Accepted for publication. DOI: 10.1109/WoW.2018.8450923
© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Challenges for Wireless Power Transfer in Building-Integrated Photovoltaics

Ben Minnaert
KU Leuven
DRAMCO
Dept. of Electrical Engineering
Ghent, Belgium
ben.minnaert@kuleuven.be

Simon Ravyts
KU Leuven, Dept. of Electrical Engineering - Electrical Energy and Computer Architectures
EnergyVille, Genk, Belgium
simon.ravyts@kuleuven.be

Johan Driesen
KU Leuven, Dept. of Electrical Engineering - Electrical Energy and Computer Architectures
EnergyVille, Genk, Belgium
johan.driesen@kuleuven.be

Nobby Stevens
KU Leuven
DRAMCO
Dept. of Electrical Engineering
Ghent, Belgium
nobby.stevens@kuleuven.be

***Abstract*—Building-integrated photovoltaics is steadily entering the market. It allows for solar cells to be an integrated part of the building itself, contrary to installing the photovoltaic modules onto the finished building. Unfortunately, several challenges such as the creation of thermal bridges and moisture intrusion hinder the rapid development of building-integrated photovoltaics into a mainstream mass product. Wireless power transfer systems could solve some of these challenges and contribute to an accelerated use of building-integrated photovoltaic solar cells. In this work, the advantages of wireless power transfer to building-integrated photovoltaics are presented. The different issues and technological challenges are highlighted, and possible solutions are proposed.**

***Keywords*— building-integrated photovoltaics, inductive coupling, inverters, photovoltaic systems, solar power generation, wireless power transmission**

I. Introduction

The photovoltaic (PV) market worldwide is booming. In general, 'building attached photovoltaics' is applied [1], i.e., the solar panels are added to an already finished building. For example, solar cell modules can be installed above or onto an existing roof or wall. Building integrated photovoltaics (BIPV) differs from this approach: in contrast to building attached photovoltaics, the solar panels of BIPV are an integral part of the building component itself. Their function is not only the production of electricity, but they also serve as a structural element of the building, replacing a conventional building element. In this way, they provide a significant reduced cost in terms of material costs and electricity [2].

BIPV is steadily entering the market, with an installed power capacity of 2.3 GW in 2015 [2]. It has successfully been applied for [1]:

- pitched roofs (solar tiles and shingles),
- flat and curved roofs (flexible PV laminates),
- windows and skylights (semitransparent solar cells, often also functioning as shading systems),
- curtain walls and
- external building facades (cladding PV systems).

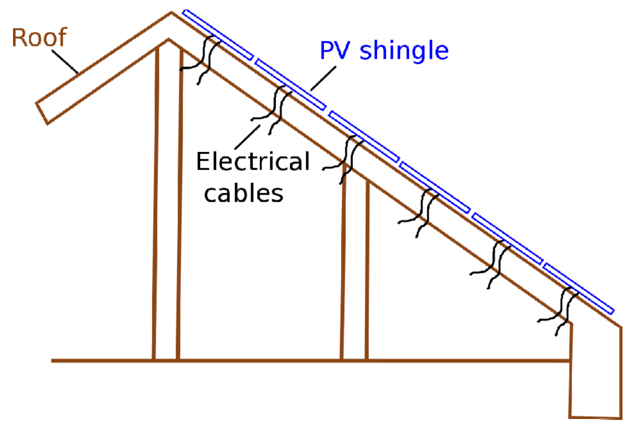

Fig. 1. Schematic overview of BIPV roof shingles: electric cables breach the thermal envelope of the building

About half of the current BIPV applications are realized in façades and one third on roofs [2]. The market potential is immense and is promoted by several governments. For example, France, Germany, Italy, Spain and Switzerland have executed feed in tariff systems [3]. However, to date, BIPV still remains a niche market with limited turnover [2-5].

Several drawbacks inhibit the rapid development of BIPV into a mainstream technology. By applying wireless power transfer (WPT), some of these disadvantages could be solved.

In this work, we present the possible advantages of applying WPT to BIPV and highlight the different challenges. As far as we know, this is the first work that discusses the application of WPT into BIPV.

II. Advantages of WPT in BIPV

A building-integrated solar module, whether it takes the form of a window, or a roof shingle, is located at the exterior of the building envelope. It contributes to realizing the physical barrier between the unconditioned outside and the conditioned inside environment. It protects the inside climate of the building against unwanted water, heat, light, noise or air. Unfortunately, a prerequisite for any BIPV system is the wired electrical connectivity from the solar panel to the inside of the building. This implies two consequences.

First, the electric cables are breaking the thermal envelope of the building by the creation of thermal bridges. This reduces the building insulation and creates unwanted heat loss or gain. As an example, consider Fig. 1 which shows a representation of BIPV roof shingles. The separate shingles are connected with each other (usually in different strings) by electric wires which have to be connected to the inverter in the interior of the building. These connections breach the thermal envelope of the building. Thermal bridges are created and impact the energy requirements to heat or cool the building. This can result in thermal discomfort. Notice that thermal bridges are not restricted to roof shingles, but apply to all BIPV applications, for example, the frame of a window covered with semitransparent solar cells will have to be pierced for the electric connections.

Second, the perforation of the electric cables through the insulation potentially causes condensation and water penetration. This results in moisture intrusion, as well for the building as for the BIPV installation, leading to a faster degradation of the PV cells, and thus a shorter lifetime of the BIPV system [6, 7].

By installing a WPT system, the produced energy from the solar modules can be transferred wirelessly over the building envelope, without the creation of any physical piercings. In this way, a nearly perfect thermal, air, and water tightness can be created, resulting in a better conditioned indoor environment and a longer lifetime of the total system.

Moreover, BIPV systems with WPT could allow for an easy "plug-and-play" mechanism for installation. Nowadays, discussions arise over who is responsible for the BIPV construction elements: the construction worker or the electrician. In practice, construction workers are now educated to correctly handle the different wiring schemes of WPT. A plug-and-play system would facilitate the set-up of the system.

Aside from the plug-and-play and improved insulation, WPT would also contribute to solving the problem of reduced efficiency caused by, a.o., partial shading [8]. We elaborate this matter in the following section.

III. Challenges for the Practical Implementation of a WPT System in BIPV

A. *WPT technique*

We now discuss the challenges for implementing a WPT design into BIPV. The first question that arises is the choice of the WPT technology. A wide range of possibilities exist to realize WPT. Fig. 2 shows an overview of the most promising technologies, which can be divided into WPT by acoustic or by electromagnetic means.

The acoustic power transfer technique uses pressure or acoustic waves to transmit energy [9] and is targeted to long-range energy transfer and for powering electronic devices inside sealed metal containers. At this point, the technology is still at its infancy stage.

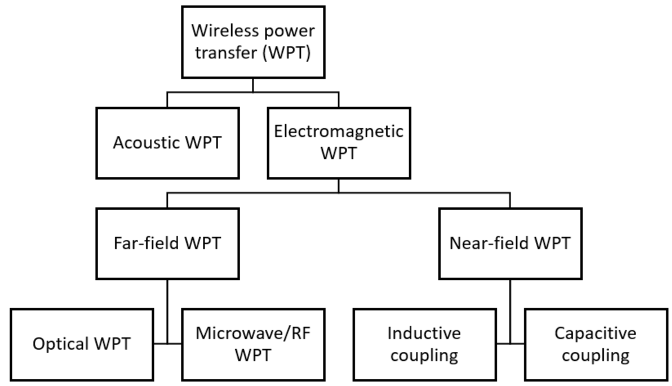

Fig. 2. Classification of the most promising WPT technologies

The other wireless power transfer techniques utilize the energy in electromagnetic waves to transfer power. Two categories can be distinguished: far-field (or radiative) and near-field (or non-radiative) techniques.

The far-field techniques are targeted towards long transmission distances. The first one, optical WPT is a highly directional technique. It uses frequencies near the visible region of the spectrum to transfer power by converting electrical energy into a laser beam, which can be captured by a photovoltaic cell to convert the energy back to electricity [10]. The other far-field technique is microwave/radio-frequency (RF) WPT. It applies electro-magnetic waves in the range from 300 MHz to 300 GHz for the transfer of power [10].

Since the main applications for both acoustic and far field WPT are long range, they are not appropriate for the implementation of WPT into BIPV. However, near-field techniques focus on short-range applications and are therefore possible candidates for BIPV. They use either the magnetic field (inductive coupling) or the electric field (capacitive coupling) to transfer power wirelessly.

The most promising near-field technique that has already entered as well the consumer as the industrial market is inductive wireless power transfer (IPT) [10]. This technique uses a varying magnetic field to transfer energy from a transmitter to a coupled receiver (Fig. 3). By Ampere's law, an alternating current (AC) through the transmitter coil generates a time-varying magnetic field. This field passes through the receiver coil, where it induces an alternating voltage by Faraday's law of induction. A resulting AC current is created in the receiving coil. In this way, wireless power transfer is realized from a transmitting coil to a receiving coil. The magnetic flux that passes through the surface area of the receiver coil is a measure for the amount of energy transfer. Thus, the closer and better aligned both coils are, the higher the power transfer. Working frequencies typically range from a few tens of kHz to several MHz.

A wide range of applications already apply IPT, as well low power applications (e.g., portable electronics and household devices such as electric toothbrushes, smartphones, smart watches and wearables), as high power applications well above kilowatt level (e.g., automated guided vehicles, robots, and electric vehicles).

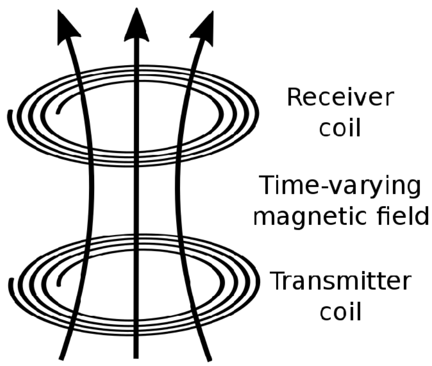

Fig. 3. The principle of inductive coupling: a transmitter and receiver coil are coupled through a time-varying magnetic field to realize wireless power transfer.

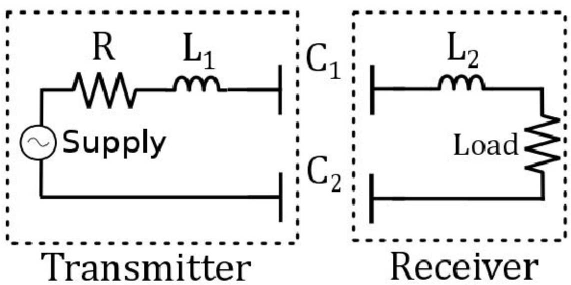

Fig. 4. A general capacitive power transfer system transfers power from a supply wirelessly to a load by applying an alternating voltage at the plates of the capacitors C_1 and C_2. The other plates of the capacitors, at a certain distance of the first plate, capture the energy of the generated electric field for the generation of current in the receiver. Series inductances can be applied to increase the efficiency of the system.

Another near-field technique is capacitive wireless power transfer (CPT) that uses the electric field to transfer energy from a transmitter plate to a receiver plate (Fig. 4). It uses one plate of a capacitor to generate an electric field by an alternating voltage. The other plate of the capacitor, at a certain distance of the first plate, captures the energy of this electric field for the generation of current [11].

However, CPT has not yet significantly entered the market and its technology is not as maturely developed as IPT. Moreover, in general, the operating frequency for CPT is higher than for IPT, in the range of several MHz to tens of MHz. For these reasons, an IPT system is preferable. The losses due to the inductive WPT link itself will be limited, on the one hand because an almost perfect alignment is possible between transmitter and receiver coil, and on the other hand because the distance between both coils can often be restricted to a few mm.

B. Frequency converters

Photovoltaic solar cells generate DC, which has to be converted to AC for connection to the electrical grid. This conversion can occur at several locations [12, 13]. For a centralized configuration, the PV modules are connected in series and parallel arrays and the DC/AC conversion is realized by a single central inverter (Fig. 5a). For a string (Fig. 5b) or multi string (Fig. 5c) configuration, each series string of PV modules has its own DC/AC or DC/DC inverter, respectively. None of these configurations are applicable to WPT, since a prerequisite of any near-field WPT system requires AC. In order to transfer the DC electricity generated at the solar modules wirelessly, it has to be converted to AC at the solar panel itself. Therefore, a micro inverter topology is preferable (Fig. 5d) since the DC is transformed to AC at each separate module itself.

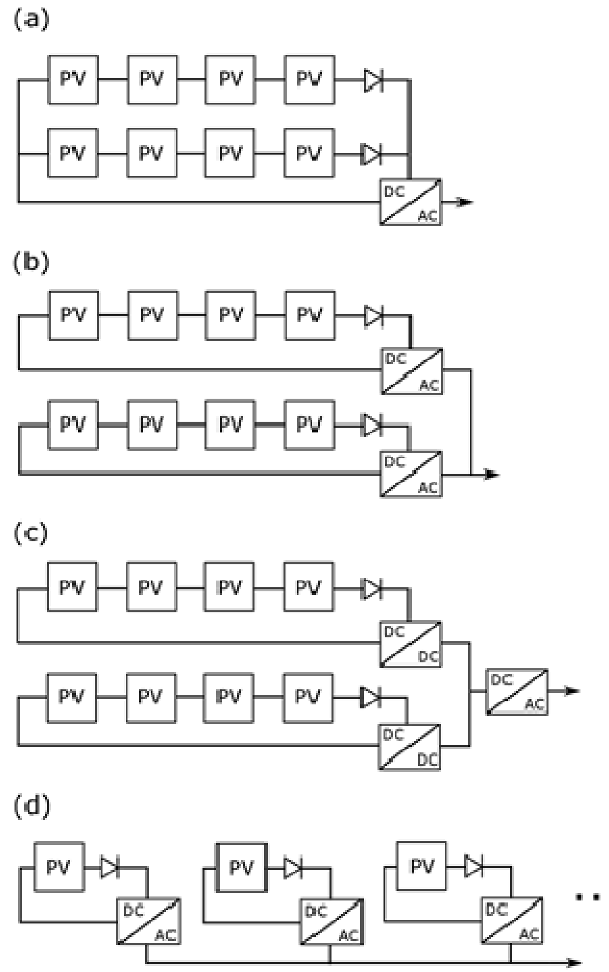

Fig. 5. (a) Centralized configuration (b) String configuration (c) Multi string configuration (d) Micro inverter configuration

A second issue is the difference in frequency necessary for WPT and the frequency of the electrical grid. For WPT, frequencies in the range from 100 kHz to several MHz apply, thus much higher than the 50/60 Hz of the grid. This implies the addition of an extra micro inverter to the system. Fig. 6 gives a schematic overview of the necessary conversions.

First, the DC is converted to high frequency AC in order to allow the WPT. After the wireless transfer, the high frequency AC is either converted to low frequency AC to distribute to the grid, or to DC again (which can be converted to low frequency AC to connect to the grid). All these conversions result in

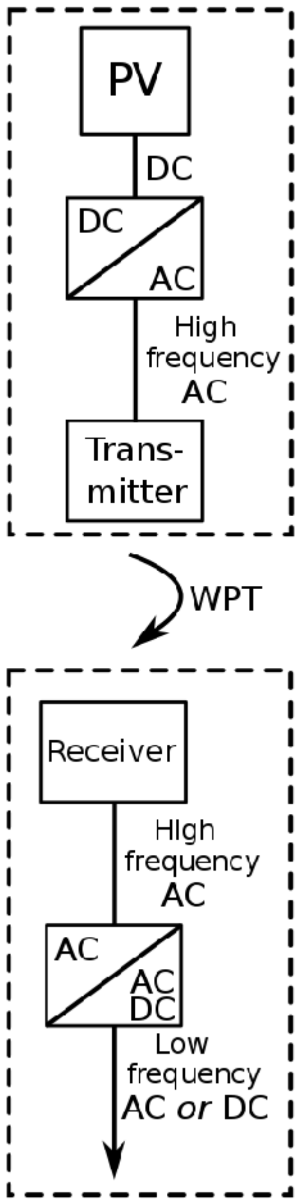

Fig. 6. Schematic overview of the necessary frequency conversions for a WPT system implemented in BIPV

efficiency losses (e.g., the Enphase M215 micro inverter converts DC to AC with an efficiency of 96.5% [14]).

There is another reason a micro inverter topology is preferable: if WPT is ever to enter the market, it will only be possible if the WPT system is compatible with current systems. For example, a BIPV setup should be able to modularly accept as well a photovoltaic window implemented with WPT, as a traditional photovoltaic window without WPT. This implies the development of a modular WPT system, integrated into the BIPV component itself. A modular inverter lowers the efficiency, but it allows for a plug-and-play solution that can possibly reduce the design and installation cost of the BIPV system [15]. Moreover, it contributes to solving the problem of reduced efficiency caused by partial shading or module mismatching [12]. Indeed, a photovoltaic plant requires maximum power point tracking to optimize energy capture. However, if parts of the solar modules are shaded, not equally illuminated, or showing different performance (e.g., due to ageing phenomena), the location of the maximum power points on the current-voltage characteristics of the different modules is different. It the inverter is centralized and not modular implemented per module, this results in a significant energy loss. A micro inverter system increases the energy-yield in turn reducing the payback time of the installation, especially for a multifaceted BIPV setup. It also protects the entire plant for malfunctioning solar modules: whereas one defective module can significantly influence the yield for a centralized or (multi)-string topology, a micro inverter topology avoids this problem.

DC/AC inverters are inherently large devices and it is not always straightforward to have enough space available to implement them into an existing BIPV solution, especially with regard to the height. Typically, the total height of the micro inverter, including casing, should be limited to 40 mm in order to fit into the frame [15]. However, if the structure is designed from the start with WPT in mind, it should be possible to provide the necessary room for the WPT system. For example, [16] developed a micro invertor for BIPV applications with dimensions 127 mm x 76 mm, and a very limited height of only 3 mm. The micro inverter operates at high frequency and at power levels that are required for BIPV applications.

A non-negligible heat is produced by the converters. Thus, the reliability of the electronics might also be an issue, in particular since also the solar cells achieve high temperatures. This can lead to a faster degradation, while on the other hand, the value of electronic components is temperature dependent. For example, a variable temperature changes the value of the resonator capacitance in an IPT circuit, and thus the resonant frequency of the WPT circuit. However, a dynamic tuning mechanism [17] can solve this issue. The reliability can be increased by adding sensors (temperature, voltage,…) to monitor the system and dynamically adjust its performance. In other words, it will be necessary to integrate a self-regulating solution for each module. In certain applications, cooling can be achieved by introducing air flow [5] or by passive cooling, e.g., the frame of a curtain wall or BIPV window. The reliability and the requisite for long lifetime of the converter is in particular of importance since the electronics will be embedded in a small BIPV frame. Replacing the device in case of malfunction will not be straightforward, if possible at all.

The BIPV converter will necessarily also need a wide operating range [15]. It needs to be able to work for a wide range of voltages and current since it must be able to efficiently convert the solar light into useful power, for as well different illumination conditions, as for different types of solar cells. (monocrystalline, polycrystalline, or amorphous cells), each with their voltage-current characteristics.

Finally, the input current ripple of the converter should be small in order to avoid oscillations around the maximum power point of the photovoltaic installation [15]. High current ripples lead to lower power conversions for the incident solar light to electricity.

IV. Conclusions

Applying WPT to BIPV has distinct advantages, such as the reduction of thermal bridges and moisture intrusion. However, it also introduces novel challenges. To date, there is no scientific literature that describes this application. In this work, we performed a first step by listing the advantages and challenges, providing different solutions. We proposed applying a micro inverter topology with IPT as WPT technology. Implementing modular micro inverters will not only increase the compatibility for market integration, but also contribute to solving the problem of reduced efficiency due to partial shading or module mismatching.

References

[1] Heinstein, P., Ballif, C. and Perret-Aebi, L.E., 2013. Building integrated photovoltaics (BIPV): review, potentials, barriers and myths. Green, 3(2), pp. 125-156.

[2] Tabakovic, M., Fechner, H., Van Sark, W., Louwen, A., Georghiou, G., Makrides, G., Loucaidou, E., Ioannidou, M., Weiss, I., Arancon, S. and Betz, S., 2017. Status and outlook for building integrated photovoltaics (BIPV) in relation to educational needs in the BIPV sector. Energy Procedia, 111, pp. 993-999.

[3] Shukla, A.K., Sudhakar, K. and Baredar, P., 2017. Recent advancement in BIPV product technologies: A review. Energy and Buildings, 140, pp.188-195.

[4] Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., Yao, R., Shao, L., Essah, E., Oliveira, A.C., del Caño, T., Rico, E. and Lechón, J.L., 2017. A key review of building integrated photovoltaic (BIPV) systems. Engineering Science and Technology, an International Journal, 20(3), pp. 833-858.

[5] Jelle, B.P., 2015. Building integrated photovoltaics: A concise description of the current state of the art and possible research pathways. Energies, 9(1), pp. 21.

[6] Quintana, M.A., King, D.L., McMahon, T.J. and Osterwald, C.R., 2002, May. Commonly observed degradation in field-aged photovoltaic modules. 29th IEEE Photovoltaic Specialists Conference 2002, pp. 1436-1439.

[7] Yang, R.J., 2015. Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies. Automation in Construction, 51, pp. 92-102.

[8] Ikkurti, H.P. and Saha, S., 2015. A comprehensive techno-economic review of microinverters for Building Integrated Photovoltaics (BIPV). Renewable and Sustainable Energy Reviews, 47, pp. 997-1006.

[9] Roes, M.G., Duarte, J.L., Hendrix, M.A. and Lomonova, E.A., 2013. Acoustic energy transfer: A review. IEEE Transactions on Industrial Electronics, 60(1), pp.242-248.

[10] Lu, X., Wang, P., Niyato, D., Kim, D.I. and Han, Z., 2016. Wireless charging technologies: Fundamentals, standards, and network applications. IEEE Communications Surveys & Tutorials, 18(2), pp.1413-1452.

[11] Minnaert, B. and Stevens, N., 2017. Conjugate image theory applied on capacitive wireless power transfer. Energies, 10(1), p.46.

[12] Liu, B., Duan, S. and Cai, T., 2011. Photovoltaic DC-building-module-based BIPV system—Concept and design considerations. IEEE Transactions on Power Electronics, 26(5), pp. 1418-1429.

[13] Enphase, 'Enphase M215 Microinverter', datasheet, Nov. 2016.

[14] Erickson, R.W. and Rogers, A.P., 2009, February. A microinverter for building-integrated photovoltaics. In Applied Power Electronics Conference and Exposition. 24th Annual IEEE APEC 2009, pp. 911-917.

[15] Ravyts, S., Dalla Vecchia, M., Zwysen, J., Van den Broeck, G. and Driesen, J., 2018, February. Study on a cascaded DC-DC converter for use in building-integrated photovoltaics. IEEE Texas Power and Energy Conference (TPEC), 2018, pp. 1-6.

[16] Qiang, H., Huang, X., Tan, L., Ji, Q. and Zhao, J., 2012. Achieving maximum power transfer of inductively coupled wireless power transfer system based on dynamic tuning control. Science China Technological Sciences, pp.1-8.