig. 17 Capacitive method: equivalent circuit

Taking into consideration the other geometrical parameters (r_1 and r_2) of the conductors this result in a capacitance of 5.89 nF. Because the main harmonic of the ripple voltage is the eleventh (550 Hz), this results in a resonant inductance of L_r = 14.39 H. Figure 18 shows the ripple voltage, the primary and secondary voltages of the transformer.

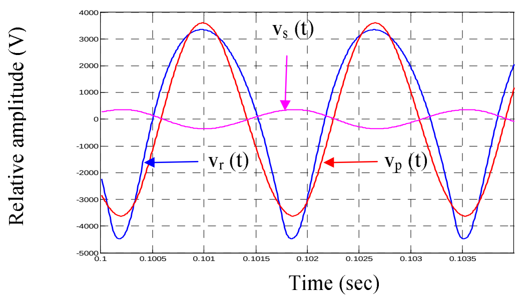

Fig. 18 Simulation results for capacitive coupling

Simulations based on the above situation showed this method to be capable of delivering 600 W to a100 Ω load. A high quality factor results in a significantly improved power transfer capability.

4.4 Non-contact methods: inductive coupling

This method is also using the harmonic content of the current on the transmission line. If the same case as above (4.3) is considered, the main harmonic component which can produce inductive coupling is of 13.5 A amplitude and 550 Hz frequency (see Figure 19).

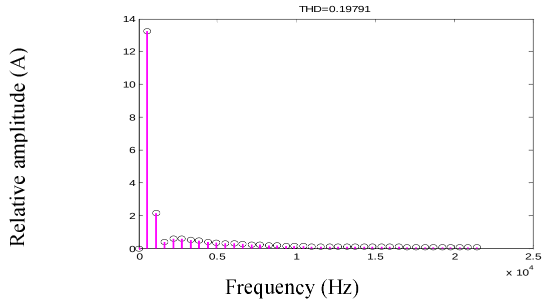

Fig. 19 Current ripple: frequency spectrum

The magnetic field created by this current can induce an emf into a pick up coil placed next to the HVDC line (Figure 20).

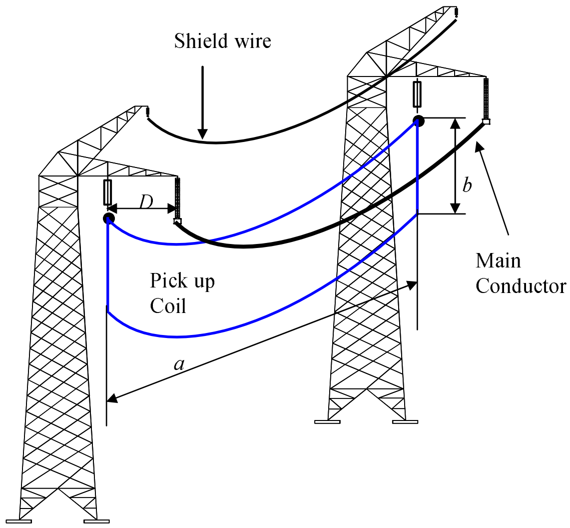

Fig. 20 Inductive method illustration

The emf ($\mathcal{E}$) induced in one turn can be determined using relation (17):

$$\mathcal{E} = \omega \cdot I \cdot a \cdot 10^{-7} \ln \frac{D^2 + b^2}{D^2} \qquad (18)$$

where ω is the frequency of the main harmonic, a is the length of the pick up coil which is the same with distance between two towers, b is the width of the coil and D is the distance between the main conductor and the plane of the coil.

Using the parameters D = 4 m, a = 500 m, b = 9 m, ω = 550 Hz and I = 13.5 A, the emf per turn will be 2.97 V. For a reasonable power it is necessary to have a big number of turns and for the length of the coil to be extended over two towers.

4.5 Inductive method-wind powered

This method is using the strong magnetic field created by the dc current which is in the range of 2000 A and a pick up coil that is rotated by wind force.

The emf induced into the (wing-powered) rotating coil has the same expression as (18). Because the angular speed ω is not constant, an ac-to-dc converter coupled with a storage element (battery) is necessary. The power drawn could be in the range of a kilowatt.

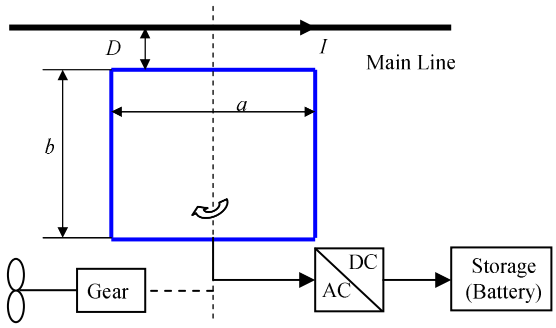

Fig. 21 Inductive method-wind power illustration

4.6 Inductance modulation

The main idea of this method [22] is to modulate the self inductance of a coil carrying a very high dc current. The self inductance of a coil can be written as [23]:

$$L = 4\times\pi^2\times10^{-7}\times a^2\times n^2\times b^{-1}\times K \qquad (19)$$

where a is the radius of the coil, b is its length, n represents the number of turn and K is a coefficient depending on the ratio $2a/b$.

If the length of the coil can be periodically varied, then:

$$b = b_o\left[1+\varepsilon\sin(\omega t)\right] \qquad (20)$$

with ε being the amplitude of the relative variation. Because the variation ε is much smaller then unity and using equation (16), the instantaneous available power can be written as:

$$p_m = 2\cdot\pi^2\cdot10^{-7}\cdot a^2\cdot n^2\cdot I^2\cdot K\cdot b_o^{-1}\cdot\varepsilon\cdot\omega\cdot\cos(\omega t+\pi/2) \qquad (21)$$

In order to get a significant output power of few tens of kilowatts from this method, two ways are under investigation:

- Low frequency (ω), but relative high amplitude (ε) with a prime mover provided by wind power.
- High frequency and low amplitude with the movement provided by field-driven piezo-type materials [21].

4.7 Flux modulation

The modulation of the flux produced by a dc current going through a magnetic circuit can be obtained varying the reluctance of that circuit. The magnetic flux depends on the current, number of turns and mainly on the air-gap reluctance:

$$\Phi_m = \frac{I_p N_p}{\mathscr{R}} \qquad (22)$$

where I_p is primary dc current, N is the number of turns in primary and $\mathscr{R}$ is the reluctance. But the air-gap reluctance is a function of the air-gap (g) and the overlap area between stator and rotor (A_r):

$$\mathscr{R} = \frac{g}{\mu_o A_r} \qquad (23)$$

When air-gap reluctance is varied by moving the rotor, then g, A_r and consequently the flux will be a function of time and Faraday's law becomes valid and a certain amount of power can be transferred to a secondary winding.
A basic example is shown in figure 22; the prime mover could be wind or an electric motor.

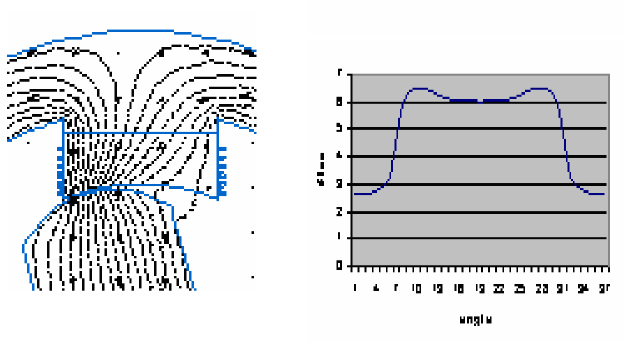

Fig. 22 Variable reluctance: basic model

As can be noticed from figure 22, the flux is a function of rotor angle, though it is a function of time.

5. GENERAL COMMENTS ON TAPPING

A wide range of methods for tapping electric power from both ac and dc HV transmission lines have been presented. The tapping methods from the HVAC are much more common due to the simplicity of the principles. Although some of these methods are relatively old, some new methods for tapping from ac line have emerged.
The tapping methods from HVDC are much more challenging and some of them require high reliable semiconductor devices. These methods will benefit from the development of the new emerging devices based on new materials such as silicon carbide which have large breakdown dielectric field strength and the operating temperature above eight hundred degrees Celsius.
As a general note, the methods presented could be classified into: a) direct contact and b) non-contact methods. The direct-contact methods have the advantage of enhanced power delivery capability. They present the disadvantage of excessive stress from the current point of view - for series connected methods, and from the voltage point of view - for the parallel methods.
The non-contact methods have as main advantage non-intrusion in the transmission line. The influence on the transmission line is minimum and in case of fault, the protection of the main line is not triggered. However, the

power tapping capacity of non-contact methods is comparatively lower than of direct contact. This represents the drawback of the non-contact methods. Nonetheless, in the remote and very poor areas, few kilowatts of electric power can bring the main advantage of modern civilization; for an example communication such as radio and tv.

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