Solar Energy Harvesting Strategies for Portable Devices such as Mobile Phones

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***Abstract*—In this paper we present strategies to harvest solar energy for mobile phones. Thereby, we discuss system structures, in which mobile phones act as either active or passive devices depending on an available communication between smartphones and their solar chargers. Both design approaches have their advantages and disadvantages, which we will elaborate in more detail in our analysis. At the moment, conventional solar chargers do not meet user expectations and need substantial improvements. We aim to establish design guidelines to make solar chargers competitive with normal chargers, which are plugged into electric sockets. As a result, we achieve appropriate recharging times for smartphones on the one hand and satisfy user requirements on the other hand.**

***Keywords*—harger, mobile phones, photovoltaics, photovoltaic energy, recharge, smartphone, solar energy.**

I. Introduction

Today's mobile phones provide countless features for their users. Unfortunately, this variety on functionalities has its price. A few years back, outstanding standby and operating times were provided, while nowadays a recharge is needed every single day. Smartphone batteries cannot keep up with power demands, even though battery technologies were improved in terms of performance and capacity [1]–[3].

Small gadgets such as photovoltaic (PV) chargers for mobile phones were introduced to offer an opportunity for a recharge during a day. These type of chargers contain small photovoltaics and a battery, which can be either recharged by solar energy or electric sockets. However, energy from the power grid is predominately produced by nuclear power and fossil fuels such as coal, oil and gas [4], [5]. This takes away the meaning of solar power and its benefits as a renewable energy resource.

Fig. 1 shows an example of conventional PV chargers, which are available at the moment on the market. The size of photovoltaics is too small to produce the amount of power, which is suitable for the demand of users [1], [3], [7]–[9]. Additionally, weak electronics lower the overall degree of efficiency. Hence, current PV chargers receive negative feedbacks from their users. Research needs to be carried out to develop adaptive and intelligent PV chargers, which produce a notable amount of energy even under unfavourable and indoor environmental conditions.

Fig. 1. Example of a conventional PV charger

II. Related Work and Background

A. Energy Harvesting from Renewable Energy Resources

There are different types of energy sources, which are suitable to recharge mobile phones during a day. Table I presents output performances of various energy harvesting technologies from renewable energy resources [6]. Out of them, solar energy is the most promising one [2], [6], [8], [9]. As mentioned above, mobile phones have high power consumption. This is why we consider the use of photovoltaics, because we require a power source with a magnitude of at least several milliwatts to recharge the mobile phone significantly.

TABLE I. POWER DENISITIES OF HARVESTING TECHNOLOGIES

Harvesting technology	Usage information	Power density
Photovoltaics	indoors	20 μW/cm^2
Photovoltaics	outdoors at noon	15 mW/cm^2
Piezoelectric	inserted in shoes	330 μW/cm^3
Thermoelectric	10 °C gradient	40 μW/cm^3
Acoustic noise	100 dB	960 nW/cm^3

B. The Photovoltaic Energy Harvesting System

The basic system structure, which is shown in Fig. 2, contains a power source, in our case photovoltaics (PV cells) at the input side, and a power sink, which is for our type of application a battery at the output side. Between these two components, we have a management structure, a so called maximum power point tracking (MPPT) unit. Basically, we need this MPPT unit to obtain as much power as possible from our power source [8], [10].

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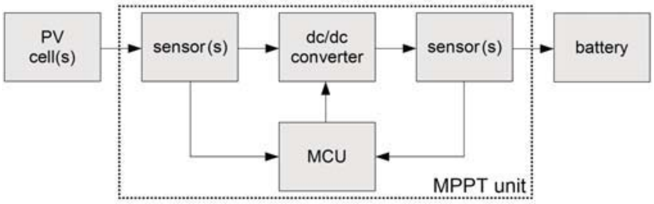

Fig. 2. Structure of a photovoltaic energy harvesting system

C. Behaviour of Photovoltaics

We choose photovoltaics as power source, because of their high power density. One disadvantage of photovoltaics lies in their strong non-linear behaviour. The I-V (Current-Voltage) curve describes the characteristic of the possible output power from PV cells; as shown in Fig. 3.

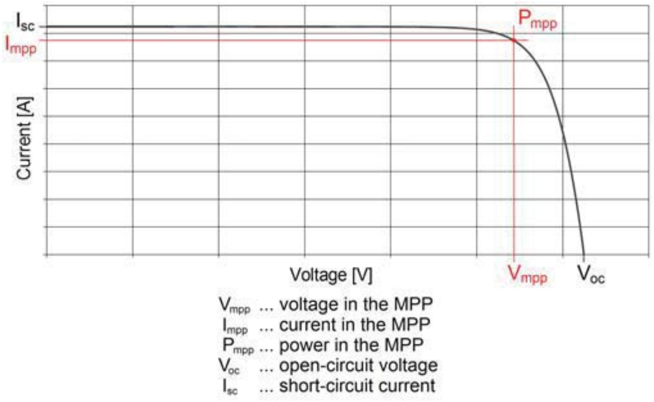

Fig. 3. Output power characteristics of a PV cell

This illustration is important, because the slope of the curve varies between different types of photovoltaics. On the entire I-V curve one point exists, in which the product of the possible output voltage and current - the output power - becomes a maximum. This point, in which the highest amount of power can be obtained, is referred as the maximum power point (MPP). Hence, the operating voltage V_{op} needs to equal the voltage in the MPP (V_{mpp}). If the operating point is set to a different voltage level, a different output power is obtained. Then, the amount of power is less than the power, which can be gained in the MPP (P_{mpp}); summarised as follows [9]:

$$\begin{cases} P_{out} = P_{mpp} & \text{if } V_{op} = V_{mpp} \\ P_{out} < P_{mpp} & \text{if } V_{op} \neq V_{mpp} \end{cases}$$

D. Necessity of a Management

Unfortunately, the MPP varies under different ambient conditions and depends on solar radiation (λ [W/m^2]) and temperature (T_c [K]) levels; as illustrated in Fig. 4. This means that the same operating voltage (V_{op}) cannot be always used to obtain the maximum output power (P_{mpp}). Thus, the position of the MPP needs to be monitored.

This task is carried out by the MPPT unit, which contains commonly voltage and/or current sensors and a microcontroller unit (MCU), which controls a dc/dc converter; as illustrated in Fig. 2. The management structure modifies the operating voltage (V_{op}) and tries to set V_{op} equal to the voltage in the MPP (V_{mpp}). For example, if the solar radiation level is 600 W/m^2 and the temperature decreases by 10 K, V_{op} needs to be changed from $V_{mpp,1}$ to $V_{mpp,2}$, as illustrated in Fig. 4.

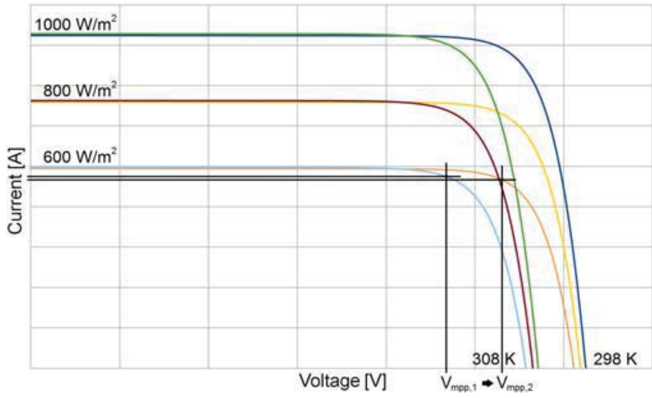

Fig. 4. I-V curve under different ambient conditions

E. The Impact of the new, dynamic Environment

There are more than 19 different approaches available to establish MPPT [10]. Depending on the requirements from the application, the approaches differ from each other for example, in the required amount and type of sensors, the efficiency, and costs. At the moment, portable devices such as mobile phones represent a new, dynamic environment for the use of solar energy. Hence, it is difficult to state, which MPPT techniques are more appropriate than other ones [9].

The choice of the suitable MPPT algorithm is difficult due to differences on the effort for the implementation. For example, MPPT algorithm *a* has a better performance than MPPT algorithm *b*, but has a higher power consumption for its hardware. Furthermore, strategy *c* can be more suitable for fast changing ambient conditions than strategy *b*. However, we can classify algorithms by factors such as [10]:

- control complexity
- power converter structure
- used sensor(s)
- convergence speed
- periodic tuning

F. System Structures of PV Chargers

In one of our previous papers, we analysed different system structures of PV chargers [9]. Moreover, the design, function and performance of conventional PV chargers were discussed. In this paper, we concentrate on the function of the mobile phone within several structures. Hence, we classify the interaction between the mobile phone and the charger into two cases. The mobile phone can act either as an active device and communicate with the PV charger, as shown in Fig. 5 or as a passive device, which means that no communication is present, as illustrated in Fig. 6.

In structure 1, the communication between mobile phones and PV chargers can be seen as a control loop. Hereby, the

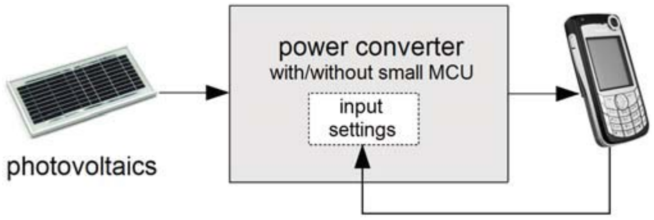

Fig. 5. Structure 1: Mobile phone as active device

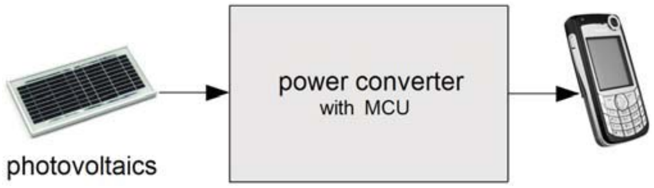

Fig. 6. Structure 2: Mobile phone as passive device

smartphone intends to maximise the power, which can be gained from the photovoltaics, by setting the parameters of the power converter. Thereby, the operating voltage (V_{op}) is alternated to match the voltage in the MPP (V_{mpp}); in the same way as it is the case within a MPPT unit. Nowadays, smartphones provide more than enough process power and memory to carry out all necessary instructions. However, the challenge lies in a suitable interface for the communication as reported in [8].

Structure 2 has the advantage that PV chargers can be used independently from mobile phones. While users are indoors, for example at their home or office, their PV charger can be outdoors and needs to be only indoors whenever a recharge of the mobile phone is needed. In general, Structure 1 and 2 provide different advantages and disadvantages to users of smartphones, which we discuss in more detail in Section IV and V.

III. Recharging Times for Mobile Phones

A. Power Consumption and Battery Size

Batteries of smartphones have capacities of about 1500 mAh [1]. However, some high-end models nowadays have batteries, which have a greater capacity than 2000 mAh to support all available features with sufficient energy [9]. The battery voltage level is typically 3.7 Volts, which corresponds to about 7.4 Watt-hours. Even though the performance of batteries has been improved over the past years, the demand on energy cannot keep up with the requirements of users and an additional recharge is needed during the day [1], [8], [9].

In future, the functionality of smartphones will continue to raise and thereby the demand on battery power [12]. However, there are limitations on the possible capacity of the battery. Nowadays mobile phones need to be recharged every day, even though the capacity of their battery has more than doubled. If energy for mobile phones is harvested, the standby time can be prolonged and energy demand from the power grid can be reduced [9].

Studies are available, which investigated the charging behaviour of smartphone users [1], [11]. Fig. 7 shows the durations during which mobile phones are recharged by the help of alternating current (AC) and universal serial bus (USB) chargers [1]. We see that the majority of users connect their devices for a short period of time, which is up to one hour. Conventional PV chargers are not capable to satisfy these requirements on charging power [9]. Hence, we concentrate on design to develop new PV chargers, which fulfil user requirements.

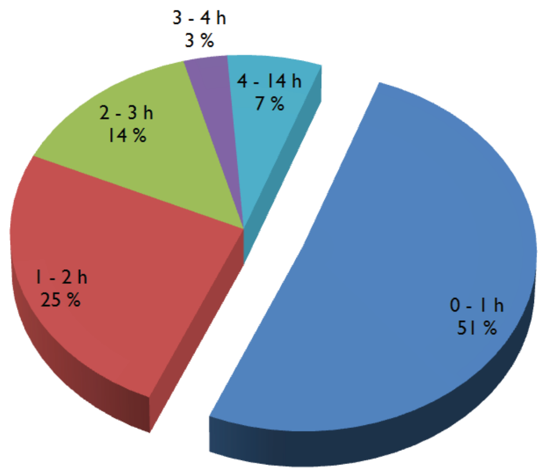

Fig. 7. Charging times of smartphone users

B. Estimated Charging Times without Power Losses

As mentioned above, conventional PV chargers include batteries, because their photovoltaics are too small to charge mobile phones directly [8], [9]. This means that we are dealing with two batteries, one in the PV charger and one in the mobile phone, which we would like to recharge. Hence, we define two recharging times, t_1 and t_2, respectively. The time t_1 represents the time during which we charge the battery of the PV charger, while t_2 is the time the mobile phone is connected for charging.

The longer users connect their portable devices, the larger will be t_2 and thereby the amount of energy (E_2), which the battery of the PV charger needs to provide - in case the battery of the mobile phones is not fully recharged. In other words, t_1 needs to be large enough so that the PV charger's battery has enough energy (E_1) for the charging procedure and to satisfy t_2. Otherwise, the charging procedure stops or gets interrupted, which is undesirable for users of smartphones.

Nowadays, USB is widely used as standard interface for charging portable devices. AC chargers also charge via the USB interface, but deliver higher output currents than USB ports from personal computers (PCs). The output power level of PV chargers (P_2) needs to fulfil the requirements of the USB specifications. According to the specifications for USB 2.0, a voltage level (V_2) of 5 V $\pm$ 5 % and a current (I_2) of up to 500 mA needs to be provided.

Our first measurements indicate that requirements on I_2 vary within different mobile phone manufacturers and also depends on the state of charge (SoC) of the smartphone's battery. For example, if the SoC is at 80 %, I_2 is lower than when the SoC is at 30 %. Hence, it is not easy to state, what is the minimum amount of current ($I_{2,min}$), which needs to be provided from the PV charger. We plan to conduct further measurements and experiments to verify a suitable value for $I_{2,min}$.

Fig. 8 shows current flows within the basic structure of PV chargers [9]. P_{in} is the output power of the photovoltaics, while P_1 represents the amount of power, which is used to recharge the battery of the PV charger. It is worth to note that I_1 is much smaller than I_2 and the reason why a battery is needed within the structure of PV chargers. In other words, I_1 cannot be used as charging current directly.

In our previous work, we discussed output performances of conventional PV chargers such as the Patona 7-in-1 [9]. In the following example, we calculate the time to completely charge the battery ($t_{1,max}$) of the Patona 7-in-1. We calculate values based on the performance under a solar radiation level (λ) of 700 W/m^2 and at cell temperature T_c of 298 Kelvin [9]. At first and for simplicity, we assume an optimal degree of efficiency. The charging time will be reduced at higher solar radiation levels and prolonged at lower solar radiation levels.

Time to completely charge the battery of the PV charger:

PV charger battery size: $Q_{battery1}$ = 1000 mAh = 1 Ah
Battery voltage: $V_{battery1}$ = 4.2 V
Charging time: $t_{1,max} = (Q_{battery1} \times V_{battery1}) / (P_{in} \times \eta_{charge1})$
Charging efficiency: $\eta_{charge1}$ = 100% ($P_1 = P_{in}$)
Power from photovoltaics: $P_{in} = V_{in} \times I_{in}$
V_{in} = 5 V
I_{in} = 0.04 A
P_{in} = 0.2 W
$t_{1,max}$ = 21 h

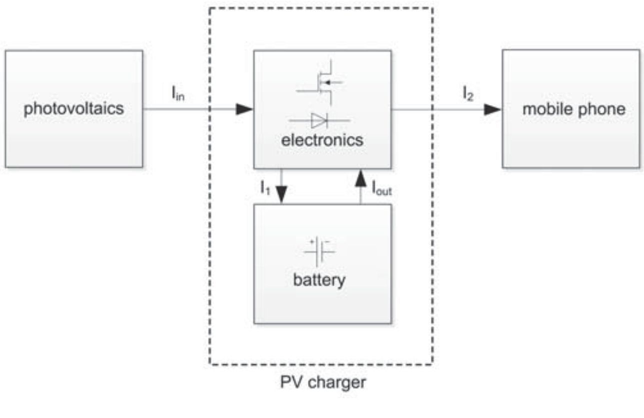

Fig. 8. Structure with current flows

In the next step, we calculate the output power (P_2), which is provided from AC and USB chargers.

$$P_2 = V_2 \times I_2$$

For AC chargers:	For USB chargers:
V_2 = 5 V	V_2 = 5 V
I_2 = 1 A	I_2 = 0.5 A
P_2 = 5 W	P_2 = 2.5 W

We assume that P_2 needs to be 2.5 Watts to satisfy user requirements and USB specifications. If a mobile phone is put for a one hour charge (t_2 = 1 h), we need an energy ($E_2 = P_2 \times t_2$) of 2.5 Watt-hours. As mentioned above, we assume optimal conditions ($P_2 = P_{out}$). The question raises how long t_1 is in that case for the conventional PV charger.

$$t_1 = \frac{E_2}{P_1} = 12.5h$$

The conventional PV charger needs to be recharged about 12 hours beforehand, to provide enough energy to recharge the mobile phone for one hour. This equals to a recharge of about 33 % of the mobile phone's battery ($Q_{battery2}$ = 2000 mAh; $V_{battery2}$ = 3.7 V; $\eta_{charge2}$ = 100 %).

C. Estimated Charging Times including Power Losses

In reality, the degree of efficiency is smaller than 100 %. Fig. 9 shows the basic system structure of PV chargers [9], where the corresponding power losses are illustrated on the right hand side. The system structure and the internal efficiency of the PV charger have a strong impact on t_1. Including the degree of efficiency of the individual components allows to state specifications for PV chargers on the one hand and to calculate realistic charging times on the other hand. At first, an explanation of the abbreviations is provided:

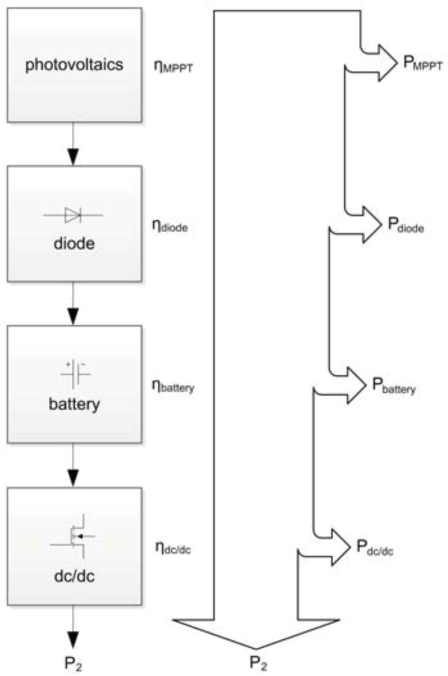

Fig. 9. Structure with power losses

1) Efficiency of the photovoltaics (η_{MPPT})
As discussed above, if the operating voltage (V_{op}) does not equal the voltage in the MPP (V_{mpp}), the obtained output power is lower than the power, which can be gained in the MPP. η_{MPPT} increases with a larger mismatch of V_{op} and V_{mpp}. η_{MPPT} varies with different solar radiation and temperature levels and depends on the implemented

MPPT technique. In case of conventional PV chargers, no MPPT is carried out. At the about λ = 700 W/m^2 and T_c = 298 Kelvin, η_{MPPT} is about 97 % [9].

2) Loss over the diode (η_{diode})
P_1 is lowered by the voltage loss (V_{diode}) over the diode. If the photovoltaics are shaded, the diode protects the battery so that no current flows from the battery to the PV cells, which behave like a resistance in that case. V_{diode} is 0.6 V and η_{diode} is about 88 % for the PV charger and the environmental conditions in our example; as stated above.
3) Efficiency of the battery ($\eta_{battery}$)
It is not possible to use all the energy, which is stored in the battery of the PV charger. Charging and discharging the battery results in a loss. $\eta_{battery}$ is about 80 - 90 % and depends on the type of battery, which is used for the PV charger. Commonly, batteries are made out of lithium ion (li-ion), lithium polymer (li-poly), and nickelmetal hydride (NiMH). It is possible to take a small self-discharge rate of the battery into considerations. This rate varies with the ambient temperature.
4) Efficiency of the power converter ($\eta_{dc/dc}$)
The battery voltage ($V_{battery}$) is lower than the voltage (V_2), which is required for the USB interface. Hence, a dc/dc converter is used. Unfortunately, the power converter lowers the degree of efficiency of the PV charger. Values for $\eta_{dc/dc}$ lie between 75 and 95 %.

We include the various factors such as η_{MPPT}, η_{diode}, $\eta_{battery}$, and $\eta_{dc/dc}$, to describe the power flows within PV chargers. We derive the following equations, 1, 2, and 3, respectively, from Fig. 8.

$$P_1 = P_{in} - P_{MPPT} - P_{diode} \tag{1}$$

$$P_2 = P_{out} - P_{dc/dc} \tag{2}$$

$$P_{out} = P_1 - P_{battery} \tag{3}$$

If we combine Equation 1, 2, and 3 with each other, we derive Equation 4, which describes the losses from the input to the output.

$$P_2 = P_{in} - P_{MPPT} - P_{diode} - P_{battery} - P_{dc/dc} \tag{4}$$

Furthermore, the overall degree of efficiency (η) can be calculated as follows:

$$\begin{aligned} \eta &= \eta_{MPPT} \times \eta_{diode} \times \eta_{battery} \times \eta_{dc/dc} \\ \eta_{min} &= 0.97 \times 0.88 \times 0.80 \times 0.75 \\ &\approx 51\% \\ \eta_{max} &= 0.97 \times 0.88 \times 0.90 \times 0.95 \\ &\approx 73\% \end{aligned} \tag{5}$$

$$E_2 = P_2 \times t_2 = P_{in} \times \eta \times t_1 \tag{6}$$

In the worst case scenario, only the half of the energy, which is possible to get from the photovoltaics, is used to recharge the mobile phone. The size of photovoltaics can be calculated by the help of Equation 5 and 6. Compared against the results from optimal conditions, the photovoltaics need to be two times larger so that t_1 is still about 12 hours; otherwise t_1 has to be about 24 hours.

For example, if we assume that we can use the PV charger about 8 hours on an average day, we need to recharge the conventional PV charger for three days, before we can charge the mobile phone for one hour. Consumer electronics usually contain low-cost electronics. However, if we assume that the PV charger operates under its maximum degree of efficiency (η_{max}), a realistic value for t_1 is about 17 hours. As mentioned above, PV chargers need a certain amount of time (t_1), before the gained energy (E_1) can be used to charge mobile phones. In the following example, we calculate the size of the photovoltaics if t_1 is four hours.

Size of photovoltaics:

Connecting time: t_2 = 1 h
USB output power: P_2 = 2.5 W
Energy demand: E_2 = 2.5 Wh
Time for the PV charger: t_1 = 4 h
Required input power: $P_{in} = E_2 / (\eta \times t_1)$
$P_{in} \approx$ 1.25 W (for η_{min})
$P_{in} \approx$ 0.85 W (for η_{max})

Beside the use of larger photovoltaics on the input side, we need to improve the degree of efficiency (η) to achieve suitable recharging times of the PV charger (t_1). Similarly, a greater η allows using smaller photovoltaics. In particular, this can be helpful if the area for photovoltaics is limited. However, the target needs to be that user requirements and expectations are fulfilled.

IV. Software and Hardware Development for Mobile Phones

A. Complexity of the Development Chain

In general, a lot of expertise is required for the design of accessories for portable devices such as mobile phones. The product development chain demands experts, both, on software and hardware engineering. This situation leads to the need of a multidisciplinary team [12]. This is also why, PV chargers are relatively expensive at the moment in comparison to their amount on provided energy for mobile phones [7], [8], [9].

However, this pressure on development effort and costs brings up the question, which system components need to be designed in software and which ones in hardware. Simplified software and/or hardware can lower performance and functionality of accessories. Moreover, the chance is given, if the available hardware of the mobile phone changes that the application, which runs on the smartphone, does not work properly anymore. Similarly, it can be the case that a specific hardware is not compatible with mobile phones from different manufacturers [8], [9], [12].

B. The Difference between the Active and Passive Device

Beside the opportunity to implement different system components either in software or hardware, we also have a look on the function and task of mobile phones within the power chain. Commonly, conventional PV chargers provide energy for portable devices, but do not interact with them. In other words, there is no communication between PV chargers and the devices, which are charged. Smartphones can be seen as existing software and hardware. Research was carried out to turn mobile phones into active devices and let them manage the power chain [8], [9].

Generally, smartphones contain powerful central processing units (CPUs) and a huge amount of memory. These performance opportunities outnumber the possibilities of other conventional possibilities to realise charging controllers [8], [13], [14]. However, it is not possible to implement every control function with smartphones. Furthermore, there are restrictions in accessing specific software and/or hardware [8]. Hereby, open source operating systems can offer a wider range on available software and hardware features [15].

C. Different Types of Software Development Kit (SDK)

Manufacturers provide tools such as software development kits (SDKs) for the implementation of applications on their smartphones. SDKs simplify the software design and are based on higher programming language such as C++. Hereby, the programmer can build an application on a computer and load it afterwards onto the smartphone. Furthermore, the application can be also debugged and an emulator helps to simulate and test the application on a computer, before it is installed on a smartphone [16], [17], [18].

If different or specific programming languages are needed as it is the case for example for iPhones, the usability for other platforms is limited [15]. Additionally, there are possible limitations for models with older software versions. The support of applications, which are addressed to the latest version of the operating system (OS) such as iOS, can be restricted and available only on new models. If smartphone users should become prosumers and contribute applications to the community, it is important that SDKs are free of charge and first steps in programming software are easy to establish [15].

D. Mobile Phones: A different Environment

Mobile phones are embedded systems and are designed for specific purposes, which they need to fulfil [8], [15], [18]. The alternation of software and/or hardware is more complicated in comparison to a conventional personal computer (PC). Furthermore, not all desired modifications are possible to realise and some variations can be easier to implement than other ones [10]. For example, if the resolution of the display changes, but the operating system remains the same, the question is how much lines of code need to be modified to adapt to these changes. Moreover, it is of interest if there is a user interaction required to carry out these kind of modifications or not [18].

E. Reuseability and Exchangeability

It can be undesirable for users that purchased accessories are not supported from newer models, which means that users have to buy also new accessories for their new mobile phones, even though old accessories are still working properly. Similarly, accessories are not exchangeable within mobile phones from other manufacturers. Hence, reusability is needed to lower costs on the one hand and exchangeability to use equipment from different manufacturers on the other hand [8], [12], [15], [18]. Nowadays, the situation has been improved due to the micro universal serial bus (micro-USB) as common charge interface and the 3.5 mm audio jack as common audio interface.

In the case of PV chargers, the target of the research is to establish a certain level of efficiency to satisfy user requirements [1], [2], [8], [9]. At the moment, it is not easy to state if existing SDKs provide all required functions for a successful charger design. At the early state of the conducted research, a first prototype of a possible new PV charger was constructed [8]. The design was established on mobile phones with a Symbian OS. The SDK and the compiler to write applications were free of charge [8], [18]. However, it was not possible to use standard interfaces such as Bluetooth or Infrared directly to establish a communication between the PV charger and the smartphone. Hence, a new, additional interface was implemented [8].

V. Possible Designs of PV chargers

A. Overview

We summarise that there are various factors, which have an impact on the design choices for PV chargers. Moreover, there are restrictions, which depend on the SDK, the platform and the OS. Opportunities to write applications on today's smartphones rely on a manifold hardware and software, which allows to access hardware features. A support for the implementation of applications is available in many cases, but there are differences along the manufacturers of smartphones. It is non-trivial to construct PV chargers, which work at a high efficiency level and with diverse mobile phone models.

Furthermore, it is a matter of costs how efficient the PV charger needs to be. Beside the choice on the amount of PV cells, we need to select a suitable management technique (MPPT) and the size of the battery to buffer the energy for the user. A wrong choice on design outlines lower the performance and possible amount on output power. The overall intention is to satisfy user expectations and provide a significant amount of charge so that PV chargers are accepted and also frequently used.

Table II summarises the major aspects on the design of PV chargers such as the requirement of a MCU, the opportunity to exchange PV chargers within different types of mobile phones, to reuse them after the purchase of a new smartphone, the level of efficiency and to reconfigure them, for example if we want to reduce the amount of PV cells and thereby the amount of weight. As discussed above, the mobile phone can act as an active device or passive device. Each role of the smartphone has its advantages and disadvantages.

B. Comparison of Development Opportunities

1) The need of a microcontroller: It is possible to implement the PV charger without an own MCU. However, the

TABLE II. COMPARISON OF THE BENEFITS AND DRAWBACKS

Aspect	Conventional PV charger		Mobile phone as passive device		Mobile phone as active device	
(1) Microcontroller	not available	(–)	required	(–)	not mandatory	(+)
(2) Battery for the charger	required	(–)	optional	(∼)	not required	(+)
(3) Response to shadow	poor	(–)	good	(+)	good	(+)
(4) Exchangeability	easily possible	(+)	easily possible	(+)	possible	(∼)
(5) Reuseability	independence	(+)	independence	(+)	restrictions	(–)
(6) Flexibility	none	(–)	low	(∼)	possible	(+)
(7) Efficiency	poor	(–)	good	(+)	good	(+)
(8) Reconfigurability	not possible	(–)	restrictions	(∼)	possible	(+)

MCU is not a big share of the power consumption of the PV charger while also the application, which is running on the mobile phone, consumes power. This amount of power is probably larger than the power, which is required by the microcontroller depending on the design of the application and the OS of the smartphone. However, in both cases it is worse to invest the power to perform MPPT, since the overall output power level is improved. In the case of conventional chargers, there is no microcontroller used, which lowers costs, but also the performance.

2) Required battery of the charger: Conventional PV chargers include only small PV cells. This is why, a battery is needed to store the gained solar energy in a battery before enough power is available to recharge the mobile phone. The capacity of the battery in the PV charger is of similar size than the one in the smartphone. However, this is not suitable high enough to give the mobile phone a full recharge. If larger photovoltaics are used as, the battery can be left out if the mobile phone is charged directly [9]. If the mobile phone acts as an active device an interruption of the charging procedure can be avoided.

3) Response to shadow: Shadow is critical, since a notable drop of the output power level of the photovoltaics occurs. MPPT reacts to changing environmental conditions such as solar radiation and temperature. In the case of changing conditions, a communication between the mobile phone and the power converter allows better to react to variations on the input side. The smartphone as an active device can set the charger, for example into pulsed mode, and try to harvest still energy from the charger. If the mobile phone is used as a passive device only the output power according to the USB specifications will be accepted.

4) Exchangeability: If the smartphone acts as a passive device, there is no interaction required between the smartphone and the PV charger. This makes it easy to exchange and use the PV charger for various mobile phones also from different manufacturers. The communication interface, which is used from the charger for interactions, must be also available on the smartphone [8].

5) Reuseability: After a new smartphone is purchased, there is no need to buy also a new PV charger, if the PV charger is working independently. This is the case for conventional PV chargers and if the mobile phone acts as a passive device. If there is a dependence, for example on the available interface on the smartphone to establish the required communication, it can be the case that new equipment needs to be purchased [12].

6) Flexibility: If users require flexibility, for example on sunny days the amount of PV cells can be reduced and thereby the weight of PV chargers. Hereby, mobile phones as active devices can help if the application allows changing certain parameters depending on the requirements of the users. It has also an impact on the flexibility of the user if the communication between the mobile phone and the PV charger has to be present all the time.

7) Efficiency: If there is a communication present such it is the case if the mobile phone is used as an active device, the internal sensors of the mobile phone can be used to manage the PV charger. This can be profitable in various ways, but in particular can improve the level of efficiency. In general, mobile phones present a new, dynamic environment. Existing MPPT techniques need to adapted to be suitable for portable devices [9]. Hereby, PV simulation models can help to improve the performance level [19], [20].

8) Reconfigureability: If an improved MPPT technique is available, the parameters or the algorithm itself can be updated if a communication interface is available. Furthermore, an application on the mobile phone is easier to update than an embedded system, which cannot be accessed directly.

VI. DISCUSSION AND CONCLUSION

We conclude that PV chargers are complex devices, which can also be constructed in a simple way with reduced efficiency and performance. Various factors, in particular the degree of efficiency, are depending on the design of the PV chargers themselves, but also on the role and function of mobile phones within the power chain. After standards were introduced such as micro-USB and the 3.5 mm audio jack, the question is, which type of new standards are thought for mobile phones in future. Due to the tendency towards open source platforms, there are more opportunities for the design and implementation of PV chargers.

However, user requirements and expectations can be fulfilled if design specifications for PV chargers are made. Beside a suitable size of photovoltaics, the PV charger needs to provide a high degree of efficiency. Hereby, each component of the system structure will have its individual degree of efficiency and has an influence on the output performance. It is a non trivial task to establish a reasonable tradeoff between charging times, battery capacity, costs and size of the PV charger, since many factors come into play and have to be considered. We propose a PV charger, which works both, under indoor and outdoor conditions. We suggest a system structure, in which mobile phones act as passive devices. Hereby, PV chargers can be deployed outdoors, while users are indoors.

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