Power Supply from the High Voltage Transmission Lines *Part 1: Conditions, Principles and Tapping from HVAC Lines*

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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. This paper therefore reviews, in two parts, the state of the art of tapping 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. The companion paper completes the study, by presenting the part two of the work.**

***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

High voltage transmission lines are known to traverse rural and remote areas, most of which do not have the benefits of electricity supply. These areas are without electricity supply sometimes because it is not economical to extend the distribution network to them, either due to the fact that the cost of doing so is just unbearable or they do not have the population density cum economic activities which justifies it. Sometimes some of these areas do have the economic potential yearning for electricity supply for them to blossom but are simply too distant to the nearest distribution substation for them to be easily connected, albeit the transmission network is passing through them.

Another problem in these areas is the supply of power to the telecommunications establishments, a problem that is presently being met partially, where feasible, by means of solar power generation. Whereas a power supply from the grid of few kW would meet many of this kind of needs for areas where solar or diesel generation or any other alternative is not feasible.

Apart from the foregoing the solution for addressing power supply inadequacies round the world seems now to be through trans-national and trans-continental transmission corridors, from which nations that are either too poor economically and financially, or poor in resources, or that wish to reduce their dependence on nuclear power, can connect to tap to meet their electrical power needs. In this case where the amount of power to be tapped or injected into the corridor is substantially significant it is presumed that the conventional transmission substation shall be employed. However, where the need is to supplement an existing supply within an amount not exceeding the distribution network level special technologies may be required for tapping power from a high voltage transmission line.

Some techniques for tapping electric power straight for consumption from the high voltage transmission lines may not be new; it is however only in recent times, about the past three to four decades, that they began to be considered as a serious alternative for energy supply [5, 10]. The capacitive divider technique, for example, 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]. Gururaj and Nandagopal [10] in 1970, and Berthiaume and Blais [11] in 1980 explored the use of the overhead ground wire as a means 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 and also unlock potential for bringing more users into the electric fold which otherwise would not be economically justifiable. Tapping from HVDC was recognized shortly after the first dc transmission systems evolved [12]. All 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.

Some of these methods have indeed left the laboratory, and have been implemented and are reported to be functioning satisfactorily. It is known [6, 7] that a 3-phase, 1.5-MW, capacitive divider system has replaced the conventional Rivière-Ste-Anne substation of Hydro-Québec in 1994. It is reported also that capacitive divider technique has been installed in Mexico and South America [6]. Even though tapping from HVDC was recognized early after its inception, it was not until 25 years later that the first applications of multi-terminal dc transmission became a commercial reality [2], [14]. The tapping of the mono-polar Sardinia to Italy HVDC line on Corsica was the first commercial installation of HVDC tapping [13]. 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 [14]. 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. As elucidated above these techniques are not only for tapping power for the electrification of rural and remote areas, or powering telecommunication equipments in these areas, but are, in some cases, applicable for tapping power from trans-national or trans-continental transmission corridors for national electricity supply.

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 reviews, in two parts, the state of the art of tapping 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. The companion paper completes the study, by presenting the part two of the work. The focus in this part is 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 multiterminal 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. Requirements For Small Power Tapping

Tapping may be treated as an intrusion, be it direct or indirect, on a well configured, nicely operating, and stable transmission line, and then analyzed for its effect on the steady-state, transient and dynamic performance of the grid particularly with respect to power flow, protection, security, and contingency plans. Tapping few kilowatts of electricity may appear in the first instance not to pose a serious treat to the stability operation and security of an HV transmission line; however this can only be ascertained through an exhaustive study. Such a study is 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.

So far studies have shown that, unlike HVAC, 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. Some authors [1 - 3] have attempted to define the requirements for a small power tapping station for DC as:

- Any fault in the local ac network must not disturb the operation of the main HVDC transmission line [3].
- Control of the tapping station should not interfere with the main system control; i.e. the tap control has to be strictly local [1], it should not be dependent upon telecommunication links to the main stations [3].
- Characteristics of the feed into the local ac network through the tapping station are to be similar to those offered by a synchronous generator with regard to fault currents. This will enable standard protection and earth fault location systems to be used in the ac network [3].

Of importance, nonetheless, are certain technical and economic considerations that must be taken into account when determining tapping as a viable option for a particular application, and when planning the tapping (particularly defining the performance specification). Bahrman et al [2] discussed some of these for the HVDC system under the headings: main circuit design considerations; control, protection and communication; dynamic performance; and reliability assessment.

III. Principle Of Power Tapping From HVAC 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:

$$P = \frac{\partial}{\partial t}\mathscr{U} \neq O \qquad (1)$$

where $\mathscr{U}$ is the energy in the 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 (Fig. 1); E_a is the electric field along the surface of the conductor and B_θ is the flux density in point P situated at distance r from the centre of the conductor.

After applying Maxwell laws to this situation, then the power density in the magnetic field and electric field respectively for the point P at distance r can be written [4] as:

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

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

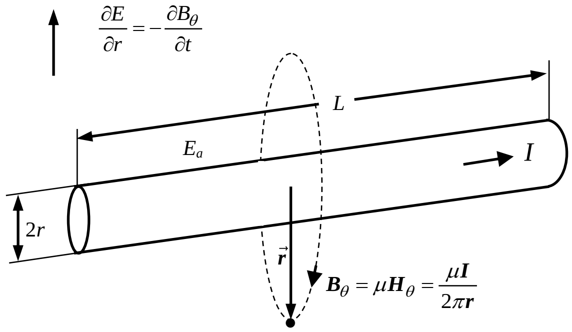

Fig. 1: An illustration of the Poynting vector for a conductor

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 indirect or non-contact methods.
- Capacitive methods and inductive methods

IV. 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.

A. 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 Fig. 2.

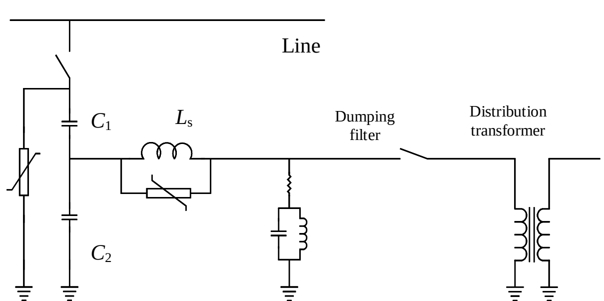

Fig. 2 Capacitive divider

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

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

The output voltage in no-load (V_o) will be:

$$V_o = V_H C_1/(C_1+C_2) \tag{5}$$

where V_H is the transmission line voltage, C_1 and C_2 are the capacitors divider.

One advantage of this method is the capacitive reactive power added to the transmission line, thus improving the voltage regulation; the reactive power (Q) can be expressed as [5]:

$$Q = (P_o/k)(V_H/V_o - 1) \tag{6}$$

where P_o is the output power, V_o is the output voltage of the capacitive divider and k is a parameter with values between 1 and $\sqrt{3}$ [5].

Fig. 3 shows the energizing behavior; Fig 4 shows the influence of sudden drop of the transmission line voltage and Fig. 5 shows the influence of the shut-on/off upon the divider voltage.

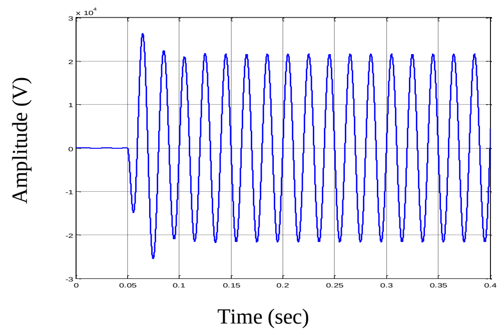

Fig. 3 Energizing behavior

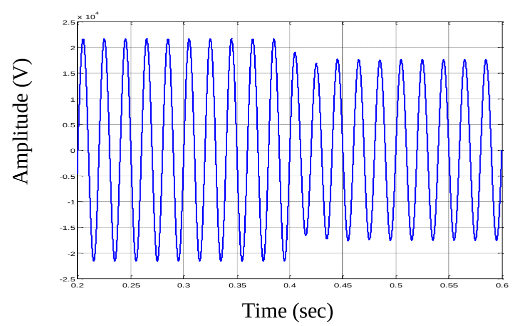

Fig. 4 Influence due to sudden drop of the V_H

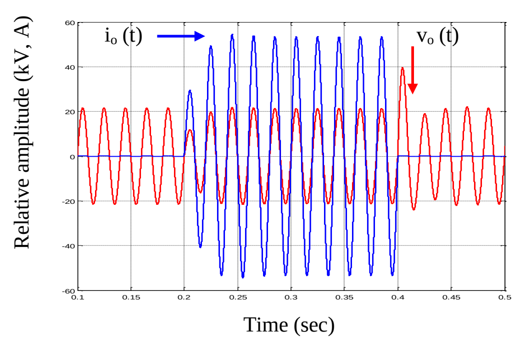

Fig.5 Influence of the load shut-on/off

The capacitive divider substations have been installed in Canada [5], [6], [7], Mexico and South America [6] as well in South Africa [8], [9]. During development, various problems have aroused.

- Ferroresonace

The phenomena of ferroresonance appear due to saturation of the transformer(s) used for distribution. The solution was to design and install the damping filter which presents high impedance for the operation frequency and a short circuit for all other frequencies [5]. Such a filter is the subject of the US Patent 05343381.

- Overvoltages

During the commissioning of the substation (installed by IREQ) connected in a large loop, the substation – at one stage – found itself at the end of the line when the loop was open and the mean voltage increased over the maximum threshold [5]. The solution was to modify the capacitor C_1 thus reducing the output voltage by a total of 6%.

- Disconnecting

An incident on the HV system, during the commissioning of the above substation, revealed that the disconnector part of the circuit switcher was not necessarily opening during switching operation so was no visible break. The control was therefore modified to force disconnector to open every time following of the switcher [5].

- Protection

Fuses are useless on the feeder because the do not operate fast enough. The same may be said of other fusses that are either too large or too slow. Care is therefore needed to coordinate the protection and fault detection methods [5].

- Non-linear load influence

During testing the Meru substation in South Africa, a large variable speed drive supplying a 1.5 MVA pump was connected. Immediately, a severe voltage instability or sub-synchronous resonance has appeared. Fig. 6 shows the ten hertz amplitude modulation of the capacitive divider output voltage [9]. Since this modulation is at 10 Hz, which is very close to the human eye sensitivity for flicker, the voltage variation were clearly seen in the fluctuation of the fluorescent lights both for customers and Meru control room.

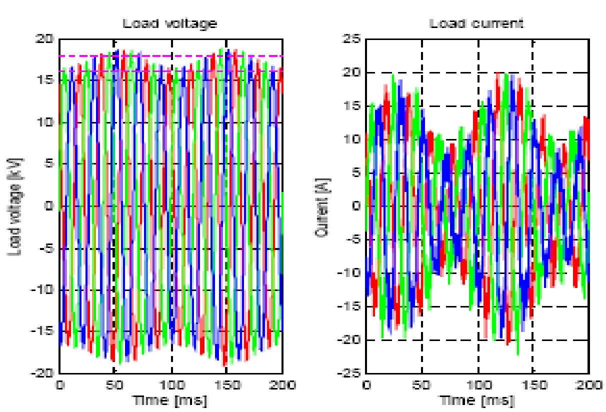

Fig. 6 Meru output voltage and current

These results seem to indicate that further studies are required before this technology can be widely applicable to embrace all types of industrial loads [9]. The issues of design considerations and non linear performance mitigation or control are particular examples.

B. Isolated shield-wire method

The method is based on isolating the shield wire for a certain length [10], [11], [15, 17]. Then the capacitance between lines and this isolated shield wire is further used to draw energy from HVAC. Same as for capacitive divider, a series inductance is inserted between coupling capacitor and step - down transformer and the circuit is tuned for the industrial frequency, which could be 50 or 60 Hz depending on the standard frequency.

B.1 Passive method

The passive method was firstly studied in South Africa by Leigh Stubbs. The result of this study was a model with a power rating of 17 kVA, which was built near ESKOM's Apollo substation on the Kendal Minerva transmission line in 1992 [15]. In this solution, shown in Fig. 7, the value of the series inductor and other elements of the system should be implemented very closely to the calculated values; any change in parameters can shift the system from resonance.

This method was further studied and improved on in a 50 kVA model [16], where a three-phase induction motor was introduced to run in the background to reduce the variation of the load and make the tuning conditions fairly constant.

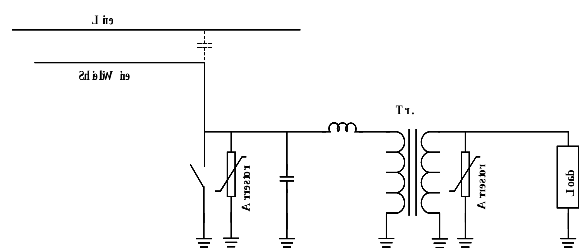

Fig. 7 Isolated shield wire - passive method

B.2 Active method

The passive method presented some problems such as resonant frequency shift, ferroresonant oscillations and voltage regulation. In this new method developed at I.R.E.Q. Canada [6] & [17] is based on a self-regulated variable reactor. "Induction Variable Auto-Controlée à Entrefers" (IVACE) is a self-regulated variable reactor consisting of passive components: magnetic cores with air gaps, four windings and a bridge rectifier. Originally designed for use as a static var compensator, it is now used by Hydro-Quebec near its 735 kV transmission lines as new voltage regulator for the overhead-ground-wire supply system for utility's microwave stations in remote areas [17].

In this method the initial series inductor plus transformer were replaced by a "self-regulated reactor with air gap”, see Fig. 8. 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. There are 30 systems (15 substations with 2 systems each, one operating, the other used as a standby) operating this way and feeding 20-50 kW.

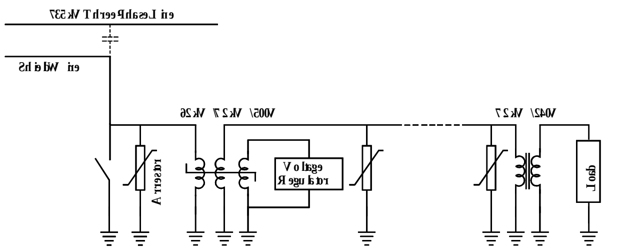

Fig. 8 Isolated shield wire – active method

B.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. Given capacitance between the two parallel wires of length L with the conductor’s radius of r_1 and r_2 and situated at the distance D [22]:

$$C = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot L}{\ln\left(\frac{D^2}{r_1 \cdot r_2}\right)} \tag{7}$$

The short-circuit power that can be extracted is given by:

$$P = \omega \times C \times V^2 \tag{8}$$

For example: if a 16 m long antenna (L) is mounted 0.30 m (D) below a 120 kV/50 Hz conductor line (V) and if both conductors are of 1 cm radius, then the maximum power capability, according to (8) is 705 VA. If losses are further considered, it means that a 50 W load, such as a radio transmitter, receiver or a neon light could be supplied [6]. The last application is widely used by EDF in France to light transmission lines [6].

C. 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, however, that this method presents a major advantage of reactive compensation, to improve voltage regulation of the line, in addition to feeding loads, if placed between two classic inductive substations.

V. Inductive Methods

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.

A. Current transformer tapping method

One of the inductive methods is based on current transformer (CT). Normally, current transformers are designed to measure currents. With a different approach to design, however, a CT can be made to handle a reasonable output power. The generic model is as presented in Fig. 9. Consideration has to be given to physical realization, however.

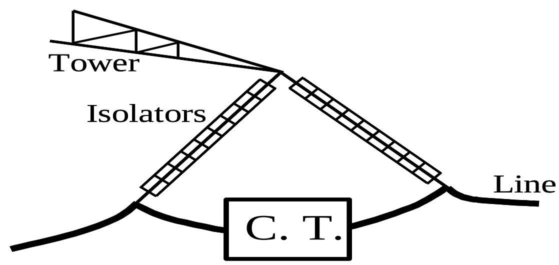

Fig. 9 Current transformer method

B.1 Current-to-voltage conversion with dc storage

In this method [18], the input current that feeds a CT is converted into voltage via a boost converter and by means of 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 as shown in Fig. 10. 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.

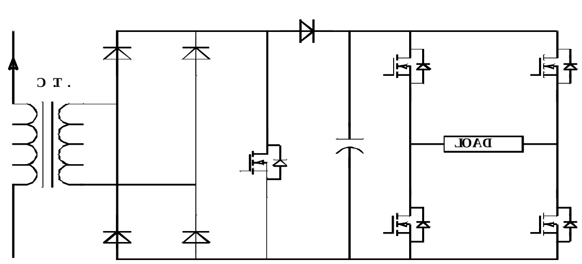

Fig. 10 Basic diagram of current-to-voltage with dc storage – CT-based tapping method

B.2 Direct alternating current to alternating voltage conversion

In this method [19], [20], a new design of the power CT permits a direct conversion of alternating current into alternating voltage using an additional secondary, which by means of PWM switching modulates the magnetic flux and thus the output voltage of the main secondary coupled to the load via a low-pass filter (see Fig. 11).

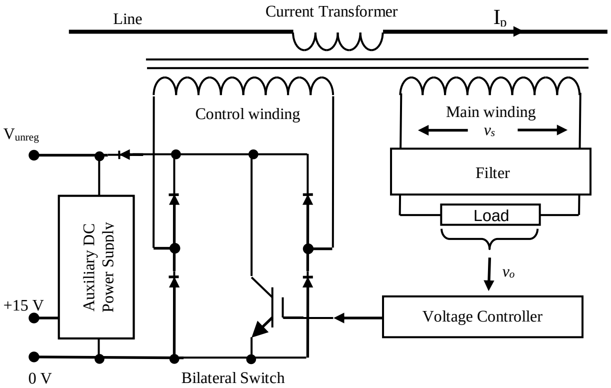

Fig. 11 Direct ac current to ac voltage conversion-basic circuit

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.

The load secondary (v_s) is designed for a voltage higher than the required output voltage. 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 follows a sinusoidal shape. In this way a 50 Hz output-voltage amplitude-modulated is obtained [19]:

$$v_s(t) = (1-k)V_s \sin\omega_p t + V_s \sum_{n=1}^{\infty} \left\{ \frac{\sin nk\pi}{\pi n} \left[\sin(\omega_p + n\omega_c)t + \sin(\omega_p - n\omega_c)t \right] \right\} \tag{9}$$

After the low pass filter, the output voltage will be:

$$v_o = (1-k)V_s \sin\omega_p t \tag{10}$$

where k is the duty cycle.

Fig. 12 shows the output voltage versus input current for a control signal with 30 percent duty cycle.

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.

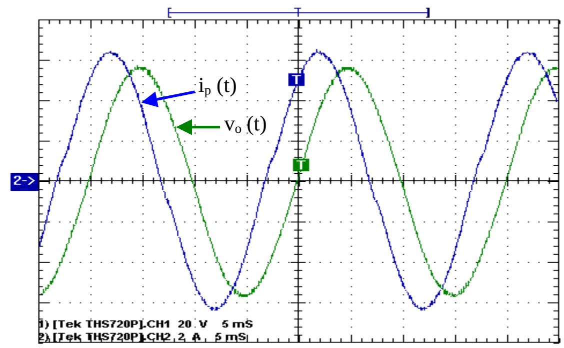

Fig. 12 Input current & output voltage for 30% duty cycle

C. Air-core transformer method

If a passive 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 [21], 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 (Fig. 13).

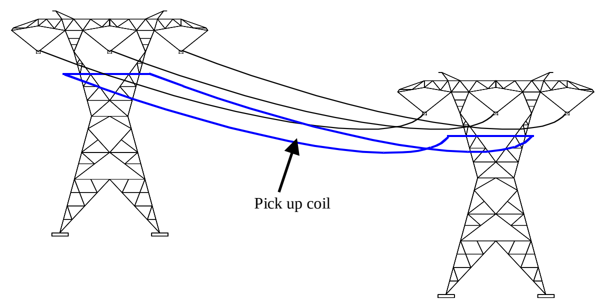

Fig. 13 Air-core transformer method

This method is discussed further in [4]. It has been validated in the laboratory on a reduced scale model. The induced voltage into the pick up coil is given by [21]:

$$E = \omega \times I \times N_t \times a \times 10^{-7} \times \ln \frac{(D_L + b/2)^2 + D^2}{(D_L - b/2)^2 + D^2} \tag{11}$$

where I is the current in the transmission line, N_t is the number of turns in the pick up coil, b and a are the width and length of the coil, D_L is distance between the conductors of the transmission line and D is the distance between the plans of the lines and coil.

Fig. 14 shows the output voltage and input current for a three-phase small scale model and that emf induced in the pick up coil 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.

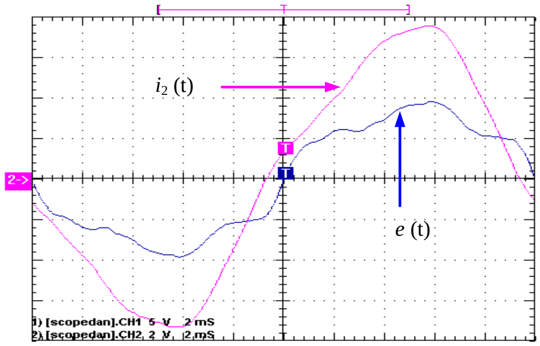

Fig. 14 Output voltage versus input current

Taking into consideration the safety and mechanical constrains of a 440 kV transmission line with the distance between lines D_L = 8.5 m, the recommended position of the coil is horizontal at D = 3.5 m below the lines plane installed between two consecutive towers which gives an approximate coil length of 300 m, and having a width of 9 m. Considering the amplitude of the line current of 1500 A and with the above geometrical parameters, the estimated amplitude to emf will be 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.

D. Tapping Using Power Voltage Transformer

Power voltage transformers (PVT's) are an adaptation of the standard VT used as a measurement instrument. The German company Ritz has developed PVT's as a method of obtaining low voltage from HV lines [23], [24].

PVT's can be connected to supply single phase or three phase power, of up to 300kVA. The output voltage can be a single phase of 220V, or 3.6kV to 7.2kV if a small reticulation distance is to be covered before consumption [23], [24]. The transformer requires special design, particularly with respect to insulation between the primary and the secondary.

E. 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 intervention only one tower is necessary, 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.

VI. General Discussion On Tapping From HVAC

This paper has presented a wide range of tapping methods from HV transmission line both ac and dc. The tapping methods from the HVAC are much more used due to the simplicity of the principles. Although some of these methods are relatively old, still new methods for tapping from ac line emerged.

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 on the hardware and protection problems.

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.

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