APPLYING WIRELESS POWER TRANSFER FOR CURTAIN WALL BIPV ELEMENTS

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ABSTRACT:
In building-integrated photovoltaics or BIPV, the solar cell module not only functions as energy source, but also acts as a structural element of the building. Curtain wall elements are abundantly applied in the construction sector and are particularly suitable for BIPV applications. Unfortunately, electrical cables must connect the outside solar module to the inside inverter, breaking the thermal envelope of the building. This creates a number of problems such as the creation of thermal bridges, condensation and water ingress. By means of inductive wireless power transfer, the energy from the solar module can be transferred over the insulation to the inverter, without breaking the thermal envelope. In this work, we present a wireless prototype BIPV system, designed for curtain wall elements, that applies inductive wireless power transfer. Measurements show that the system performs adequate for variable input power conditions, a prerequisite considering irregular solar radiation. Among others, we demonstrate experimentally that having a higher load resistance increases the voltage gain, while not significantly decreasing efficiency when operating at the optimal frequency. This can reduce stress on the voltage converters.
Keywords: Building Integrated PV (BIPV), building integration, façade.

1 INTRODUCTION

New building projects are increasingly making use of building-integrated photovoltaics (BIPV). In a BIPV system, the solar panels themselves are part of the building envelope, for example as a roof, as a facade or embedded in a window. The function of the solar panel is not only the generation of electricity, but it also acts as a structural element of the building. As a building element, it provides thermal insulation (as well from winter cold as excessive summer heat), safety, and protection against sun radiation, wind, noise and water ingress [1]. BIPV modules have been successfully applied for (pitched, flat and curved) roofs, windows and skylights, curtain walls and building facades [2].

The lack of ground space in urban areas, and large availability of unused roof space facilitate the increasing popularity of BIPV [3], in particular since energy-neutral offices and buildings are incentivized, e.g. in the EU by the European Strategic Energy Technology Plan and the European Energy Performance of Buildings Directive [4].

However, roof areas on urban buildings with more than three floors may not be sufficient to generate enough electricity to meet the building's demand [5]. An extension to energy production via facades and windows, as part of the building itself, is the next logical step. Nowadays, about half of the BIPV modules are formed by curtain walls and one third by roof elements [1]. They have the great advantage that they produce clean electricity without any visual or noise nuisance.

Because a BIPV solar module replaces another element of the building, a considerable cost saving is realized [6]. The total installed capacity of BIPV solar panels continues to rise worldwide, from 1.5 GW in 2014 to 8.8 GW in 2019, and an expected value of 11.1 GW in 2020 [1,7]. The financial turnover is estimated at 9 billion dollars in 2016 [8], and 26 billion dollars expected by the end of 2022 [7].

It is a misconception that the market for BIPV is limited in comparison with the market for "traditional" solar panels. After all, 2% of the roofs in Europe are replaced annually [2]. Even if only a small part of these roofs were replaced by photovoltaic roof slates, this is a turnover market of several billion dollars.

Unfortunately, electrical cables must be routed from the outside to the inside of the building for BIPV systems. This creates a number of problems [9, 10, 11].

- Firstly, the electric cables break the thermal envelope of the building by creating thermal bridges and breaking the airtightness. This reduces the insulation of the building and causes undesired heat loss or gain. Consider for example the curtain wall with an embedded photovoltaic panel of Figure 1a: the electrical wires from the PV module outside the building connects to the inverter inside the building. These connections break through the thermal envelope and lead to thermal discomfort and heat loss.
- Secondly, the perforation of the electrical cables through the building envelope causes condensation and water ingress. The resulted moisture penetration and mold formation can cause damage, not only to the building, but also to the photovoltaic cells and BIPV installation, leading to a shorter lifespan.

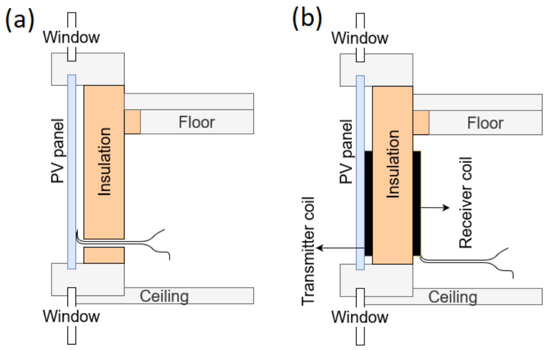

Figure 1: A PV panel embedded in a curtain wall (a) The electric wires from the PV panel at the outside to the inverter at the inside of the building break the thermal envelope. (b) Wireless power transfer over the insulation by means of coils allow for an intact thermal envelope.

In addition, BIPV installers experience two additional practical problems when installing the system:

- BIPV is by definition multidisciplinary: the installation requires coordination between different work profiles, among others, a construction worker, roofer and an electrician. The cooperation between the different profiles is not always optimal. Training construction workers to correctly install or handle the BIPV is time-consuming for the employer.
- BIPV installations are oftentimes characterized by large voltages, which create an electrocution hazard for employees in the event of incorrectly installed systems.

The issues above can possibly be solved by introducing a wireless power transfer system that transfers the energy from the photovoltaic cells wirelessly over the building envelope:

- A wireless energy transfer system eliminates the need to drill holes through the thermal building envelope. An almost perfect thermal, air and water tightness is created, which results in a better conditioned indoor environment and a longer lifespan of the total system.
- BIPV systems with wireless energy transfer allow a "plug-and-play installation". A construction worker can install the system easier and quicker via a plug-and-play configuration, reducing the risk of errors.
- Wireless energy transfer leads to a significant improvement in safety. Indeed, the electronic components can be fully embedded in a non-conductive housing. A complete galvanic isolation exists, lowering the risk of electrocution. In addition, a fail-safe mechanism is automatically created during operation: the failure of one converter does not affect the rest of the system due to the complete galvanic isolation.
- A photovoltaic system requires maximum power point tracking to realize optimal operation. However, in BIPV applications, it is not uncommon that part of the solar modules are shaded, not equally radiated, or performing at different conditions (e.g., by fabrication variations or ageing). This partial shading or module mismatching results in different maximum power points for the different solar modules, causing an energy loss when the inverter is centralized [4,12]. The plug-and-play mechanism of a wireless power transfer system with a converter implemented per module allows for a solution; it increases the energy-yield, reducing the payback time of the installation, especially for a multifaceted BIPV system.
- The wireless transmission of electricity immediately generates a high step-up of the voltage, which can be a positive asset for the total system efficiency. Moreover, it ensures that more components of the converter are located on the interior of the house, instead of in the “hot zone” at the outside. Indeed, the photovoltaic solar modules reach high temperatures, which can be detrimental to the electronic components. More components indoors improve reliability and lifespan of the electronics.

An overview of the possible advantages and drawback of WPT implementation into BIPV can be found in [11].

In this work, we present a first prototype of a BIPV system with a wireless power transfer module for curtain wall elements. The application of a wireless power transfer system for photovoltaic solar plants was already suggested in literature [11,13], but, as far as we know, it is the first time that a practical setup is realized and measured.

2 SETUP

Curtain walls consist of a thin outer frame (typically aluminium), containing in-fills of e.g., metal, glass, plastic or stone. They are abundantly applied in the construction sector, since their simplicity and prefabrication facilitate façade installation and reduce construction costs. Usually, curtain walls are split into two parts: a window and a non-transparent part located between two adjacent floors. This last part is by several companies substituted by a photovoltaic module, resulting in a BIPV solution [14].

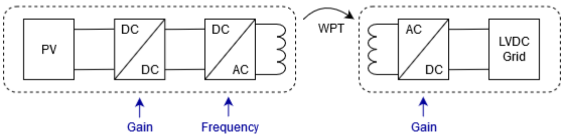

Figure 2: Schematic overview of the necessary frequency conversions for a WPT system implemented in BIPV. The indicated gain and frequency are managed by a feedback control driver.

In this work, we present the results of a prototype for the implementation of inductive WPT into curtain wall BIPV elements. Figure 2 presents a high level overview of the system. The main difference, compared to ‘wired’ BIPV, is the need to convert the DC voltage of the polycrystalline PV panel to an intermediate AC voltage which strongly influences the efficiency of the WPT link and is dependent on the instantaneous output power of the solar module. In other words, the system does not only has to take into account the maximum power point of the solar module, but also the optimal working point for WPT.

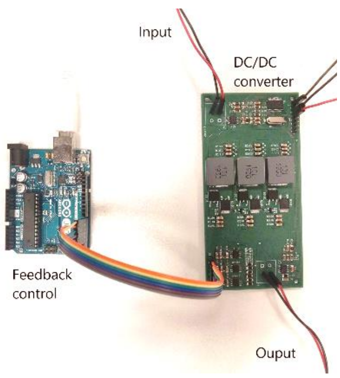

Figure 3: The prototype DC/DC converter and feedback control driver at the transmitter side.

Moreover, typical WPT applications usually have a constant input power, whereas, due to variable solar radiation, the input power for the WPT link is highly variable. Other disadvantages of WPT in BIPV include the possible vicinity of metal and the more challenging control of the system. On the other hand, an almost perfect alignment between transmitter and receiver coil can be achieved in a BIPV setup. The converter and feedback control drivers are shown in Figure 3.

The DC voltage is converted to AC (165 kHz) for realizing the inductive WPT from transmitter (primary side) to receiver (secondary side). At the receiver, the AC voltage can be converted to the required voltage for an AC grid, or, as in our setup, converted to DC for a Low-Voltage DC (LVDC) architecture.

The inductive wireless link is realized by magnetic coupling: an AC current through a transmitter coil induces an AC voltage at a receiver coil. The energy is transferred wirelessly from transmitter to receiver by the generated magnetic field. The inner and outer diameter of the planar transmitter and receiver coils are 140 mm and 290 mm, respectively. The coils have 35 number of turns and consist of 0.75 mm² (No. 18 AWG) wire. The dimensions of the coils are chosen such that they easily fit in a typical off-the-shelf BIPV curtain wall [14]. The set-up can be seen in Figure 4.

Figure 4: Set-up of the WPT prototype for curtain wall BIPV elements.

3 MEASUREMENTS AND DISCUSSION

First, we measure the coupling factor k and efficiency η of the WPT link as function of the distance between the coils. The efficiency η is defined as the ratio of the output power dissipated by the load to the input power into the system. The coupling factor k is a measure for the strength of the magnetic coupling between the transmitter and receiver coil ($0 \leq k \leq 1$).

We apply a sinusoidal 20 V peak-to-peak signal to the input at an optimal working frequency of 165 kHz and an optimal terminating load of 1.74 kΩ. Figure 5 shows the measurements results as function of the coaxial distance between the transmitter and receiver coil with air as medium. The larger the distance between the coils, the lower the coupling factor and efficiency.

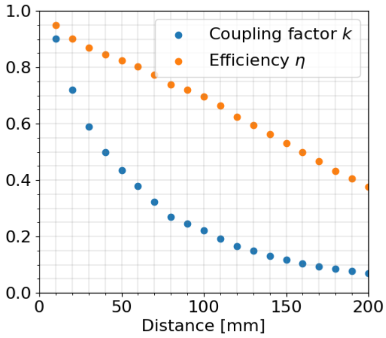

Figure 5: Measurement results of the coupling factor k and the efficiency η as function of the coaxial distance between the WPT coils.

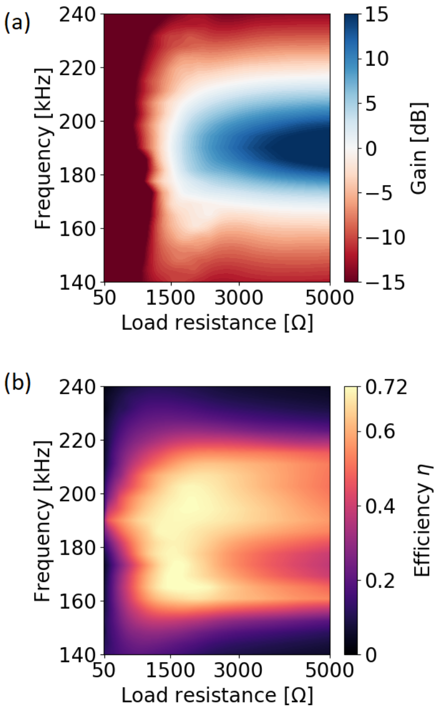

Figure 6: (a) Measurements of the voltage gain between the transmitter and receiver coil as function of load resistance and frequency. (b) Measurement of the efficiency η of the WPT as function of load resistance and frequency.

Next, the coils are positioned coaxially at 90 mm distance, a typical insulation thickness for a curtain wall. As both the voltage of the grid and the (optimal) voltage of the PV panel are fixed, voltage converters are placed at both the primary and secondary side of the wireless link. These converters are able to convert to a broad range of voltages in order to achieve maximum efficiency. For low input power, it is not required to boost the voltage of the PV module to high levels but a high step up is necessary to convert to grid voltage. At high input power, the opposite is true. Most step-up converters have dramatically reduced efficiency for increasing voltage gains, as a consequence of the larger conduction losses due to the required larger duty cycle. Operating at both low and high voltage gains thus presets a technical challenge.

Figures 6a and 6b show the measured voltage gain and the efficiency η of the wireless link as function of load resistance and frequency, respectively. A maximum efficiency is reached at an operating frequency of 165 kHz and an optimal terminating load of 1.74 kΩ. The range of 'acceptable' loads is quite broad, from 1.5 kΩ to 2.0 kΩ and higher.

For any input power produced by the PV panel, a corresponding voltage over the receiver coil can be achieved to realize maximum efficiency (Figure 7). Notice that deviating slightly from this optimal voltage might only impact efficiency to a small degree, especially when operating at a variable frequency. This does however impact voltage gain, which might both be beneficial or detrimental to the efficiency of the overall setup.

It is also apparent from Figures 6a and 6b that having a higher load resistance (and thus a higher voltage on the secondary side) increases the voltage gain of the transformer, while not significantly decreasing efficiency when operating at the right frequency. This can reduce stress on the voltage converters.

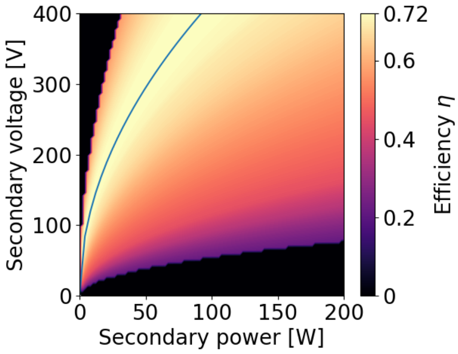

Figure 7: Efficiency η of the WPT link as function of power transferred to secondary side and voltage on secondary coil. The blue line represents the calculated operating voltage and power such that the load resistance (1.74 kΩ) and operating frequency (165 kHz) are optimized for efficiency and yield a voltage gain close to 0 dB.

The first preliminary experiments in realistic test environments were performed with a multi-crystalline Si solar panel of 1.53 m^2 (24 V). A total system efficiency (from solar panel to load) of 75 % is obtained for a distance of 4 cm between the coils. As future work, outdoor experiments and iterations of the set-up are planned to improve the operation.

4 CONCLUSION

In this work, we presented a prototype BIPV system that applies inductive wireless power transfer. Typical curtain wall dimensions and operating conditions were taken into account for the design. Measurements show that the system performs adequate for variable input power conditions, a prerequisite considering irregular solar radiation.

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