Accepted for publication. DOI: 10.1109/WPT.2017.7953805

Optimal Energy Storage Solution for an Inductively Powered System for Dairy Cows

Ben Minnaert*, Bart Thoen*, David Plets†, *Member, IEEE*,
Wout Joseph†, *Senior Member, IEEE* and Nobby Stevens*, *Member, IEEE*
*Department of Electrical Engineering, KU Leuven, Technology Campus Ghent, Ghent, Belgium
†Department of Information Technology, IMEC-Ghent University, Ghent, Belgium
Email: ben.minnaert@kuleuven.be

***Abstract*—In order to remain cost competitive, dairy farmers are equipping their animals with automatic health monitoring systems. An important obstacle for integrating these systems is the high energy consumption of the on-cow components. A solution is wireless charging of the automated system at a feeding trough by inductive coupling. We developed an inductively powered system that is charged each time the cow eats at a feeding trough. We study which energy buffer is preferable for this application: rechargeable Li-ion batteries or supercapacitors. From measurements at a dairy farm, we obtain that the rate at which energy is captured is too high for an efficient use of Li-ion batteries. Supercapacitors are able to store energy at a very high rate, making them better suited for this application.**

Keywords: wireless power transfer, inductive coupling, supercapacitors, rechargeable batteries, dairy cows

I. Introduction

Nowadays, dairy farmers are prompted to increase their farm size to remain cost competitive [1]. Indeed, an increase of the herd size has an advantageous impact on the relative cost [2]. For example, in the European Union, the average dairy cow herd size increased with 30 % from 2007 to 2010 [3] whereas in the United States, the number of cows per farm increased by 325% from 1980 to 2004 [4].

When the farmer has a limited number of cows, he is able to individually monitor all the cows on a regular basis. Obviously, this is no longer practically feasible for farms with several hundreds of cows. Even for a farm of less than hundred cows, the follow-up of all individual animals is a very labor-intensive task for the farmer. As a result, automatic health monitoring systems for cows are steadily entering the market. A timely detection of health problems of farm animals leads to a significant cost reduction for the farmer. For example, a late detection of mastitis or lameness of cows costs at least 150 euro and 250 euro per cow and per year, respectively [5], [6], [7].

A way to monitor cattle and their health is to collect and interpret data, delivered by on-body sensors [7]. An obvious example is a temperature sensor that can detect fever. This temperature sensor can also be applied to predict the calving moment. Another example is the early detection of lameness by analysis and interpretation of the localization and movement data of each individual cow. The on-body data is ideally wirelessly transferred to a back-end server [8] and the automated system alerts the farmer when it detects a possible health problem. But even small dairy farms can realize a significant cost reduction by implementing more technology solutions [9].

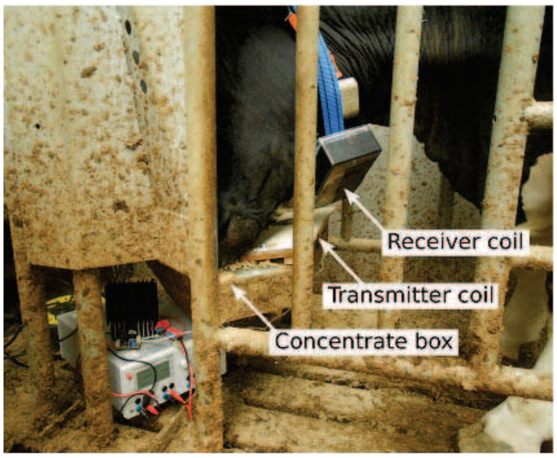

Fig. 1. A dairy cow is equipped with a collar containing a receiver coil. A transmitter coil, located at a feeding trough, transmits energy to the receiver when the cow eats.

Nowadays, an integrated sensor system that measures and analyzes different parameters as heat, movement and location does not exist yet, requiring the farmer to buy and integrate different systems. An important obstacle for an integrated sensor system is the high energy consumption. This limits the lifetime of the device or requires the farmer to regularly replace the batteries of the sensor system. A solution is wirelessly charging the automated system at the eating or drinking trough by inductive coupling. Each time the cow eats or drinks, energy can be wirelessly transmitted from a transmitter coil at the trough to a receiver coil at the system. Our configuration consists of a collar which acts as a central hub for the different sensors [7]. By installing a receiver coil in the collar and a transmitter coil at feeding trough (Fig. 1), the on-cow system can be inductively charged each time the cow eats at the feeding trough.

The energy that is captured by the receiver coil has to be stored in an energy buffer. The question arises which

978-1-5090-4585-3/17/$31.00 ©2017 IEEE

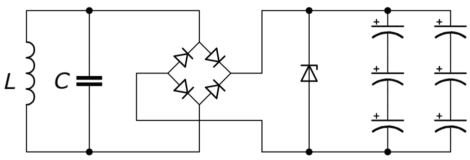

Fig. 2. Schematic layout of the receiver with supercapacitors containing from left to right: the receiver coil L, the parallel resonance capacitance C, a bridge rectifier, a power Zener diode, and a bank of six supercapacitors.

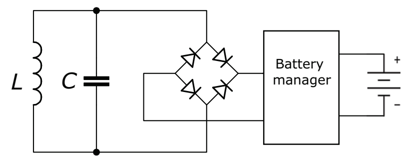

Fig. 3. Schematic layout of the receiver with a Li-ion battery containing from left to right: the receiver coil L, the parallel resonance capacitance C, a bridge rectifier, the battery manager and a rechargeable Li-ion battery.

energy storage device is preferable. Since the final goal is that every cow is equipped with a (preferably small) collar, a prerequisite of the energy buffer is low cost and high energy density. Li-ion rechargeable batteries are the obvious choice here. They are the most cost-efficient energy storage device available on the market today [10] and can store a large amount of energy with specific energy densities from 430 to 720 kJ/kg [11]. Moreover, Li-ion batteries have the advantage of high electrical and thermal stability, very low discharge rate and an absence of memory effect [12], [13].

However, rechargeable Li-ion batteries also have some disadvantages. Since the energy is stored by the use of chemical reactions, their charging speed is limited by the charging current [14]. A low power density of 300 to 1500 W/kg is reported [14]. This may be too low for our application. Indeed, we want to assure that the cow sensors always have enough energy to ensure operation, thus even if the eating or drinking time of the cow is limited, we want to maximize the amount of energy transferred in order to continue operation of the device. Moreover, the numerous cycles of charging and discharging damages the battery and results in a decreased efficiency and limited lifetime of the device.

A possible alternative for rechargeable batteries is the use of supercapacitors. In contrast with batteries, they do not use chemical reactions to store energy. This allows them to take energy at a very high rate, with power densities in the range from 1 to 5 kW/kg [11], [12]. They also have a longer life expectancy than Li-ion batteries since they can withstand a high number of charge cycles without significant degradation [12]. The disadvantage is the lower specific energy density (from 7 to 18 kJ/kg) compared to batteries [11]. However, this lower energy density might be an acceptable trade-off in exchange for the faster charging rate. Moreover, another prerequisite is a low cost system. For the same cost, a supercapacitor has a longer lifetime. The energy cost of cheap off-the-shelf supercapacitors and Li-ion batteries is 300 and 500 US dollar per kWh, respectively [12].

In this work, we study which energy buffer is best suited for the application of inductively charging an on-body dairy cow sensor system. To that end, we perform a field test in a dairy farm to measure how fast energy is transmitted from a transmitter coil at a feeding trough to a receiver coil at the collar of the cow. Due to variable distances and orientations of the receiver coil to the transmitter coil when the cow eats or drinks, an optimal power transfer will not be possible. Therefore, it is necessary that the power transfer is maximized when the orientation and distance is acceptable (even only during a brief moment).

II. The Experimental Setup

For the field test, we build a receiver coil of L = 4.71 μH with a ferrite core (Fig. 2). The diameter of the receiver coil is 11.0 cm which is a trade-off between an optimized energy transfer and the space restrictions. We apply a resonance capacitance of C = 633 nF in parallel, corresponding with a resonance frequency of 92 kHz. A bridge rectifier with SR1204 Schottky diodes converts the AC to DC. We use regular, off-the-shelf supercapacitors (Panasonic$^{\text{TM}}$ EEC-HZ0E106) of 10 F with a maximum operating voltage of 2.5 V. We connect two parallel modules with each three individual supercapacitors in series in order to achieve a higher energy capacity and voltage rating [13]. A power Zener diode 1N5342 protects the supercapacitors from overvoltages. The dimensions of the bank of 6 supercapacitors is 30.0 mm x 20.0 mm x 30.0 mm = 18 cm^3 containing 83 J at 5.0 V. This corresponds with a volumetric energy density of 4.6 J/cm^3 at 5.0 V.

In order to make a fair comparison, we build a receiver with a regular, off-the-shelf rechargeable Li-ion battery as energy buffer (model no. 103456A-1S-3M) that has about the same purchase price and volume as the 6 supercapacitors together. The Li-ion battery has a capacity of 2050 mAh, a maximum charge current of 1.025 A and a nominal and charge voltage of 3.7 and 4.2 V, respectively. This implies that on average, the maximum charging power is limited to 4 W. The dimensions of the battery are 56.0 mm x 36.5 mm x 10.7 mm = 22 cm^3 containing 37 kJ at 5.0 V. Notice that the volume is comparable with the supercapacitor bank, but the possible energy content is two orders of magnitude higher. This corresponds with a volumetric energy density of 1.68 kJ/cm^3 at 5.0 V.

A battery manager, containing an overcurrent and overvoltage protection system, is necessary to charge the Li-ion battery [10]. For our application, the most optimal battery manager we found is the bq24266 of Texas Instruments$^{\text{TM}}$, a standalone single-input, single-cell switchmode Li-ion battery charger. Fig. 3 shows the layout of the receiver with the Li-ion battery as energy storage.

III. Measurements and Results

We performed field measurements at a research dairy farm at the Research Institute for Agriculture, Fisheries and Food Research in Melle, Belgium. We installed an oval transmitter coil of 27.0 cm x 13.5 cm on a layer of ferrite at a feeding box. We experimentally determined the optimal dimensions of the transmitter coil for a maximum power transfer, taken into account the space restrictions from the feeding trough. The transmitter with an input supply power of 24 W, generates an AC-current of 90 kHz through the transmitter coil. A cow is equipped with a collar, containing the receiver. As the cow eats, the voltage over the supercapacitors is registered every second with a voltage data logger in the receiver. This voltage is a measure for the energy captured by inductive coupling and stored in the supercapacitors.

Fig. 4 shows a typical measurement as function of time. In 63 s, a total of 168 J is stored in the supercapacitors. The energy transfer rate is not constant. There are horizontal plateaus where the cow stops for a moment with eating and increases the distance between transmitter and receiver, thus halting the energy transfer. The slope of the transfer varies, depending on the distance and orientation of the receiver coil to the transmitter coil. At 12 and 34 s, we notice a small decrease in the energy stored. This is attributed to the redistribution of charge over the different supercapacitors due to different equivalent series resistances.

On average, 2.67 W is transferred within this measurement of 63 s. However, there are intervals where the power transfer is much higher. For example, in the interval from 22 to 34 s and from 43 to 50 s, an average power transfer of 7.0 and 8.5 W is realized, respectively, with a maximum of 14 W in 1 s. Those high power transfer rates would not have been possible with our setup with a Li-ion battery as energy storage since the maximum charging power for the battery is limited to 4 W.

We now calculate the energy transfer of this measurement if the battery receiver would have been used instead of the supercapacitor receiver. For this purpose, we limit the maximum energy transfer to 4 W. We obtain a total energy transfer of 100 J during 63 s, or an average of 1.59 W. We notice that the system with the Li-ion battery receives less than 60% of the transferred energy, compared to the system with supercapacitors. This indicates that the periods with higher power transfer than 4 W (32% of the time in this measurement) form an important share of the total energy transfer. We can conclude that the limited charging power rate of our setup with the Li-ion battery is not high enough. Our setup with supercapacitors is required to get the maximum out of the inductive charging solution.

When high charging times and high energy density is required, a hybrid system which uses supercapacitors as energy buffer and Li-ion batteries as energy storage for the system, is a possible solution. The hybrid system combines the high power rate of supercapacitors and the high energy density of Li-ion batteries.

IV. Conclusion

In this work, we studied which energy storage option is preferable for an on-body dairy cow sensor system, charged at discrete times by inductive coupling each time the cow eats.

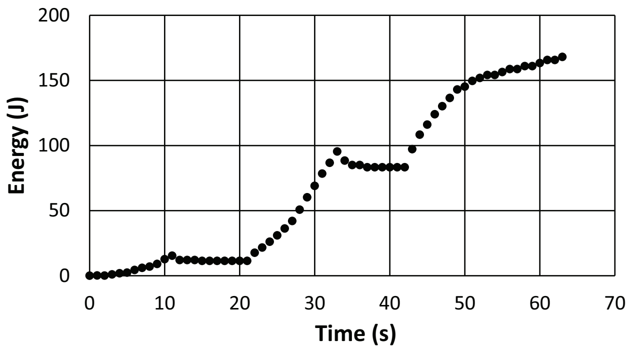

Fig. 4. The captured energy in the supercapacitor bank as function of time.

We compared rechargeable Li-ion batteries with supercapacitors. The first option has the advantage of high specific energy density, the latter has high power density. Our measurements indicate that the rate at which energy is captured is too high for the efficient use of Li-ion batteries. The high power density of supercapacitors is required to optimally exploit the energy transfer.

Acknowledgment

This work was executed within MoniCow, a research project bringing together academic researchers and industry partners. The MoniCow project was co-financed by imec (iMinds) and received project support from Flanders Innovation & Entrepreneurship. We thank the Research Institute for Agriculture, Fisheries and Food Research for their assistance with the measurements at the dairy farm.

References

[1] B. Jones, "Growth in dairy farms: the consequences of taking big steps or small ones when expanding", *Four State Dairy Extension Conf.*, pp 7, March 1999.

[2] L.W. Tauer and A.K. Mishra, "Dairy farm cost efficiency", *Journal of Dairy Science*, 89(12), pp.4937-4943, 2006.

[3] "EU dairy farms - Report 2013. Based on FADN", European Union, 2014.

[4] L.E. Chase, L.O. Ely and M.F. Hutjens, "Major advances in extension education programs in dairy production", *Journal of Dairy Science*, 89(4), pp.1147-1154, 2006.

[5] J. Krieter, D. Cavero and C. Henze, "Mastitis detection in dairy cows using neural networks", *GIL Jahrestagung*, 101, pp.123-126, 2007.

[6] J. Haugen, "Lameness in dairy cows in freestall barns with automatic milking systems", Doctoral dissertation, Faculty of Veterinary Science, Szent Istvan University, Budapest, Hungary, 2011.

[7] S. Benaissa, D. Plets, E. Tanghe, G. Vermeeren, L. Martens, B. Sonck, F.A.M. Tuyttens, L. Vandaele, J. Hoebeke, N. Stevens and W. Joseph, "Characterization of the on-body path loss at 2.45 GHz and energy efficient WBAN design for dairy cows", *IEEE Trans. Antennas Propag*, 64(11), pp.4848-4858, 2016.

[8] S. Benaissa, D. Plets, E. Tanghe, L. Verloock, L. Martens, J. Hoebeke, B. Sonck, F.A.M. Tuyttens, L. Vandaele, N. Stevens and W. Joseph, "Experimental characterisation of the off-body wireless channel at 2.4 GHz for dairy cows in barns and pastures", *Computers and Electronics in Agriculture*, 127, pp.593-605, 2016.

[9] L.W. Tauer and A.K. Mishra, "Can the small dairy farm remain competitive in US agriculture?", *Food Policy*, 31(5), pp.458-468, 2006.

[10] V.A. Boicea, "Energy storage technologies: The past and the present", *Proc. of the IEEE*, 102(11), pp.1777-1794, 2014.

[11] A. Du Pasquier, I. Plitz, S. Menocal and G. Amatucci, "A comparative study of Li-ion battery, supercapacitor and nonaqueous asymmetric hybrid devices for automotive applications", *Journal of Power Sources*, 115(1), pp.171-178, 2003.

[12] I. Chotia and S. Chowdhury, "Battery storage and hybrid battery supercapacitor storage systems: A comparative critical review", *Innovative Smart Grid Technologies-Asia (ISGT ASIA), IEEE*, pp. 1-6, Nov. 2015.

[13] S.R. Raman, X.D. Xue and K.E. Cheng, "Review of charge equalization schemes for Li-ion battery and super-capacitor energy storage systems", *Advances in Electronics, Computers and Communications (ICAECC), IEEE Int. Conf. on*, pp. 1-6, Oct. 2014.

[14] P. Thounthong, V. Chunkag, P. Sethakul, B. Davat and M. Hinaje, " Comparative study of fuel-cell vehicle hybridization with battery or supercapacitor storage device", *IEEE Trans. Veh. Technol*, 58(8), pp.3892-3904, 2009.