http://dx.doi.org/10.5755/j01.eee.20.7.8020 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 20, NO. 7, 2014

Powering Environmental Monitoring Systems in Arctic Regions: A Simulation Study

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***Abstract*—This paper describes a long-term simulation of an environmental monitoring system. This innovative approach combines harvesting-aware power management with primary batteries used as a back-up. It significantly extends the operational life of the device, while avoiding loss of data due to insufficient solar energy during winter in the harsh Arctic environment. The simulation considers the device to be located in the Arctic environment. Its main operation modes involve measurement from sensor interface, data storage and transmission. To perform an effective data-for-energy exchange, the device is controlled by a fuzzy energy management strategy. The new structure of the fuzzy rule-based system independently controls two separate variables related to data collection and the operation of a data buffer. The simulator uses meteorological data from Inuvik, Northwest Territories, Canada, to estimate the amount of energy available for solar harvesting. This site, located above the polar circle, receives very limited amounts of solar radiation during winter. Operation of the device is evaluated over a two-year period. The simulation results are described both numerically and using time-series plots of energy- and data-related variables. The performance is adequate for unsupervised operation of the system with annual maintenance visits to replace batteries.**

***Index Terms*—Energy management, simulation, arctic, solar harvesting, environmental monitoring.**

I. INTRODUCTION

Implementation and deployment of solar-powered environmental monitoring systems (EMS) in Arctic regions has a number of challenges related to the energy supply and management [1]. The solar radiation in circumpolar regions has a wide range of intensities throughout the year. During the winter season, when sunlight is unavailable for several months, it is necessary to use an energy reserve, e.g. in form of primary batteries. EMSs must collect data (e.g. CO_2, photo-synthetically active radiation, soil moisture) independent of weather conditions. To facilitate their continuous operation, they must be equipped with a controller that can perform efficient energy management interventions, e.g. to modify their operational duty cycle [2].

A generic model of EMS was introduced in [3], including a simulation study of its deployment in subarctic regions of Canadian boreal forest. In this contribution, the system has been expanded by including the energy reserve to support its independent operation in the Arctic. Simulation results confirm the suitability of the new, expanded energy management system for operation in the harsh environment of the Arctic.

This article is organized in five sections. The second section provides the background information. It is followed by the description of energy management strategy and simulation results. The final section brings major conclusions and outlines possible directions for future work.

II. BACKGROUND

A. *Environmental Monitoring Systems*

This section, describes a general platform for EMS that can be powered by various energy sources [3]. Its basic block diagram is shown in Fig. 1.

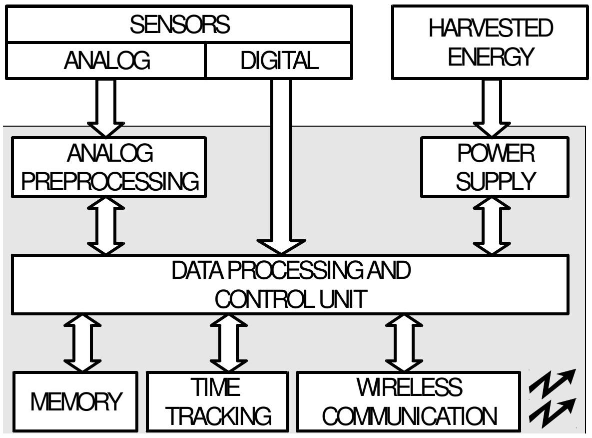

Fig. 1. A conceptual block diagram of the environmental monitoring system sensor platform (adopted from [3]).

The *analog preprocessing* block receives signals from analog sensors. It provides signal filtration, amplification and A/D conversion. Data from digital sensors is processed directly, without any signal conditioning. The *data processing and control unit* uses a microcontroller (MCU) to process the digital data from the sensors and sensor interfaces, and to coordinate all functions of the system. The *memory* block, implemented using non-volatile memory

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Manuscript received January 7, 2014; accepted May 23, 2014.
This work was supported by TECTERRA and by project SP2014/156, “Microprocessor based systems for control and measurement applications” of VSB-TU Ostrava.

elements, provides temporary or permanent storage of the collected data and EMS configuration. The *time tracking* module establishes the basis for accurate timekeeping by implementing a real-time clock. The *power supply* block provides the energy to power the sensor platform by converting power from a combination of energy sources and energy reserves.

B. EMS Simulator

The simulator (Fig. 2) contains four main function blocks: a solar panel, an energy reserve, a model of the system's hardware load, and a software controller responsible for balancing energy harvest with load consumption [3]. The *solar simulator* models the energy harvesting subsystems of the platform. Weather data, collected at the planned deployment site, is used to approximately determine how much energy can be harvested over given deployment period [3]. The solar irradiance values pass through a simple model of the panel that takes into account the area of the solar cells and their average efficiency. This simplification is adequate for the current stage of the development, but it will be replaced by a more sophisticated model in the future. The solar management models the operation of an energy harvesting circuit including maximum power point tracking (MPPT), and storage charging and state monitoring [4].

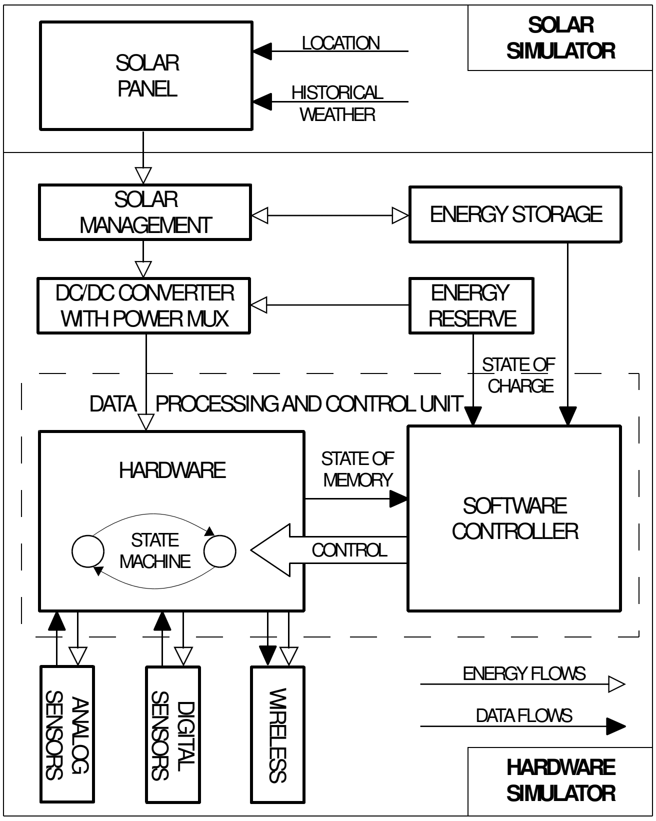

Fig. 2. A block diagram of the simulator (based on [3]).

Remaining physical components of the sensor platform are modeled within the *hardware simulator* block: DC/DC converter with power multiplexer (MUX), energy storage, energy reserve, sensors, and wireless communication module. This block focuses on the energy consumption of individual hardware components, and keeps track of the energy available in the storage elements of the platform. A state machine monitors (i) the length of time each hardware component operates, (ii) what operational mode it is in, and (iii) how much energy it consumes. In other words, while the solar simulator is concerned with producing energy through energy harvesting, the hardware module represents energy storage and consumption. The load of the system corresponds to the amount of energy needed to produce data through measurements and store or communicate them to the user. For simulations described in this article, the energy consumption levels have been set as follows: sensors 2 J, data buffer 322 μJ, permanent data storage 2 mJ, data transmission 15 mJ.

An important characteristic of the energy subsystem is that when solar energy is unavailable in the energy buffer [3], the hardware is powered from the energy reserve [5] consisting of two 1.5 V/3.8 Wh lithium batteries. In the modelled case, the buffer represents a bank of supercapacitors, while the reserve is based on primary electrochemical batteries. The operation of this module physically executes the exchange of energy-for-data [6].

To estimate the output power of the solar panel, it is necessary to use a suitable source of data on the time distribution of solar irradiation at the planned deployment location [4]. There are several databases available for energy-related studies. TMY3 [7] data for Inuvik, Northwest Territories (NWT), Canada, is used in this work, as it corresponds to one of the Arctic locations of our interest.

III. ENERGY MANAGEMENT STRATEGY

The energy management strategy observes two state variables: the moving average of the relative size (percentage) of the energy buffer $E(t)$, and the current proportion of the data buffer occupied by recorded data $D(t)$. This provides the control module with important information on how to invest energy. The average energy buffer level is a proxy to the (average) energy available in the environment. The use of average instead of the instantaneous vales of energy available serves to filter out intermittent changes of solar irradiation caused, e.g., by passing clouds. The continually changing solar energy availability would cause abrupt changes of device operation mode, affecting the quality of data records, and possibly wasting energy. The instantaneous energy buffer levels oscillate with a daily cycle, but the average levels change with seasons [3]. Very low (or zero) average values indicate winter with low (or null) solar energy availability. This is a signal for the controller to reduce the operational level of the device to a minimum to conserve the finite energy reserve [7], [8]. The data buffer level informs the controller when storage operations are required to ensure that data is not lost (overwritten) due to buffer overflow. The use of this buffer serves to further conserve energy by chunking transfers of data to permanent storage (SD card) and thus avoiding its excessive accesses associated with a substantial energy overhead.

The control module is based on a fuzzy rule-based system developed using expert knowledge connecting the two states, energy buffer $E(t)$ and data buffer $D(t)$, to two control actions, measurement cycle $M(t)$ and data transfer $T(t)$

$$\text{IF } E \,\&\, D \text{ THEN } M \,\&\, T. \tag{1}$$

However, the device does not perform any extensive computations [7], [8]. The actual control module determines its actions from a pre-computed lookup table. The entries of this table hold the control actions and are accessed based on the state information described above. An example of a fuzzy rule-based energy management system used in a different deployment environment can be found in [3].

IV. RESULTS

The energy related output of the simulator is shown in Fig. 3. The first plot describes the hourly level of energy buffer. The flat top of the plot at the 100 % level indicates that the energy buffer was filled and the extra available energy was wasted during summer months. During winter, the buffer becomes empty. All energy is used up, but the buffer cannot be recharged due to the lack of insolation. Eventually, the supercapacitors completely discharge and drop to the 0 % level.

The second plot describes the percentage of charge available in the primary batteries. It can be seen that the reserve energy is only needed during winter. Once the device switches to the reserve, it remains dependent on the reserve energy until spring when the buffer starts recharging again.

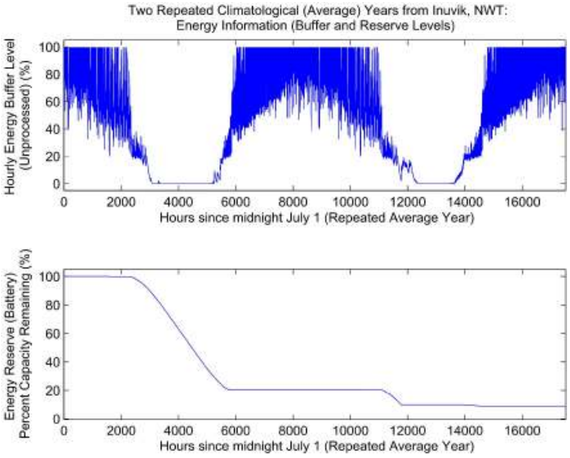

Fig. 3. Energy related output of two years simulation. Upper plot describes hourly energy buffer level in percent. Lower plot shows remaining capacity of primary batteries in the energy reserve.

The data-related output of the simulator is shown in Fig. 4. Measurement and transmission are the two major activities responsible for energy consumption. The number of measurements collected and transmitted per hour (upper plot) is related to the activity level of the device. This plot follows the availability of energy from the environment. The large oscillations in the fall of each year are due to the significant reduction of daylight in the polar region. In contrast, during summer the sun sets only briefly, or not at all, and thus there is plenty of solar energy available. During winter, the sunlight is very scarce or completely nonexistent during polar night.

During the first year, the energy reserve prevents the device from failing by ensuring its continued winter operation, albeit at the minimum activity level (duty cycle). However, the reserve is fully exhausted during the second winter of continuous operation. The device then ceases its functioning until spring when the renewed sunlight starts to charge the energy buffer and operation resumes.

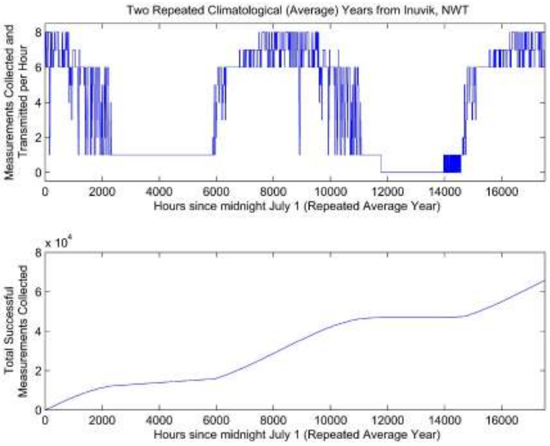

Fig. 4. Data related output of the simulator. Upper plot counts Measurements Collected and Transmitted per Hour. Lower plot is the Total Successful Measurement Collected during operational period.

The bottom plot shows the number of data points captured over the year. It is effectively an integration of the upper plot. During the summer the value increases quickly, because a large number of measurements are captured as a result of operation in full duty cycle.

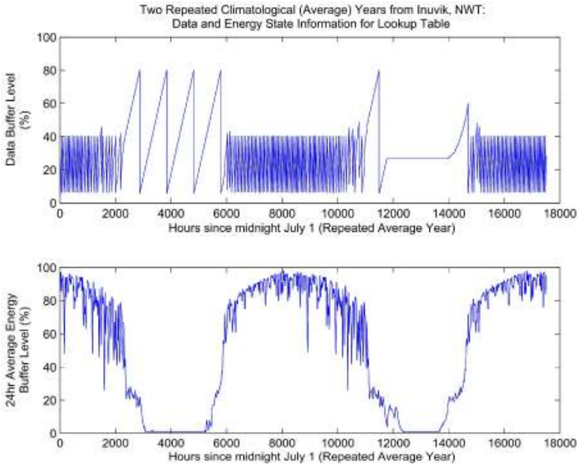

Fig. 5. State related output of the simulator. Upper plot describes data buffer (EEPROM) level in percent. Lower plot shows day average of energy buffer level in percent.

The state of the device is shown in Fig. 5. The upper plot shows the data buffer level. First, data are stored to the internal buffer (an EEPROM memory). When the number of measurements taken per hour is high, the buffer fills quickly and must be frequently emptied to the permanent storage (SD card). During winter, data is not collected as often and the data buffer fills very slowly or not at all. This is obvious from the dense and oscillatory waveforms during summer and the wide, slow waveforms during winter. During the second year, the device fails, but the data is safely stored in the permanent memory. Data collection then resumes with the overall restoration of the device.

The bottom plot shows the 24 hr moving average of the percent energy buffer level. It can be seen that the energy buffer (the supercapacitor bank) completely depletes during both simulated winters due to low (or nil) insolation. Very high averages, particularly during the summer months, indicate that some available energy is being wasted. The energy buffer remains at maximum for the most parts of the summer days, so the average is close to 100 %.

Numerical description of the simulations is shown in Table I. The data is divided into two years that are analyzed separately to allow comparison. The table clearly shows how the fully functioning energy reserve supports operation of the device during the first year. During the second year, the performance clearly suffers from the reserve depletion.

TABLE I. SIMULATION RESULTS (INUVIK, NWT, CANADA).

Simulation period	1st year	2nd year
Simulated hours (index)	1 - 8760	8761 - 17520
Total # of failures/year	0	2519
Total # of measurements/year	34140	31666
Relative number of failures	0 %	7.95 %
Hours failed per year	0 %	28.78 %
Total energy harvest	95.487 Wh	95.487 Wh
Total reserve energy consumed	6.0505 Wh	0.8688 Wh
Energy per sample (average)	2.974 mWh	3.042 mWh
# of measurement/Watt hour	336.2283	328.6341

During the 1st winter, the device does not fail. However, once the reserve is largely used up, the device becomes vulnerable. This is obvious from the percentage of hours failed per year: almost 29 % of the 2nd year, the system cannot produce any data with at least one hour sampling frequency. The abundance of data produced during summer cannot compensate for this massive data loss.

The total amount of energy harvested each year is identical, because the same average year (the climatological year) was used twice in a row. The amount of consumed reserve energy shows how the batteries were used. Because of the finite size of the reserve, close to 90 % of its capacity were used in the 1st year, not leaving enough for the 2nd year.

From the total number of measurements per year, it is obvious that the winter measurements do not significantly impact the total number of measurements or the number of measurements per unit of energy. However, they have a significant influence on the quality of the collected data sets: the first set is complete with measurements throughout the year, while the other only provides measurements collected during spring, summer, and fall.

The data collected during the 1st year (with the energy reserve present) is more valuable than the second data set. The 2nd year did have a small amount of reserve energy left to consume. However, this amount was not sufficient to power the system through the winter. This demonstrates that matching the size of the energy reserve with the demand of the device is very important. The reserve only makes a difference when it is adequately sized. In the simulated configuration, the reserve was sufficient to carry the device through one full season, but would have to be replaced annually to ensure its continuous uninterrupted operation.

V. CONCLUSIONS

This article presents a simulation of a solar powered EMS with energy reserve. The simulation, implementing a fuzzy control energy management strategy, was performed using an MATLAB Simulink-based tool and climatological data from Inuvik, NWT, Canada. The simulation results demonstrate the importance of the energy reserve in environments that have irregular supply of energy available for harvest. In the modelled case, the lack of adequately-sized energy reserve caused a significant portion of consecutive measurement to be collected with insufficient sampling frequency. The simulated energy reserve was almost depleted after one season of operation and the system did not survive another winter without major data loses.

The simulated energy management strategy above is not optimized. However, its optimization using computational intelligence methods [8] is expected to further improve its performance. In addition, there are two other possible solutions to the data loss issue: (i) the primary batteries would have to be replaced annually during regular maintenance visits, or (ii) the primary batteries could be substituted by secondary (rechargeable) batteries charged by the excess energy available during the summer.

The simulation results have been used for development of the software controller, currently being implemented in the fabricated hardware device. As the next step, the completed device will be tested for long term functionality.

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