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Short communication

Towards a more efficient energy use in photovoltaic powered products

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Abstract

This paper analyzes the energy saving and power management solutions necessary to improve the energy consumption efficiency in photovoltaic powered products. Important in the design of such products is not only the energy supply optimization required to deliver the actual energy to fulfil their function, but also efficient energy transfer along the energy chain. In this paper, several methods to improve the efficiency of the energy chain are described. This includes an analysis of optimization methods for photovoltaic powered products, its functional system and product use.

Keywords: Photovoltaic; Power management; Energy storage; Energy management; Energy conversion; Sustainability

1. Introduction

In photovoltaic powered products, the energy of the photovoltaic cells can either be used directly or can be used to recharge batteries which in turn can power the functional system [1]. Important in designing such photovoltaic powered products is an efficient energy transfer along the energy chain. Photovoltaic powered products must anticipate on the growing demand for energy caused by an increase in functionality. An increase in functionality results in new design requirements. Examples are small dimensions, acceptable working time, intuitive interaction with the user, multimedia functions and low design complexity. Also, aspects related to the systems architecture, wireless communication and energy usage will have to be taken into account [2].

In this paper, we treat a photovoltaic powered product as a chain of sequential electrical circuits. We define the photovoltaic product system as a system that consists of the photovoltaic product together with the user (Fig. 1). The battery is the central part of the PV product which this paper discusses. We will describe both sides of the battery, namely how to acquire as much energy possible from the photovoltaic (PV) cells into the battery and how to use the available energy as efficiently as possible. In our opinion, the general applicable methods are needed to obtain an efficiency improvement through the entire energy chain. In fact, the discussed energy efficiency steps could lead to the innovation cascade that will make an increasing amount of photovoltaic powered products feasible.

The emphasis in this paper will be on energy management and power management of photovoltaic powered products. First, we will give an overview of energy management methods typically used in photovoltaic powered products in Section 2. Secondly, we will describe several power management methods that can be used to design energy efficient systems. In Section 4, some smart methods to reduce unproductive energy consumption are explained. Finally, in Section 5, the main conclusions and recommendations will be summarized.

2. Optimizing energy efficiency in photovoltaic powered products

The first part of the energy chain in photovoltaic powered products consists of the photovoltaic cells, power converters and batteries.

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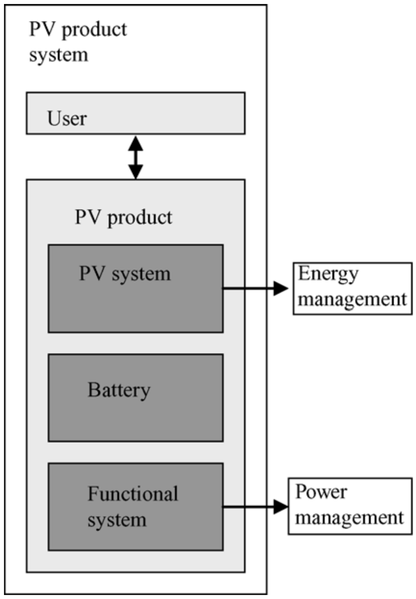

Fig. 1. Photovoltaic product system.

2.1. *Optimizing the power output of the photovoltaic cells*

The power output of a photovoltaic system is dependent on the application and depends on the irradiance on the photovoltaic cells, the type of photovoltaic cells used and the effective area of the photovoltaic cells. Therefore, the type and size of photovoltaic cell must be chosen in accordance with the application. Some examples are outdoor, outdoor and indoor combined and indoor. Because the application influences the choice of photovoltaic type and the maximum photovoltaic conversion efficiency [3], it also influences the product design. Once the photovoltaic type and application are known, the output power of the photovoltaic cell can be maximized as follows:

- minimize the effect of shadows;
- increase the incident light;
- maximal power point (MPP) tracking.

The drawbacks of shadows can be overcome by designing with photovoltaic use in mind. First, the photovoltaic cell placement must be such that the amount of shadow is minimized. In addition, it is necessary to detect and trace those photovoltaic cells inside shadow areas and apply a bypass in order to reduce series resistance. Finally, the photovoltaic cells can be connected in parallel.

To increase the incident light, several solutions are already in the market, such as sun tracking mechanisms which track the sun position for optimal light incidence angle and complicated mirror constructions. However, these solutions are not practically usable in wireless/mobile products.

Photovoltaic cells/modules have an optimal operating point called the maximum power point. This MPP is dependent on the cell temperature and the available irradiance. To

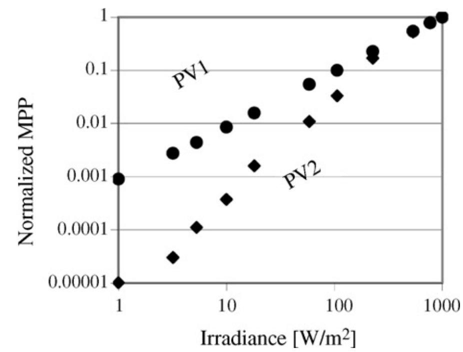

Fig. 2. Maximum power point path of two different photovoltaic cells.

trace the locus, which means path, of the MPP, several maximum power point tracking (MPPT) methods are in use [4]. Depending on the type of photovoltaic cells used, the varying irradiance will influence the maximum available current from the photovoltaic cell and the open-circuit voltage. As a result, the MPPT is photovoltaic cell type-dependent (Fig. 2). The discrepancy of the two PV types in Fig. 2 is caused by the difference in response of the photovoltaic open-circuit voltage. For PV1, the open-circuit voltage remains nearly constant as function of irradiance. Therefore, the MPP is about linearly dependent on the irradiance. For PV2, however, the open-circuit voltage drops drastically, in particular, at low light irradiance levels. Thus, knowing the type of photovoltaic cell helps predicting the MPP and results in a simplification of the MPPT algorithms.

To obtain an efficient power output from the photovoltaic conversion, it is important to cope with the fluctuations in incident light by anticipating towards the fluctuations of the MPP with the aid of a MPP tracker. For accurate estimation of the locus of the photovoltaic modules MPP at different incident light conditions, some measurements on several types of photovoltaic cells have been conducted [5].

2.2. *Smart predictive energy management*

Another parameter that can be used to improve the overall efficiency is to combine knowledge about future light abundances and energy need. Although it was a winning factor for the NUNA II team during the Australian solar car race, weather forecasts are not yet incorporated in the energy management of photovoltaic powered products! Future design methods should find ways to intelligently anticipate on the availability of the (light) energy with regard to time. Such data can be applied to improve energy efficiency of power management scheduling mechanisms.

3. Power management mechanisms for photovoltaic systems

In microprocessor-based wireless/mobile products, power management is used to minimize the energy consumption during product use. Power management includes a range of techniques that are used to slow down or shut down components which prevents the use of energy due to unnecessary execution of tasks. Power management has potential in the development of energy efficient products and successful research has already been executed on several design levels discussed in power management literature, such as system level, architecture level and technological level [6]. Power management is necessary to make the application of processors with high performance and the use of various multimedia applications possible in the design of wireless/mobile devices.

3.1. Battery management

One of the aspects that is important in the amount of deliverable energy in wireless/mobile products is the battery. Especially in portable devices, the battery is an important issue due to the influence its weight has on the portability of the product. There have been several research papers which investigate the possibilities of pulsed discharge to increase battery lifetime [7–9]. This is possible due to the recovery effect of batteries that occurs during interruptions between current drain. By intelligently applying a discharge technique, the battery capacity can be improved. Chiasserini and Rao [9], for instance, describes the importance of monitoring and recovering battery cells to obtain maximum available capacity. Another point of attention is battery temperature. For example, in order to reduce capacity fading, batteries can be cooled to maintain a temperature of about 30 °C [10].

3.2. Scheduling

Although currently scheduling is mainly used to prioritize actions in an operating system, it could offer some options for reducing energy consumption [11,12]. Some scheduling mechanisms that can be used are: processor time scheduling, which allows energy reduction by lowering supply voltage in a microprocessor, file system scheduling, which implements the advantages of turning the hard disk off, backlight luminance scaling and battery relaxation, which improves the battery capacity by adjusting to its recharge characteristics. An example is AMD's cool'n'Quit^{TM} technology which incorporates efficient scheduling principles in their processors [13].

It would also be of interest to investigate the possibilities of implementing scheduling to dynamically available alternative power sources, such as photovoltaic technology. This could possibly improve the implementation of alternative power into wireless/mobile products.

3.3. Communication

With increasing advances in hardware and software, the amount of energy needed for computation is decreasing and the role of communication is getting more important [14]. Because of the dynamically changing environment that the mobile devices are in the adaptability of mobile systems becomes important and a reconfigurable approach is necessary to reduce the energy use [15]. In addition, several causes of energy consumption in a wireless channel, such as idling of transceiver, overhead, collisions between data and a high error rate [16] should be taken into account.

The energy consumption of communication activities can represent over 50% of total power in the case of hand-held computers and up to 10% for laptops [17]. Communication thus significantly contributes to the energy consumption of these devices. The main principles proposed in literature to increase efficiency of both communication and computation are to prevent unsuccessful tasks and to minimize the amount of information communicated [15].

Previous research shows that controlling the "suspend/resume cycle" can result in "power savings of up to 83% for communication" [17]. Key issue in this technique is suspending and resuming the device from idle periods. During idle periods, a significant amount of energy is used by "listening for incoming data". Important to recognize is the trade off, an increased transmission delay, with such techniques.

3.4. Hardware configuration

The hardware configuration encompasses a trade off between flexibility and efficiency. General purpose processors show a high degree of flexibility which is needed for increasing flexibility and adaptability of products in a varying environment. In addition, the use of a general purpose processor prevents high costs of developing application-specific chips. However, the main problem is that the flexibility invokes a considerable amount of overhead tasks that increase the energy dissipation of the device. On contrast to this stands the use of application-specific chips that dissipate a significant amount less energy but have the disadvantage of lacking flexibility. Because in wireless/mobile applications, both flexibility and energy efficiency is of importance, application domain-specific modules are an acceptable solution. This is accurately described in Ref. [15]. In our opinion, the degree of programmability of a device should be dependent on the type of application, usage and should be consistent with optimizing marketability and reducing costs.

3.5. Software policies

Research in the area of power management, especially in the case of general purpose microprocessors, focuses on mechanisms, policies and architectures [18]. Policies determine the management of a component on the basis of utility curves, which describe performance or quality with regard to power consumption or other costs. The mechanism has the intelligence to actually control the component. A reduction of the energy consumption of components is realized by improving the use of mechanisms, such as exploiting sleep modes, voltage/frequency scaling and battery recovery.

Two main sources of energy drain in the majority of microelectronic-based portable electronic products are distinguished [15]. First, energy consumption is caused by communication of internal and external transfer of information. Second, computation energy is consumed by processing tasks. In optimal product design, both energy drains need to be discussed.

According to literature [15,18], energy consumption can be reduced by regarding high layers of a microelectronic system, systems architecture, operating system, entire communication networks and taking into account use-aspects, such as contextual relations and user intention [19]. The key to designing energy efficient wireless/mobile products is to take energy efficiency into account on all levels of product design. In addition, it can be said that most important energy consumption improvements can be implemented on higher levels of a system. However, at higher levels, the calculation of energy consumption is less comprehensive.

Important in the development of power management techniques is the development of power efficient components. Developers mainly focus on interfaces, information storage, efficient processors and power sources of which mainly batteries.

4. Reducing 'unproductive' energy consumption

4.1. Difference between energy supplied and utilization

One of the main causes for unproductive energy consumption is the mismatch between the nature of electrical power provided by the electrical grid or mains and the nature and voltages needed to power the circuitry inside mobile/wireless products today. At this moment, most of the mobile/wireless products have rechargeable batteries. These batteries are recharged by the mains. The mains outlet provides electric power with alternating current (ac) at voltages of 110–250 V. This is in contrast with the battery and most of the electronics inside mobile/wireless products which need direct current (dc) at a much lower voltages of about 3–12 V. The mains power characteristics are thus not compatible with the common rechargeable energy storage media in use today. To bridge the differences, ac–dc converters are introduced between the mains and the product circuitries. These ac–dc converters consist of one or more voltage step-down transformers, some rectifier circuits, filters and switching circuitry. All those devices have each an efficiency below 100%, which means energy losses. A charger plugged in the main even if it is not recharging a battery will be dissipating power in the primary coil of the transformer and the interconnections wires.

4.2. User unawareness and behaviour provoke unproductive energy consumption

The user is unaware that leaving the mains adapter plugged inside the mains socket will cause energy losses even if the product has been switched off. To avoid this waste, there should be a switch between the mains and the ac–dc converter to turn the product really off. Another more elegant option would be to eliminate the need of ac–dc converters by the use of photovoltaic cells.

Also, it is convenient for the user to leave the product on 'standby' or 'sleep mode'. The user is unaware that the product in these modes is still consuming energy.

5. Conclusions

This paper shows that energy consumption can be optimized by applying energy management of the photovoltaic cells, power management of the functional system and by reducing the performance to a level of "just fit for the job". It is particular this latter item that will be a crucial issue since it is at the end the user who decides to what extent the performance can be reduced to save energy consumption.

Optimization of the power output from the photovoltaic cells is possible by proper choice of photovoltaic cell type. In addition, by using precognition of the PV type-dependent maximum power point values, the tracking can be simplified.

Current literature describes many theories on power management of electronic products. Although we believe that the development of power management mechanisms and policies is extensively being researched, we have the opinion that current literature is limited on two issues. First, no significant literature was found on using contextual relations, functionality and application of use profiles in the design of energy efficient products. Although we did find some attempts on this area [19,20], no major study was found. It is our opinion that in order to optimize the energy efficiency of portable devices, the use of contextual relations, such as use profiles is necessary to optimally control power management activities. Second, the effect of applying power management mechanisms based on the dynamic behaviour of power sources has not been extensively studied. Although some papers were found on the improvement of batteries [7–9], no significant research on the use of alternative power sources in relation to power management was found. Our explanation for this is that alternative power sources are currently not practically and appropriately applicable for use in commercial portable products due to a lack of knowledge and research in this area.

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References

[1] S.Y. Kan, PV powered mobility and mobile/wireless product design proceeding ISES, Solar World Congress Gotenborg, ISES, Sweden V1–1, 2003.

[2] P.M. Havinga, G.M. Smit, Design techniques for low-power systems, J. Syst. Architecture 46(1) (2000) 1–21.
[3] S.Y. Kan, S. Silvester, H. Brezet, Design applications of combined photovoltaic and energy storage units as energy supplies in mobile/wireless products, in: Proceedings of the TMCE 2004, Lausanne, Switzerland, Milpress, Rotterdam, 2004.
[4] D.P. Hohm, M.E. Ropp, Comparative study of maximum power point tracking algorithm: progress in photovoltaics, Res. Appl. 11 (2003) 47–62.
[5] N.H. Reich, S.Y. Kan, W.G.J.H.M. van Sark, E.A. Alsema, S. Silvester, A.S.H. van der Heide, R.W. Lof, R.E.I. Schropp, Weak light performance and spectral response of different solar cell types, in: Proceedings of the 20th European Photovoltaic Solar Energy Conference and Exhibition, Barcelona, Spain, 2005.
[6] J.M. Rabaey, M. Pedram, Low Power Design Methodologies: The Kluwer International Series in Engineering and Computer Science, Kluwer Academic, Boston, 1996, pp. 336–367.
[7] L. Benini, G. Castelli, A. Macii, E. Macii, R. Scarsi, Battery-driven dynamic power management of portable systems, Proceedings of the 13th International Symposium on System Synthesis, ACM Press, New York, NY, USA, 2000, pp. 25–30.
[8] L. Benini, G. Castelli, A. Macii, E. Macii, M. Poncino, R. Scarsi, Extending lifetime of portable systems by battery scheduling, Proceedings of the Conference on Design, Automation and Test in Europe, IEEE Press, Piscataway, NJ, USA, 2001, pp. 197–203.
[9] C.F. Chiasserini, R.R. Rao, Energy efficient battery management, IEEE J. Sel. Areas Commun. 19 (7) (2001) 1235–1245.
[10] J. Shim, R. Kostecki, T. Richardson, X. Song, K.A. Striebel, Electrochemical analysis for cycle performance and capacity fading of a lithium-ion battery cycled at elevated temperature, J. Power Sources 112(1) (2002) 222–230.
[11] M. Weiser, B. Welch, A. Demers, S. Shenker, Scheduling for reduced CPU energy, in: Proceedings of the First Symposium on Operating Systems Design and Implementation, 1994, pp. 13–23.
[12] J.M. Chang, M. Pedram, Energy minimization using multiple supply voltages, IEEE Trans. Very Large Scale Integr. (VLSI) Syst. 5 (4) (1997) 436–443.
[13] D. Sadowy, Energy efficient microprocessor design: more performance with less power, in: Proceedings of Electronics Goes Green 2004, 2004, pp. 629–634.
[14] P. Lettieri, M.B. Srivastava, Advances in wireless terminals personal communications, IEEE [see also IEEE Wireless Commun.] 6 (1) (1999) 6–19.
[15] P.J.M. Havinga, Mobile Multimedia Systems, University of Twente, 2000.
[16] P.J.M. Havinga, G.J.M. Smit, Energy-efficient wireless networking for multimedia applications, Wireless Commun. Mobile Comput. 1 (2) (2001) 165–184.
[17] R. Kravets, P. Krishnan, Power management techniques for mobile communication, Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking, ACM Press, New York NY, USA, 1998, pp. 157–168.
[18] J.A. Pouwelse, Power Management for Portable Devices, Delft University of Technology, 2003.
[19] A.B. Dalton, C.S. Ellis, Sensing user intention and context for energy management, in: Workshop on Hot Topics in Operating Systems (HOTOS), 2003.
[20] I.V. Nicolaescu, W.F. Hoffman, Energy consumption of cellular telephones, in: IEEE International Symposium on Electronics and the Environment, Denver, CA, USA, 2001, pp. 134–138.