Energy Harvesting Approaches For Wireless Sensor Nodes In High Voltage Direct Current Systems

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***Abstract*—Power distribution systems are very complex. For this reason, they are quite prone to failures. Therefore, it is inevitable for the operators of such systems to monitor the health status of the system in real time. Wireless sensor nodes are important tools to support this demand. However, every node needs a certain amount of energy. To prevent costly maintenance, those nodes best should not depend on any battery inside. One approach to face this challenge is to equip the nodes with energy harvesters. While this is a well solved task in High Voltage (HV) alternating current (AC) installations, for HV direct current (DC) systems the problem is not quite solved. In this paper novel approaches towards efficient energy harvesting in HVDC are presented and challenges towards implementations are faced.**

I. Introduction

The Internet of Things (IoT) and its implementation in industrial, infrastructure, and consumer applications is seen as a huge emerging market and the next step in the ongoing industrialization process of modern societies. Also for applications in power generation and distribution systems the IoT turns out to generate huge benefits for the operators. Distributed wireless sensor networks are able to provide measurement data from many sensor nodes all over the electrical energy infrastructure including power plants, substations, transmission lines, distribution grids, and end consumers' house holds [1]. The gathered data will allow operators to identify and monitor suboptimally used capacities, power quality, energy efficiency, loads, and excess generated power in real-time and consecutively drive actuators and initiate actions in the process control center or in the sensor nodes themselves to more efficiently use all components of the smart grid. Although up to 300 days of operation with batteries can be achieved in Smart Grid applications this still requires maintenance more than once per year of every single sensor node [2]. Only autonomously powered sensor nodes harvesting energy from their ambient surroundings can provide a sufficient amount of energy over long term deployment with little to no required maintenance [3]–[5]. There are many different ways to harvest energy from environmental sources [6]. They include solar, thermal, flow of matter, mechanical and electromagnetic sources as well as activity-based and physiological human sources. The achieved energy densities range from few μW to several mW per cm^2. For smart grid applications, especially, the electro-magnetic fields around AC power lines caused by the alternating current being transported on the lines are used with either capacitive or inductive energy harvesting methods since these are easy to use, reliable and provide high power density. Recent research projects like WSAN4CIP and ASTROSE have shown viability of both technologies in demonstration projects [7], [8]. Unfortunately, the electro-magnetic fields around a DC power line are static on a macroscopic observation basis. Therefore, energy can not be harvested as easily as in AC systems. In this paper some proposals to circumvent this problem using various physical aspects will be discussed in Section II. It will be shown, that the proposed methods face the problem of very low voltage U output of the energy harvester, while the power is not limited. Two solutions to boost the voltage U will be provided in Section III. Section IV provides an overview on open and planned research activities in this field, while Section V concludes the work.

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II. Proposed Basic Energy Harvesting Concepts

In the following some ideas towards novel energy harvesting approaches to be used in HVDC systems will be described.

A. Tapping the electrical line to grip voltage

The method to be discussed here involves electrically tapping the blank HVDC line at two distinct points, e.g., one meter apart from each other, as illustrated in Fig. 1a. Usually, overhead lines are blank cables. Tapping them is physically possible in a very simple manner. As there is a certain current I flowing through the line, which has a certain ohmic resistance R, a voltage U can be measured between the two tapping points. The amplitude of the voltage U depends on the actual resistance R and current I only. In realistic systems, approximately $I = 500\text{A} \sim 2500\text{A}$ are flowing inside the line, while the specific resistance ρ per meter and area depending on the material can be looked up in public tables. Typically, electrical lines consist of copper ($\rho_{cu} = 1.70 \cdot 10^{-2}\Omega \cdot \frac{\text{mm}^2}{\text{m}}$), aluminum ($\rho_{al} = 2.65 \cdot 10^{-2}\Omega \cdot \frac{\text{mm}^2}{\text{m}}$), and steel ($\rho_{steel} = 1 \cdot 10^{-1} \sim 2 \cdot 10^{-1}\Omega \cdot \frac{\text{mm}^2}{\text{m}}$). Based on those numbers, the relevant combination of materials used in practical systems, and typical cross-sectional areas A of the installed electrical lines, the dropped voltage U along a chosen length l of the considered part of the electrical line can be calculated as

$$U = R \cdot I = \rho \cdot \frac{l}{A} \cdot I. \tag{1}$$

It can be calculated, that for typical systems between two electrical tapping points being $l = 1\text{m}$ apart a voltage $U = 30m\text{V} \sim 150m\text{V}$ can be gripped. A practical installation may be $l = 20\text{cm}$ long. Therefore, typically a voltage $U = 5m\text{V} \sim 30m\text{V}$ will be available using this approach. To be mentioned in this context is, that while the voltage U is limited due to physical constraints, the potentially gripped power P is not limited assuming a typically needed power consumption of a wireless sensor node (meaning, the overall transmitted power via the electric line is much higher than the power consumed by the wireless sensor node). Unfortunately, the amplitude of the voltage is not high enough to power a wireless sensor node directly. For this reason, any kind of voltage boost mechanism has to be added to the system, which is not a trivial task for the mentioned very low voltage levels. However, this is not impossible as will be shown in Section III.

B. Varying magnetic field caused by load and environmental temperature variation

In the same context a different power source could be considered for the same type of system. This idea profits from the fact, that the transmitted power through the energy transmission system is never exactly constant. Given a fixed physical installation, varying transmitted power leads to varying currents I flowing in the electrical line, again causing the magnetic field around the line to change. This fact allows to use similar approaches known from AC power lines to extract energy via an inductive transformer, as shown in Fig. 1b. Of course, the harvested energy is much lower compared to the steady state approach used in AC installations. As discussed in [9], the magnetic flux density B close to the electrical line is of magnitude $B = 10m\text{T}$. Assuming a diameter $d = 5\text{cm}$ of the electrical line, one induction loop around this line will cover an area $A_{loop} = 2\pi \frac{d}{2} = 15.7\text{cm}^2$. For practical implementations a certain distance to the electrical line may be needed. Therefore, in the following $A_{loop} = 16\text{cm}^2$ may be assumed. If the loop is oriented perpendicular to the electrical line, which is a reasonable assumption in practical installations, a magnetic flux

$$\phi = B \cdot A_{loop} = 10^{-2}\text{T} \cdot 16 \cdot 10^{-4}\text{m}^2 = 1.6 \cdot 10^{-5}\text{Vs} \quad (2)$$

may calculated. Generally, the induced voltage U_{ind} can be calculate by solving

$$U_{ind} = -\frac{\text{d}}{\text{d}t}\phi(t). \quad (3)$$

This means, the faster and bigger the change of the magnetic flux ϕ is, the higher is the induced voltage U_{ind}. For the sake of simplicity, we assume linear changes of magnetic flux ϕ only, allowing to estimate typical values for U_{ind} by calculating

$$U_{ind} = -\frac{\phi(t_1) - \phi(t_2)}{T}, \quad (4)$$

where the observation period $T = t_2 - t_1$ specifies the period where the magnetic flux is changing. Exemplarily, if ϕ changes by 1% of the maximum $\phi_{max} = 1.6 \cdot 10^{-5}\text{Vs}$ within $T = 10^{-3}s$, the induced voltage in one loop will be

$$U_{ind} = \frac{1.6 \cdot 10^{-7}\text{Vs}}{10^{-3}\text{s}} = 1.6 \cdot 10^{-4}\text{V} = 0.16m\text{V}. \quad (5)$$

An actual installation may consist of, e.g., 100 loops in series. With this approach $16m\text{V}$ may be harvested. This voltage is very low, however, may be boosted to a usable range by using approaches described in Section III.

In practical systems there are various sources of fluctuations of the magnetic flux ϕ within different periods of change T. E.g., the difference of ϕ between night and day might be up to 90% of the maximum value. As, however, the period of change is very long, the induced voltage is very low, but available over a long period. On the other hand side, very small fluctuations of the magnetic flux due to

- small, however, fast load changes causing current fluctuations in the electrical line,
- temperature changes of the electrical line due to sudden wind, which is cooling the line and is causing changes in resistance of the line, which consequently changes the current flow in the line,
- any kind of malfunctions in the system causing current fluctuations,
- other undetermined effects (e.g., birds causing a short circuit) causing the fluctuation.

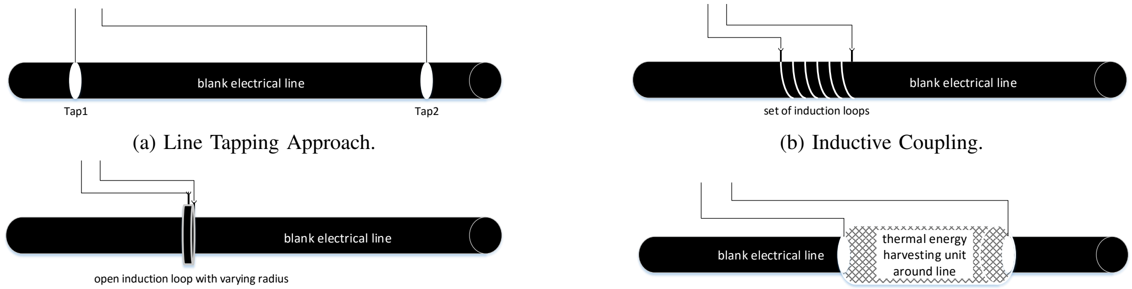
As will be discussed in Section IV the best configuration to choose is the objective of further research in this field. Although in any case the harvested voltage level is very low, using the approaches introduced in Section III allow to use the approach in practical installations. Summarized, considering the never constantly flowing current in HVDC lines at certain small sections, the magnetic field in HVDC is also never as constant as one may expect. This changing magnetic field may be used to harvest energy using well known approaches involving inductive transformers.

C. Mechanically moving coil

Derived from the method in Section. II-B a further methodology might be derived, which is based on a mechanically moving coil around the wire. The coil is constructed in a way, that surrounding wind is moving the coil like a spring in a watch. A possible setup is shown in Fig. 1c. Doing so, the diameter of the coil continuously varies. As in this way the metal of the coil is moving through the electro-magnetic field which naturally radially decreases in strength, from the coil's perspective a varying electro-magnetic field is observed. Consequently, this varying field induces a tiny voltage which again can be converted to a higher voltage using the approach described in Section III. This idea may be seen as an extension to the approach given in Section II-B. The relevant physical background and the according equations and considerations are valid as derived in Section II-B. No practical feasibility checks have been performed yet and are objective of further research as discussed in Section IV.

D. Thermal energy harvesting approach

A further source of energy harvesting might be the temperature difference on cables using thermoelectric effects with thermoelectric generators illustrated in Fig. 1d. It is well known that a conductor heats up when a current flows through it due to ohmic resistance. If a thermoelectric generator is wrapped around the cable it is possible to harvest the power of the heat flux between the warm conductor cable and the environment. The basic principle has been described in the recent past [10]. The generator can either be made of cylindrical modules, small rectangular modules that are fitted around the cable or be made of flexible material and then get wrapped around the cable itself. Between the thermoelectric generator



(a) Line Tapping Approach. (b) Inductive Coupling. (c) Mechanically Moving Inductive Coupling. (d) Thermal Energy Harvesting.

Fig. 1. Illustration of the various energy harvesting approaches.

and the cable a heat transmitting material should be placed to achieve a large heat flux. Outside the thermoelectric generator a circular heat exchanger with the surrounding air made of a good heat conducting material should be placed to achieve a maximum temperature difference over the thermoelectric generator. The maximum temperature of a common power line cable is 80°C during normal operation and can reach up to 170°C in overload cases. High temperature cables can even operate at up to 210°C. A conservative assumption of the maximum ambient temperature is 35°C which coincides with cases when the maximum cable temperatures are reached. This leaves a usable temperature difference of $\Delta\mathrm{T} = 45\mathrm{K}$ for a normal case which results in an energy density of more than $3.5 \frac{m\mathrm{W}}{\mathrm{cm}^2}$ in the thermoelectric generator if the heat can be efficiently transferred away from the generator to the environment. Unfortunately, this high temperature difference is not constantly available due to variable load in the conductor cables and forced convective cooling by the wind. Realistic temperature differences can be in the range of 10K or even lower for longer times which reduces the harvesting power density drastically. But the temperature can also be a lot higher and is not constant along a transmission line. Thus, the location of a thermoelectric generator can be important in order to achieve high temperature differences.

The length of a thermoelectric generator along a transmission line can be conservatively estimated as follows: assuming an outer diameter of the cable of 4cm, a power requirement of the sensor node of $100m\mathrm{W}$, a DC-DC converter efficiency including other losses of 40% and an energy harvesting density $3500 \frac{\mu\mathrm{W}}{\mathrm{cm}^2}$ at $\Delta\mathrm{T} = 30\mathrm{K}$ the length of the thermoelectric generator would need to be 5.7cm for constant operation. When assuming a power density of $3.5 \frac{\mu\mathrm{W}}{\mathrm{cm}^2}$ at $\Delta\mathrm{T} = 5\mathrm{K}$ a constant operation would require a 1000 times longer generator. But when the sensor node only operates (sensing and sending) every 15 minutes for 5 seconds and an energy storage efficiency of 80% is assumed, the generator would need to be only 6.3cm long even at very low temperature differences. A larger conductor diameter of 6cm would reduce the estimated lengths by about 2cm. These rough calculations show that a sensor node harvesting thermal energy from the power line itself would be feasible when integrated in sensors with a similar form factor as those already existing today. In any case thermal energy harvesters are comparably expensive. The smaller the installation is, the better it is for the provider concerning costs. The boost approach discussed in Section III used for energy harvesting implementations presented in the previous sections allows to install a tiny thermal energy harvester minimizing the overall system costs.

III. Methods to boost voltage

The energy harvesting approaches introduced in Section II suffer from a significant problem. All methods provide only very low voltage levels at the outputs of the harvester. This voltage is too low to use classic voltage boost converters, as the threshold voltage is far below the switching voltages of known bipolar or CMOS implementations. Nevertheless, it has been shown, that for input voltages $U_{in} \geq 20m\mathrm{V}$ simple boost converters can be built [11], [12]. Commercially, e.g., a chip (LTC3108) containing this technological solution is available from Linear Technology [13]. For some applications this might be a good solution. However, first of all it has been derived in Section II, that for cost sensitive implementations the voltage might even be below this threshold. Second, implementations using this chip require a non-negligible sleep current due to the additionally needed passive components, which might be critical for some applications. Therefore, at this point a new approach will be introduced here, which circumvents this drawback.

The main concept is based on a parallel arrangement of capacitors as illustrated in Figure 2. Each capacitor can be charged to the maximum of the available voltage level delivered by the energy harvester. afterwards, the capacitors are connected in serial by a CMOS based switching arrangement to sum up the low voltages to a usable amount. The problem here is, that directly from the harvested voltage levels the switching process can not be initiated, as the switching level of the harvesters does not exceed the switching level of any known bipolar or CMOS structure as discussed before. Therefore, a second stage needs to be developed, which is capable to perform this task. The following two methods might be used. A first possible implementation involves a switching logic which is powered by a pre-charged energy source providing high voltage in the region of $3\mathrm{V} \sim 24\mathrm{V}$ depending on the specific desired implementation. The main message to provide here is, that only the voltage has to be within a certain range to provide electrical switching capability, while just a negligible amount of energy is needed to start the switching process due to the nature of the CMOS based implementation. The sleep current of this implementation is far below the one needed for the LTC3108 based approach. In one cycle of the operation, all of the storage capacitors are connected in parallel and are charged with the voltage provided by the individual energy harvester.

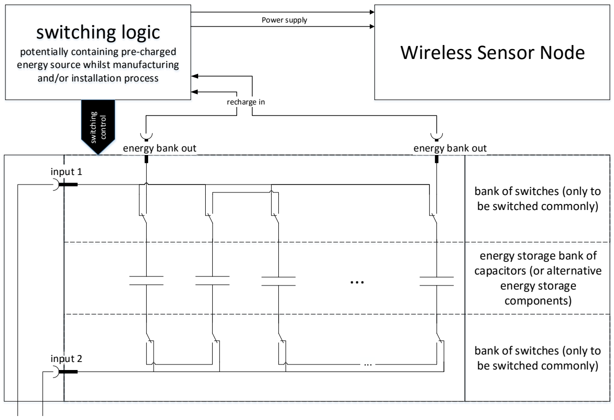


Fig. 2. System Architecture of the Overall Sensor Node System Including Voltage Boost Unit.

Here the voltage is very low, while there is no limitation of the power being able to be gripped and stored. In a second phase of operation, the capacitors are switched to all-in-series mode by the switching logic. Now, the capacitors are no longer connected to the energy harvester, but to the switching logic and consequently also wireless sensor node logic. In this mode, the power stored in the multiple capacitor bank is used to power the wireless sensor node transmission and logic part, and as well recharges the switching logic power supply. As soon as the power transfer to the switching logic power supply and also the actions to be done in the connected wireless sensor node are done, the switching logic idles the state of the energy bank from in-series mode to parallel mode and the operation mode starts from the first phase again. An alternative to the pre-charged energy source for the switching logic is to use very cheap low power solar cells. The difference and advantage compared to using solar cells for the whole power supply is, that the power harvested from the solar cell may be very low, as the switching logic does not need high power as mentioned before. It is well known, that also traditional Light Emitting Diodes (LEDs) provide energy at the output when exposed to light. Of course, LEDs are not as efficient as solar cells as they are manufactured for a different purpose. However, they are available in high volumes at low price and might fulfill the needs of the described system as well. Basically, with this proposed hybrid approach, high availability of the sensor nodes power consumption can be guaranteed as long as the power transmission system is in operation at a lower price compared to, e.g., solar panel only powered approaches. In real systems a combination of the capacitor bank and the LTC3108 may be used.

IV. Further Research Activities

Further activities are planned to discover realistic scenarios for the presented harvesting approaches, decoupled from theoretic investigations. Final implementations will deliver the most suitable solution which is additionally the most reliable and also most cost effective. A measurement campaign in conjunction with a data collection based on profile analysis from power providers will be performed. The outcome will be the basis for a decision on which magnetic flux fluctuations within which time frames may be expected, and how big realistic temperature differences will be in which geographical regions. Those findings will be the basis for planning the optimum implementation of prototypes, which will be tested online in the field afterwards.

V. Conclusion

In this paper several approaches for energy harvesting in HVDC systems have been introduced. As the harvested voltage levels turn out to be very low, various methodologies have been proposed being able to boost the latter to a useful threshold. The proposed methods are basically easy to install, cost effective, and robust. Therefore, those are promising candidates for future installations. Finally, to provide optimal solutions, further research activities in this field have been outlined.

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