Power Supply from the High Voltage Transmission Lines
Part 2: Tapping from HVDC Lines, Design and System Interactions

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Abstract— Electric power may be tapped straight from the high voltage transmission lines either for consumption to meet the needs of rural and remote areas, and telecommunication establishments located in remote sites; or as a scheme to enhance the capacity of another utility or grid along a trans-national or trans-continental transmission corridor. The importance and interests the technologies to accomplish this has generated necessitate the need for a review of the state of the art of this subject so as to delimit research actions and allow research interests to be appropriately promulgated. In the first part of this work the principle, conditions and methods for tapping from HVAC lines have been discussed. This paper completes the study by looking at tapping from the HVDC transmission systems. The principles on which tapping methods from HVDC system is based are presented; and various methods, existing and novel, for multiterminal operation or integrating small tapping into HVDC links are reviewed. The paper ends with a general discussion of tapping from HVDC, and concludes with a presentation of the future direction.

***Index Terms*--** Interconnected power systems, Power distribution planning, Power electronics, Power engineering, Power systems, Power system planning, Power transmission lines, Power generation planning, DC power transmission, HVDC transmission lines.

I. Introduction

Tapping electrical power from the high voltage transmission lines has been accepted as a viable economic option for meeting the electrical energy needs of rural and remote areas, and for powering equipments, such as the telecommunication repeater stations located in these areas. It has also been identified as a key facilitation for the emergence of power pools through which global electric power supply inadequacies may be addressed. Nations that are either too poor economically and financially, or poor in resources, or that wish to reduce their dependence on nuclear power, can tap from trans-national or trans-continental transmission corridors of a power pool to meet their electrical power needs.

Tapping from HVDC was recognized shortly after the first dc transmission systems evolved [1]. Even though tapping from HVDC was recognized early after its inception, it was not until 25 years later that the first applications of multiterminal dc transmission became a commercial reality [2], [4]. Tapping of HVDC lines presents tough technical and economic challenges. These challenges are particularly hard when the power rating of the tap is small compared to that of the main terminals. The tapping of the monopolar Sardinia to Italy HVDC line on Corsica was the first commercial installation of HVDC tapping [3]. Another example of existing commercial operation of HVDC tapping is the bipolar tapping of the Quebec – New England dc link by a 2140 MW parallel tap at the Nicolet Station [4]. These successful practical demonstrations has encouraged researchers around the world to investigate other and novel techniques for electrical energy tapping from HV and EHV transmission lines.

The importance of this development necessitates the need for a review of the state of the art of this subject so as to delimit research actions and allow research interests to be appropriately promulgated. This paper therefore is the second of a two-part review of the state of the art tapping of electric power from HV and EHV ac and dc transmission lines. Part one focuses on the general conditions for tapping, presents the principles on which tapping methods are based, reviews methods for tapping from HVAC transmission systems, and concludes with a general discussion on tapping from HVAC.

This paper, the part two, completes the study, by presenting the tapping from the HVDC transmission systems. The principles on which tapping methods from HVDC system is based are presented; thereafter various methods, existing and novel, for multi-terminal operation or integrating small tappings into HVDC links are reviewed. The paper ends with a general discussion of tapping from HVDC, and concludes with a presentation of the future direction.

II. Principle of Power Tapping from HVDC Lines

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:

$$P = \frac{\partial}{\partial t}\mathcal{U} \neq 0 \tag{1}$$

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

The power density in the magnetic field and electric field respectively for the point P at distance r from the conductor of the transmission line can be written [5] as:

$$p_m = \frac{\partial}{\partial t}\mathcal{U}_m = \frac{\partial}{\partial t}\left[\frac{\mu I^2 \times L}{2\pi}\left(ln\frac{r}{r_o}\right)\right] \tag{2}$$

$$p_e = \frac{\partial}{\partial t}\mathcal{U}_m = \frac{\partial}{\partial t}\left[\frac{\pi \times \varepsilon_o^3 \times L \times V^2}{2 \otimes ln\left(r/r_o\right)}\right] \tag{3}$$

But for the HVDC lines the equation (1) cannot be satisfied due to:

$$\frac{\partial V}{\partial t} = 0 \text{ and } \frac{\partial I}{\partial t} = 0 \tag{4}$$

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.

Taking into consideration all the above, the tapping methods from the HVDC transmission lines could be classified as follows:

- Power electronics-based methods; these are in direct contact with the main line.
- Methods based on the imperfection of the dc parameters; non-contact methods.
- Parametric modulation methods; non-contact methods.

III. Direct-Contact Tapping Methods

This class of methods can achieve a relatively high power drawn from the HVDC. These methods are based on power electronics processing of the dc energy transported on the HVDC. There are two possible ways to approach power tapping:

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

A. *Current-fed capacitor-switched converter*

The method [6] implies a switching-mode converter series connected with HVDC line. The basic diagram is presented in Fig. 1. 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 air-core 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. The set voltage limits (Vc1) are determined by the switch characteristics [6].

The level of capacitor voltage (V_{c1}) depends directly on the switching frequency. Thus, by varying the switching frequency, the dc bus (V_{dc}) on C_2 can be maintained constant. Fig. 2 shows the steady state for a dc current (I_{dc}) of 2000 A, switching frequency of 830 Hz with a load of 1.4 MVA and Fig. 3 shows the situation for a switching frequency of 1200 Hz.

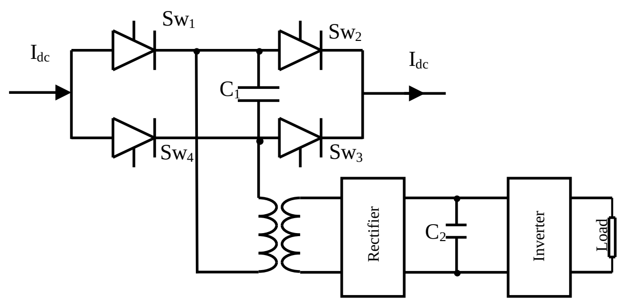

Fig. 1 Current-fed capacitor-switched converter

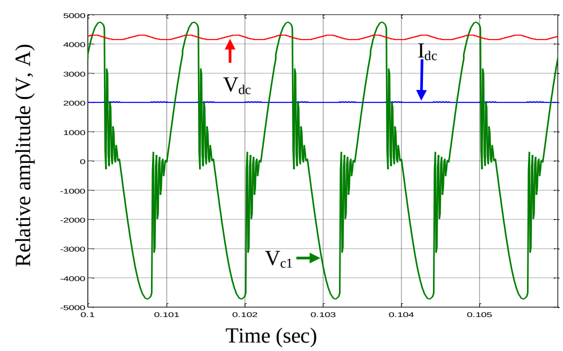

Fig. 2 Steady state for 830 Hz

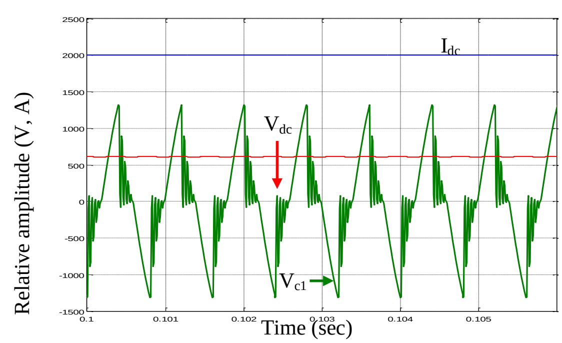

Fig. 3 Steady state for 1.2 kHz

One other aspect that should be considered is the influence on the main line. Fig. 4 shows the influence of the tapping upon the current and Fig. 5 shows the voltage across the tap. If the current ripple is very small, the voltage across the tap is relatively high.

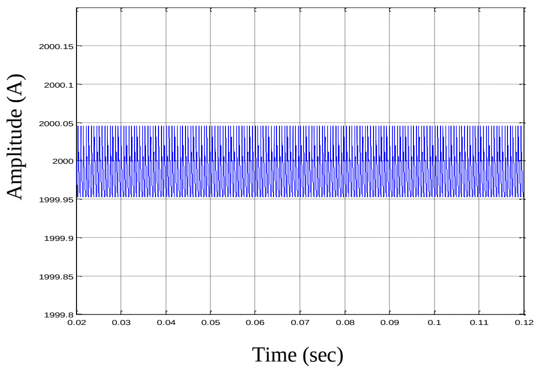

Fig. 4 Current ripple due to the tap

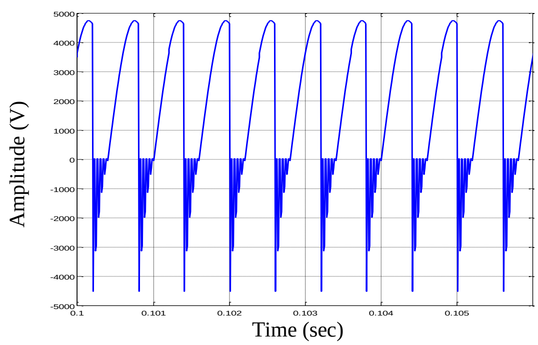

Fig. 5 Voltage across the tap

The tapped power can be increased using series connected switches.

B. Soft-switch current-fed dc to dc converter

The basic diagram of this tapping method [2] is presented in Fig. 6. 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.

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.

The control of this soft-switching dc/dc converter is based on adjusting the duty cycle while the frequency is kept constant. In [2] has been found that an efficient operation and dc regulation is optimum for duty cycle between 0.15 and 0.40; for duty cycle higher than 0.4 the power transfer becomes very low and for duty cycle lower than 0.15 the H bridge loses its soft switch capability.

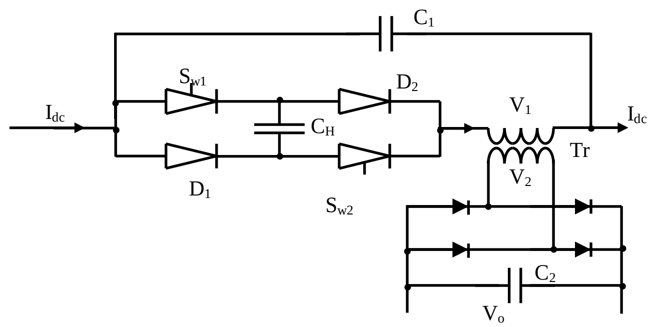

Fig. 6 Soft-switch dc to dc converter

In the simulation model the dc line current is 2000 A, C_H = 6 F, C_1 = 500 F, the air-core transformer is presented as a mutual inductance with L_{11} = 100 μH, L_{22} = 400 μH and M = 120 μH and the dc load is R = 160 Ω. Without considering the control system, steady state parameters for 20 % duty cycle are shown in Fig. 7 while Fig. 8 shows the same parameters for 40 % duty cycle. As can be noticed the output power varies between 1.3 and 2.3 MW which means a real possibility to control the output.

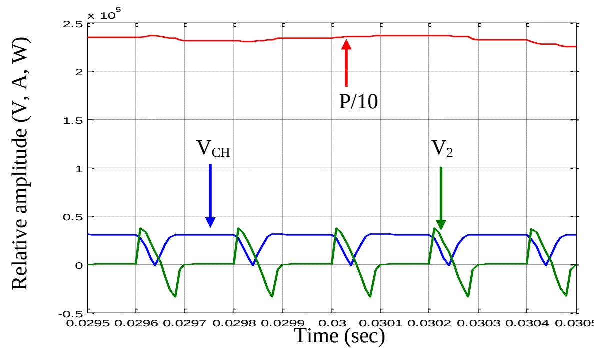

Fig. 7 Static parameters for 20% duty cycle

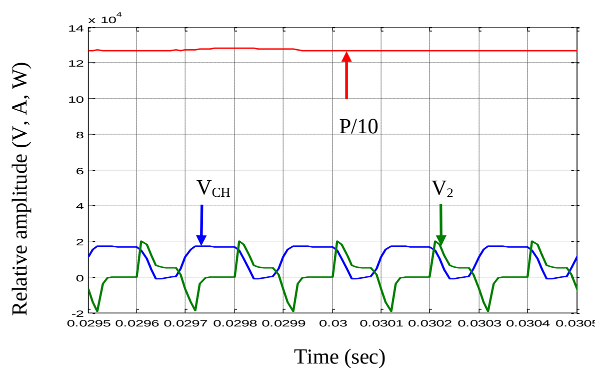

Fig. 8 Steady state parameters for 40 % duty cycle

Fig. 9 sows the influence upon the main line: the current (I_{dc}) is not affected due to the fact that at any moment in time the current flows either through D_1, D_2 or Sw_1, Sw_2.

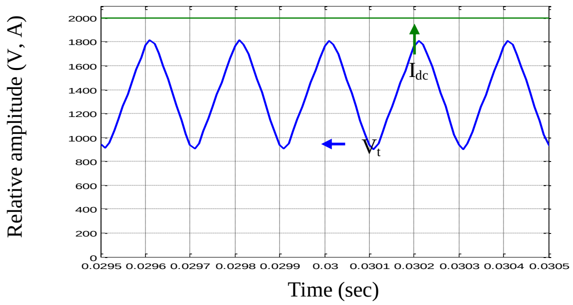

Fig.9 Tap influence upon the line

The voltage across the tap is relatively high, but due to high frequency (5kHz) and LC distributed parameters of the line, this will be very significantly reduced.

C. Current-fed inductor-switched converter

This method [7] basically uses the same configuration as *B* but the switched element is the primary of the isolation transformer (Fig. 10). The main converter is a current-source line-commutated and the control of firing angle is used to control the dc link voltage. The element L_2 is the commutating reactance for the main converter; C_1 and L_1 constitute a filter for reducing the noise introduced into the main line.

Having to switch very high current, the frequency is low (300-400 Hz) and the control is done upon the commutation margin which, as shown in [7], depends on the dc voltage across C_2.

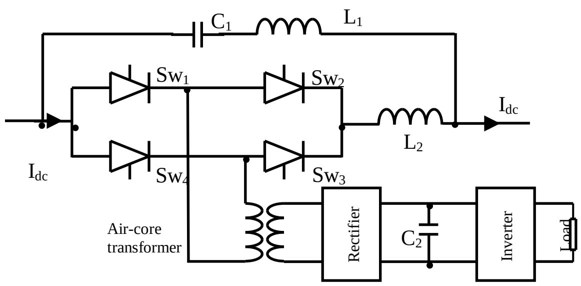

Fig. 10 Current fed inductor switched converter

Fig. 11 shows the voltage at the input of the insulation transformer in steady-state; the simulation results are obtained for I_{dc} = 2000 A, L_1 = 1.64 mH, C_2 = 1000 μF, V_{dc} = 25 kV, transformer ratio of 1.6 and a load power of 50 MW.

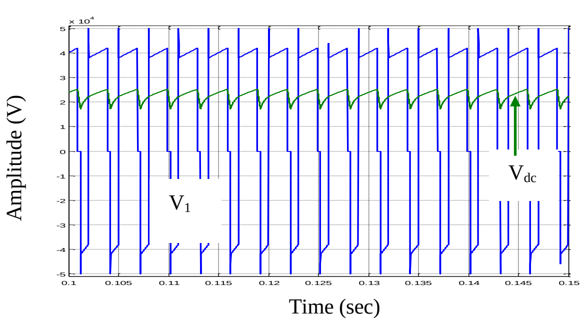

Fig. 11 Steady-state parameters

D. Current-fed PWM chopper

This method [2] consists 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 (Fig. 12).

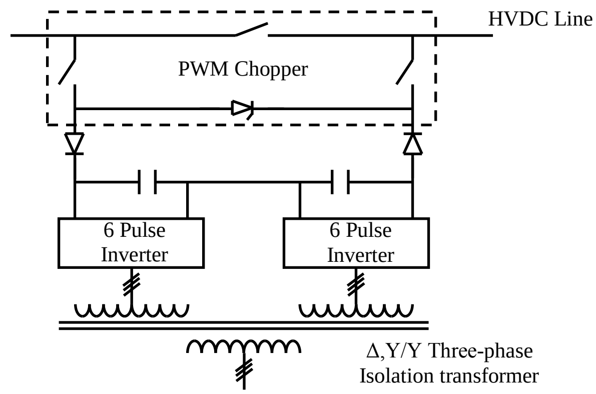

Fig. 12 Current fed PWM chopper

Parameters of the simulation are: switching frequency 5 kHz, charging capacitors of 1000 μF and resistive loads of 10 each. These parameters produce an output power of 10 MW for a duty cycle of 50 % (see Fig. 13). Fig. 14 shows the dc tap voltage for a duty cycle of 25 %. One can see a wide range of variation of the dc link which can compensate the variation of the main current and/or load fluctuation.

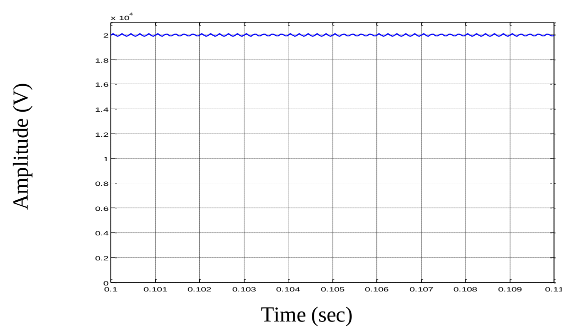

Fig.13 Output dc voltage for 50% duty cycle

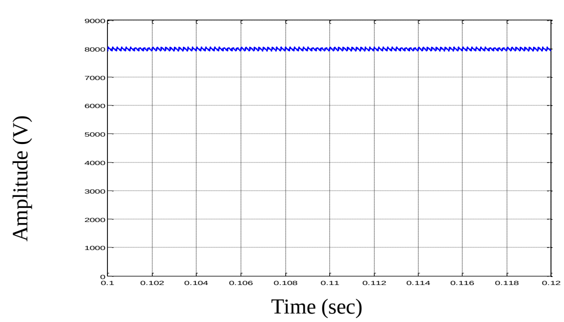

Fig.14 Output dc voltage for 25% duty cycle

Fig. 15 shows the voltage across the tap for 10 MW load; the higher the requested power the bigger influence upon the line is.

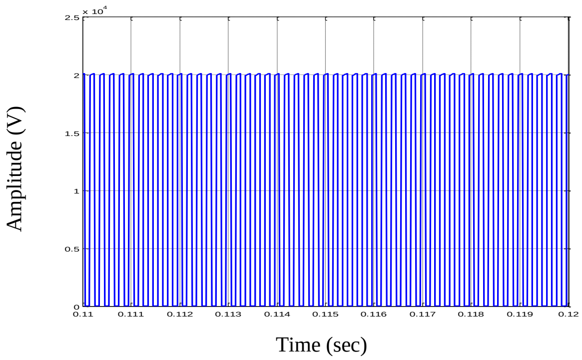

Fig. 15 Voltage across the tap for 50 % duty cycle

E. 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 tapping of small amount of energy, the number of tapping stations could be increased [8]. The method is simple (Fig. 16) and consists of an inverter (single or three-phase) which via an isolation transformer supplies various ac loads.

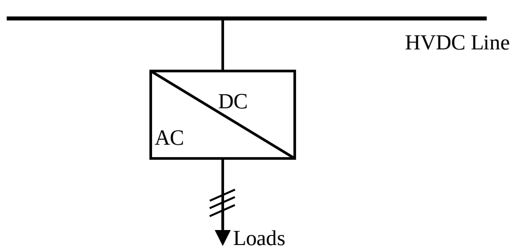

Fig. 16 Parallel taping method

IV. Non-Contact Tapping Methods

A. Methods based on dc ripple

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.

A.1 Capacitive coupling

This method [5] is based on harmonic content of the dc voltage. If an auxiliary wire is installed 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 (Fig. 17 and 18).

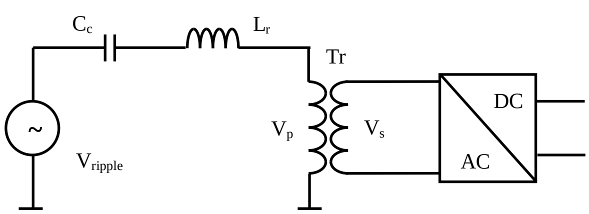

Fig. 17 Capacitive method: equivalent circuit

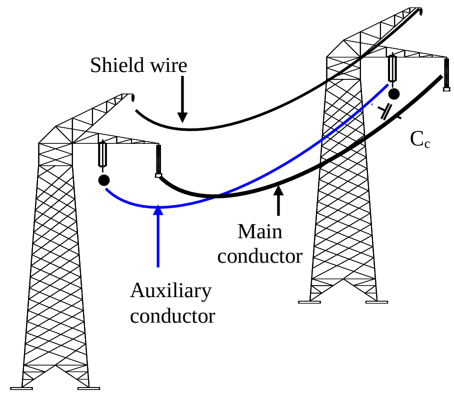

Fig. 18 Capacitive method: basic model illustration

Considering the case of Cahora-Bassa-Apollo HVDC transmission system which is a classical twelve pulse converter; the voltage is 500 kV and the load current is 1800 A. Assuming the auxiliary wire is L = 1000 m long situated at D = 4 m away of the main line. Taking into consideration the other geometrical parameters (r_1 and r_2) of the conductors the capacitance between two parallel wires can be computed to be 5.89 nF.

Because the main harmonic of the ripple voltage is the elevens (550 Hz) the resonant inductance will be L_r = 14.39 H. Fig. 19 shows the ripple voltage, the primary and secondary voltages of the transformer. From the above situation results in a 600 W power delivered into a 100 Ω load.

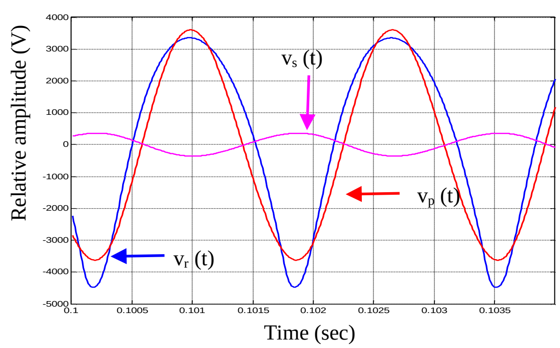

Fig. 19 Simulation results for capacitive coupling

A.2 Inductive coupling

This method is also using the harmonic content of the current on the transmission line [5]. If the same case as above (*A.1*) is considered, the main harmonic component which can produce inductive coupling is of 13.5 A amplitude and 550 Hz frequency.

The magnetic field created by this current can induce an emf into a pick up coil placed next to the HVDC line (Fig. 20). The emf ($\mathcal{E}$) induced in one turn could be:

$$\mathcal{E} = \omega \times I \times a \times 10^{-7} \times \ln \frac{D^2 + b^2}{D^2} \tag{5}$$

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 the length of the coil extended over more than two towers.

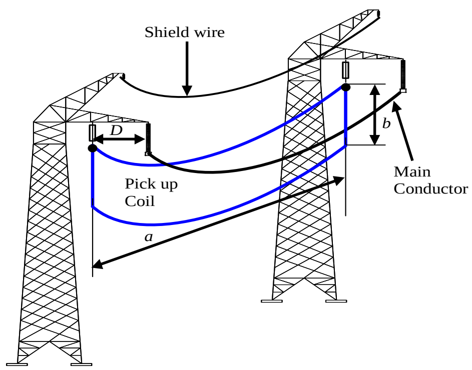

Fig. 20 Inductive method illustration

B. Methods based on parametric modulation

The trend for the future HVDC is a ripple that will be reduced more and more. 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:

$$\mathcal{U}_e = \frac{1}{2} C \times V^2 \quad (6)$$

$$\mathcal{U}_m = \frac{1}{2} L \times I^2 = \frac{\Phi_m^2}{2 \times L} \quad (7)$$

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

$$p_e(t) = \frac{\partial}{\partial t} \mathcal{U}_e = \frac{V^2}{2} \times \frac{\partial C}{\partial t} \quad (8)$$

$$p_m(t) = \frac{\partial}{\partial t} \mathcal{U}_m = \frac{I^2}{2} \times \frac{\partial L}{\partial t} = \frac{\Phi_m}{L} \times \frac{\partial \Phi_m}{\partial t} \quad (9)$$

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

B.1 Inductance modulation

The main idea of this method [9] 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 [10]:

$$L = 4 \times \pi^2 \times 10^{-7} \times a^2 \times n^2 \times b^{-1} \times K \quad (10)$$

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

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

$$b = b_o \left[1 + \varepsilon \sin(\omega t)\right] \quad (11)$$

with ε being the amplitude of the relative variation. Because the variation $\boldsymbol{\varepsilon}$ is much smaller then unity and using equation (11), the instantaneous available power can be written as:

$$p_m = 2 \cdot \pi^2 \cdot 10^{-7} \cdot a^2 \cdot n^2 \cdot I^2 \cdot K \cdot b_o^{-1} \cdot \varepsilon \cdot \omega \cdot \cos(\omega t) \quad (12)$$

Let us consider a coil with a diameter of a = 2 m. If for the conductor with isolation it is considered a diameter of 5 cm and the number of turns n = 25 then b could be 0.625 m. For $2a/b$ = 3.2 the parameter K is 0.4145 [10]. According to (10), the inductance of this coil would be L = 26.2 mH. If the relative amplitude of movement is $\boldsymbol{\varepsilon}$ = 0.01 and the frequency is 1 kHz, then the estimated power in the magnetic field, for a main current of 2000 A could be 167 kW.

Fig. 21 shows the flux into the air-coil and Fig. 22 shows the voltage that could be generated due to the variable part of this flux.

In order to get a significant output power 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 [11].

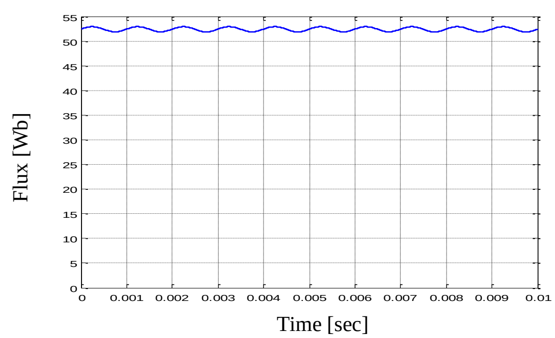

Fig. 21 Flux through coil

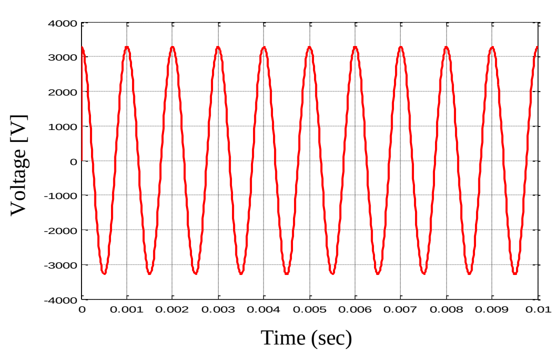

Fig. 22 Voltage generated

B.2 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 (see Fig. 23). It can be defined as a flux modulation; if an observer is placed in the frame/coil reference system, then the flux appear as variable.

The emf induced into the (wind-powered) rotating coil has the same expression as (9). 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 kilowatts.

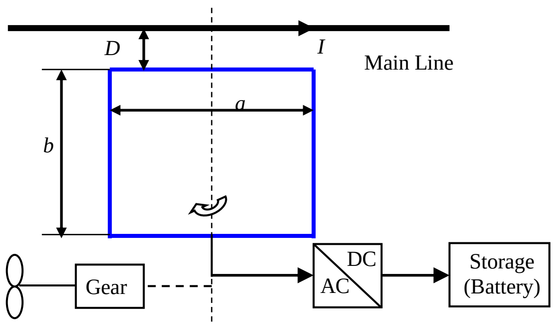

Fig. 23 Inductive method-wind power illustration

B.3 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:

$$\Phi_m = \frac{I_p N_p}{\mathscr{R}} \tag{13}$$

where I_p is primary dc current, N_p 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):

$$\mathscr{R} = \frac{g}{\mu_o A_r} \tag{14}$$

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.

This principle is old [12], but not much has been published about its application to tapping power. A basic example under investigation is as shown in Fig. 24. The prime mover could be wind or an electric motor. As can be noticed from figure 21, the flux is a function of rotor angle, though it is function of time.

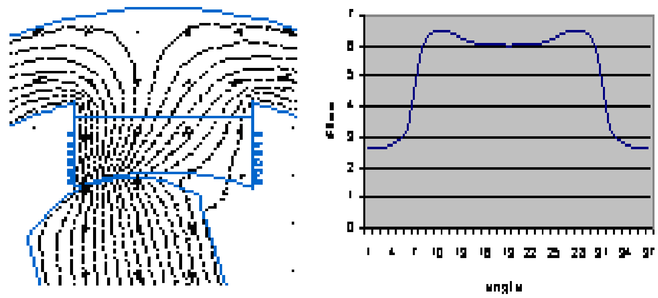

Fig. 24 Variable reluctance: basic model

V. Comments On Tapping Methods From HVDC Lines

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 higher power tapping, but 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, which constitute a major focus of on-going research, have the main advantage of minimum intrusion on the transmission line, and in case of fault the protection of the main line is not influenced. However, it has a main drawback of lower amount of power tapping. But in the remote and very poor areas, few kilowatts of electric power can bring the main advantage of modern civilization such as communication – access to radio and tv at least.

This paper has presented a wide range of tapping methods from HVDC transmission line. The methods could be classified into series and parallel connected. The parallel connected method (voltage source inverter) is more economical both with respect to installed cost and operating efficiency when the power rating of the tap is of the same order of magnitude as the main receiving station [4].

On bipolar lines, large parallel tap should be installed on each line in order to keep a balanced current system and they should be part of the central coordination of the transmission line. Smaller taps drawing currents under the main station current margin do not need central coordination [4].

In order to keep a balanced voltage on bipolar lines, the series taps should be connected on both lines. One main station would control the system dc pole voltage, the other main station would control the dc current and the series tap would control the differential voltage [15].

From the design point of view, the series-connected taps must be rated for the same transient over-currents as the main station to handle fault currents or commutation failure; the parallel taps must be rated for the same voltage as the main converter but with small dc currents. Still, a small parallel tap could be exposed to transient over-currents of twenty times its rated current during converter faults or commutation failure. The converter transformer, especially for the series-connected taps should be insulated for the full dc system voltage and located at ground potential or on the platform itself if a separate isolation transformer were used [4].

The reliability of the tapping on HVDC is a major problem. The reliability assessment should include the protection equipment, control robustness, influence of the tap upon communication and semiconductor components used for the converter. Series-connected and parallel-connected taps can be compared from the reliability point of view. Reliability can be expressed either in terms of frequency and duration of power interruption due to equipment failure or in terms of the availability of power transfer capability [4].

However, new emerging technologies are becoming available in higher power ratings making small taps feasible both technically and economically for serving isolated loads and week ac networks.

VI. Future Directions

A few of the methods presented for tapping from HVAC and HVDC systems have been implemented and have served to greatly further advance the technology. Laboratory prototypes and real life pilot project implementation of other methods are similarly necessary to further or complete the studies of many of these methods. Most of the real life implementation efforts so far have been aimed at tapping only relatively small amount of powers. The bigger challenge, however, may be in being able to tap significantly greater amount of power. This is especially so for applications in trans-national and trans-continental power pools. However, constraints inherent in most of the methods proposed that are limiting increase in capacity mainly lie with materials, particularly insulation, and the challenging technical requirements of protection. Principles governing tapping from HV lines are well established as presented in section III of the two papers. What is evident, especially for HVDC tapping, is that there are a great number of other possible methods for tapping that are yet unexplored. There are two of these that are being researched in Pretoria (TUT); one of them is looking at tapping through flux modulation and the other through inductance modulation.

The issue of ability for reversible power flow of a tapping method is an area of interest that has not received much attention. This characteristic is useful in applications where power injection is also a requirement. Often in connecting to a power pool reversible power flow is an advantage that enables surplus power to be injected into the pool when required rather than tapping from it. It will be economical if the same system employed for tapping power also does power injection into the grid.

The influence of tapping on the main network requires more attention. Exhaustive studies relating to effects of tapping on such issues as the steady-state, transient and dynamic performance behavior of the grid, power flow, protection, security, contingency plans, and reliability. Such studies are in fact essential to establishing the limits of the tapping, other effects or benefits thereof, and defining the governing rules and regulation for this action.

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VIII. Biographies

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