Samrt Structures and Systems, *Vol. 11, No. 5 (2013) 555-567*
DOI: http://dx.doi.org/10.12989/sss.2013.11.5.555

Energy harvesting techniques for remote corrosion monitoring systems

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(Received June 11, 2012, Revised November 25, 2012, Accepted November 30, 2012)

Abstract. An Remote Corrosion Monitoring (RCM) system consists of an anode with low potential, the metallic structures against corrosion, an electrode to provide reference potential, and a data-acquisition system to ensure the potential difference for anticorrosion. In more detail, the data-acquisition (DAQ) system monitors the potential difference between the metallic structures and a reference electrode to identify the correct potential level against the corrosion of the infrastructures. Then, the measured data are transmitted to a central office to remotely keep track of the status of the corrosion monitoring (CM) system. To date, the RCM system is designed to achieve low power consumption, so that it can be simply powered by batteries. However, due to memory effect and the limited number of recharge cycles, it can entail the maintenance fee or sometimes cause failure to protect the metallic structures.
To address this issue, the low-overhead energy harvesting circuitry for the RCM systems has designed to replenish energy storage elements (ESEs) along with redeeming the leakage of supercapacitors. Our developed energy harvester can scavenge the ambient energy from the corrosion monitoring environments and store it as useful electrical energy for powering local data-acquisition systems. In particular, this paper considers the energy harvesting from potential difference due to galvanic corrosion between a metallic infrastructure and a permanent copper/copper sulfate reference electrode. In addition, supercapacitors are adopted as an ESE to compensate for or overcome the limitations of batteries. Experimental results show that our proposed harvesting schemes significantly reduce the overhead of the charging circuitry, which enable fully charging up to a 350-F supercapacitor under the low corrosion power of 3 mW (i.e., 1 V/3 mA).

Keywords: energy harvesting; cathodic protection; remote corrosion monitoring system

1. Introduction

Metal in the extraction from its ore has a natural tendency to revert to original state under the action of oxygen and water. This action is called corrosion and the most common example is the rusting of steel (West 1986). Coating is widely used to protect against the long term effects of corrosion. However, since partial defects can occur in the coating, more secure method is required to protect the metal against corrosion. In this reason, corrosion monitoring (e.g., Cathodic Protection) technologies are introduced in the industrial fields, in particular, to the metal pipeline systems which are for the transmission and distribution in gas, petrochemical, and water (Rieme

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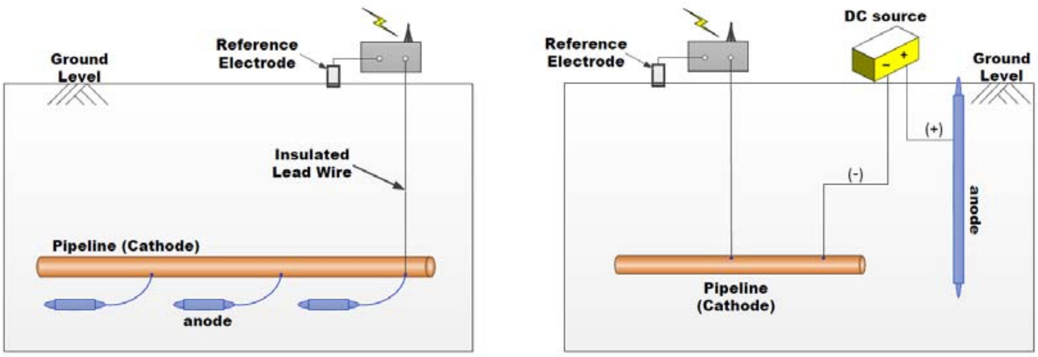
http://www.techno-press.org/?journal=sss&subpage=5 ISSN: 1738-1584 (Print), 1738-1991 (Online)

2000, Mohitpour *et al*. 2000, Peabody 2000). The principle of corrosion monitoring is to connect an external anode to the metal structures to be protected resulting in passing positive direct current (DC) between them. In this connection, the metal structure becomes a cathode which does not corrode, while the external anode is corroded. The DC current is utilized for a protective current by consuming iron of the anode (e.g., Al, Mg, and Zn). In other words, the anode is sacrificed by corrosion. It is, therefore, named a sacrificial anode system. Owing to the sacrifice of the anode, the system is required to periodically replace the sacrificed anode, which is incurring the maintenance cost. To avoid the issue, DC source is placed between metal structures and anode, and thereby the protective current can flow into the metal structures from the anode without any sacrifice of the anode. This system is called an impressed current system because the anode can have durability by the impressed current from the DC source. To determine whether both systems protect the metal structures against corrosion, a reference electrode (e.g., Copper/Copper Sulfate (Cu/CuSO4) or silver/silver chloride (Ag/AgCl)) is necessary. If the potential of the metal infrastructure against a reference electrode is obtained between - 2 V and - 850 mV, the corrosion is not processed. Fig. 1 describes these two types of corrosion monitoring (CM) systems.



(a) Sacrificial Anode System (b) Impressed Current System

Fig. 1 Remote Corrosion Monitoring (RCM) Systems

1.1 Remote Corrosion Monitoring (RCM) systems

The corrosion monitoring (CM) systems, especially *Cathodic Protection* (CP), are extensively applied to the metal pipeline systems because it can be simply employed by maintaining a voltage level and its effectiveness can be continuously monitored. For the effective operation of the corrosion monitoring, the smart sensing nodes are introduced to the pipeline systems (Jin and Eydgahi 2008, Qiao *et al*. 2011). As soon as the sensing nodes can detect or identify the incorrect voltage level between a reference electrode and a physical connection point of the pipeline, DAQ in the RCM system reports the measurement result to the central office. This measurement needs to be performed by monthly or bi-monthly at the several test points in the compliance with NACE guidelines. In case of the conventional monitoring process for the CM systems, the measurements are manually carried out employing a digital multimeter on the site.

To avoid the inconvenience of this manual measurement, an *remote corrosion monitoring* (RCM) system has been growing interest in recent years. In more detail, after the RCM system monitors the voltage at the test points on the site, if the voltage level is out of threshold level, then the system immediately reports the measured data to the central office. The RCM system is typically equipped with three main functions: corrosion sensing, data acquisition, and wireless data transmission (Blaricum *et al*. 1998, Kumar and Stephenson 2007, Al-Faiz and Mezher 2012). The RCM system is powered by a battery to activate these functions in a timely manner. The duty-cycled operation based on power modes (i.e., active and sleep modes) is helpful in extending lifespan of the monitoring systems. Even though such advanced power management techniques can achieve a reduction of power consumption of sensing nodes, battery-based powering can be still a limiting factor because it entails periodic replacement cost.

1.2 Energy harvesting techniques

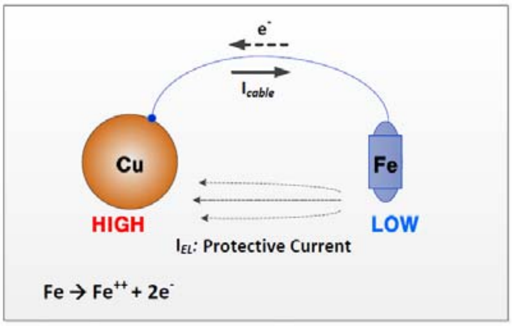
The typical RCM systems are powered entirely by batteries because of their cost, energy density, and maturity of technology. However, since they can suffer from non-ideal effects such as the memory effect and the limited number of recharge cycles, they can be the main limiting factors associated with the current RCM system. For this reason, supercapacitors, also known as ultracapacitors or electrochemical double layer capacitors (EDLCs), have emerged as a potential energy storage element (ESE) for subwatt-scale energy harvesters. This is because supercapacitors have extremely long life cycles, high power density, and eco-friendly materials (Brunelli *et al*. 2009, Kim and Chou 2011). However, scavenging energy from galvanic corrosion and storing the harvested energy to supercapacitors pose new challenges on designing subwatt-scale harvesters. The difference in the corrosion potentials between an anode and a reference electrode (i.e., -2 V~ -850 mV) is not directly usable unless up-converted to CMOS voltage levels, but this incurs nontrivial overhead. Namely, the corrosion potentials would not produce the complementary metal oxide semiconductor (CMOS) voltage levels. Furthermore, the current from the RCM environments would be varying from 2~4 mA depending on the soil condition surrounding a single reference electrode. Since such current is a small amount of current, and even it could be almost equal to the leakage current of larger size supercapacitors, it has difficulty in fully charging supercapacitors due to their high self-discharging rate. In order to ensure the feasibility of the energy harvester for the RCM system, these issues must be addressed.

2. Background and related work

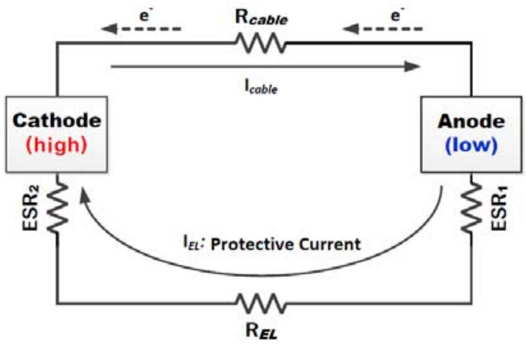
Corrosion is an electro-chemical process related to the electrical currents on a micro or macro scale. This corrosion process is produced by the natural potential difference in galvanic couples, or the variations at different points on the surface of metallic structures such as pipeline systems. To initiate the electro-chemical process, the following four components must be included: anode, cathode, electrolyte, and connecting conductor as shown in Fig. 2. Corrosion normally occurs at the anode but not the cathode.

2.1 Bimetallic corrosion theory

Bimetallic corrosion generates the galvanic currents by connecting two dissimilar metals buried in the soil (i.e., electrolyte). These galvanic currents produce as direct currents between two dissimilar metals, with an electrical conductor connecting them. Most soils contain moisture and mineral salts and thereby, it would be a good electrolyte. Fig. 2(a) describes the galvanic current resulting from the connection two dissimilar metals submerged in the electrolyte. If a copper and a metal (i.e., Fe) are electrically connected in the soil, the electrolytic nature of the soil gives rise to a galvanic action in which the copper acts as a cathode and the metal as an anode. In this closed circuit, the protective current (i.e., direct current) will flow through the soil from the metal to the copper. Metal ions leave the anode by way of the electrolyte, and electrons travel from the anode to the cathode by way of the cable connection path. This galvanic corrosion occurs only at the anode (Fe) while the cathode (copper) is protected. Fig. 2(b) shows the equivalent circuit for the galvanic current loop. The current flows are a result of potential difference (i.e., Icable · Rcable) between the anode and the cathode. The amount of current (Icable or IEL) flowing in galvanic couples depends on the magnitude of the driving voltage and the total effective resistance.



(a) Bimetallic Corrosion



(b)Equivalent Circuit

Fig. 2 Corrosion Mechanism; where, Rcable is cable path resistance, REL is electrolyte path resistance, ESR1 is apparent or effective boundary resistance at the anode, ESR2 is apparent or effective boundary resistance at the cathode

2.2 Supercapacitors for energy storage subsystems

Energy storage subsystem is one of the components for subwatt-scale energy harvesters. Although energy storage subsystem is not always required in an energy harvesting system, for the continuous power supplying under the insufficient ambient power conditions, it is almost always equipped with subwatt-scale energy harvesters. As mentioned in Section 1.2, supercapacitors can be an excellent combination with various ambient sources because the ESEs of the subwatt-scale harvester typically experience charging and discharging cycle almost every day. However, the non-ideal behavior attributed to substantial *leakage currents* and *charge redistribution* inside the supercapacitors should be addressed to use supercapacitors as ESEs of subwatt-scale harvesters (Brunelli *et al*. 2009, Zhu *et al*. 2010). The charge redistribution can be reduced by several repetition of charging-discharging cycles at the initial phase. However, the leakage currents are still considerable as well as inevitable issue. According to many literature on supercapacitors modeling, the leakage power of supercapacitors grows rapidly with the physical size and the remaining energy in a supercapacitor. For example, at 2.5 V, the leakage power of 22 F, 100 F, and 300 F is 2 mW, 7 mW, and 17 mW respectively. To charge supercapacitors efficiently at the RCM system, the leakage rate of supercapacitors should be overcome because the ambient power of the RCM system (i.e., 3 mW) is lower than the leakage power at the rated voltage of supercapacitors. For this reason, the capacitance of supercapacitors is limited when it is applied to the ESE of RCM systems. In this paper, we propose the *hysteresis charging scheme* which is helpful to extend the charging upper boundary of capacitance of supercapacitors.

2.3 RCM systems with energy harvesting

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Energy harvesting technique for RCM systems has been explored and studied by many researchers. The research approaches varied in their remote monitoring techniques, the types of corrosion monitoring system, and DAQ methods.

Mishra *et al*. (2000) introduced Solar Photovoltaics (SPV) instead of a DC power source of the impressed current type CM system. Since the output of the SPV is itself DC voltage, it is not required to rectify the alternating current (AC) source. Therefore, the advantage of the application of the SPV to the CM system is to eliminate the rectifier from the conventional impressed current system. The SVP-based corrosion protection system simply replaces the DC power source with SVP power, but there is no remote monitoring system for corrosion protection.

Ghitani *et al*. (Ghitani and Shousha 2000) presented a prototype microprocessor-based CM system employing photovoltaic (PV) energy. The PV array generates DC power from solar radiation, and a microprocessor-controlled unit enables the impressed current to make automatic adjustments according to the state of corrosion of the pipeline. However, since the pipelines generally run through inaccessible and remote locations, the PV power source would not be suitable to supply stable power to the RCM system.

Using the commercial off-the-shelf (COTS) wireless sensor node named Mica and Sun *et al*. (2011) provided the framework about the corrosion-monitoring sensor system for the reinforcing concrete (RC) structures. To reduce the power consumption of the Mica node, the system is applied to duty-cycled operation and routing policy. These technologies are helpful in extending the lifetime of the monitoring unit. However, this system adopting the Li-battery as a power source can entail additional replacement cost.

The main contribution of this research is the development of an energy harvesting technique from the galvanic current induced by natural voltage difference observed in the RCM systems. In this paper, we focus on improving the efficiency of charging and discharging phases of the supercapacitor-based energy harvester. First, we suggest a *hysteresis charging* scheme which is useful to charge the large capacitance of reservoir supercapacitors under the condition of low-power ambient source by offsetting the leakage of supercapacitors. The small capacitance of input supercapacitor accumulates the energy from the low-power ambient source, and then rapidly releases the accumulated energy to the large capacitance of reservoir supercapacitors within the hysteresis band. Accordingly, the instantaneously released charging current can overwhelm the leakage rate of the reservoir supercapacitors. Second, the hybrid-power sources are suggested to efficiently drive the target embedded loads in both active and low-power modes. Unlike batteries, since the voltage of supercapacitors drops as the stored energy is released, most supercapacitors usually need to be integrated with a dc-dc converter to provide suitable voltage levels with target loads. However, when the loads are in low-power mode, the efficiency of the dc-dc converter falls into under 50% due to extremely low load current. Our proposed scheme can address the problem by adding the near-constant voltage ESE for powering the load during sleep mode.

3. Harvesting system overview

The energy harvesting from solar irradiation is the most popular harvesting platform because it is higher power density ambient sources comparing to other sources such as vibration, wind, acoustic, thermoelectric, hydroelectric, etc. However, the deployed place of sensing nodes for RCM systems would not be accessible to the solar irradiation. Also, the power density of the ambient source from RCM environments is very low (i.e., ≤ 3 mW). Therefore, developing the energy harvesting techniques from this kind of ambient sources is a challenge. First, the total power consumption of a harvester should be lower than 1 mW. Second, the output current of the charger should be higher than the leakage of supercapacitors. Third, the efficiency of a dc-dc converter on the output stage of a harvester needs to be improved during the sleep mode of target embedded loads.

To solve these problems, we propose a new supercapacitor-based harvesting system, and validate the functions during both charging phase and discharging phase. Fig. 3 shows the block diagram for the proposed ultra-low overhead energy harvesting system.

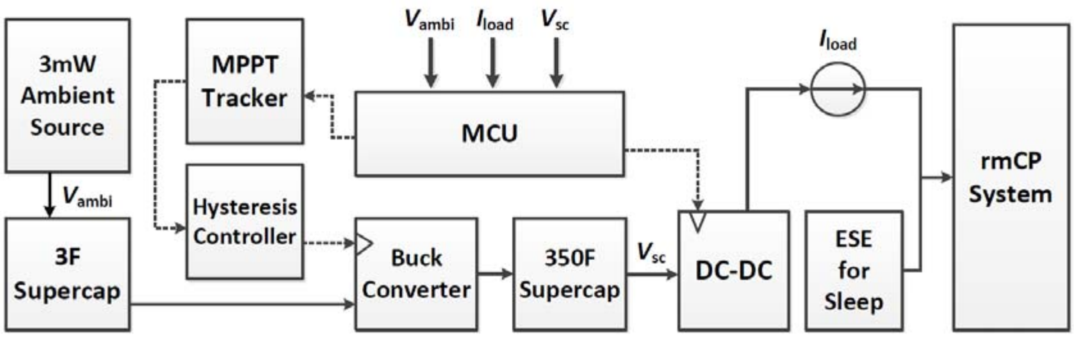
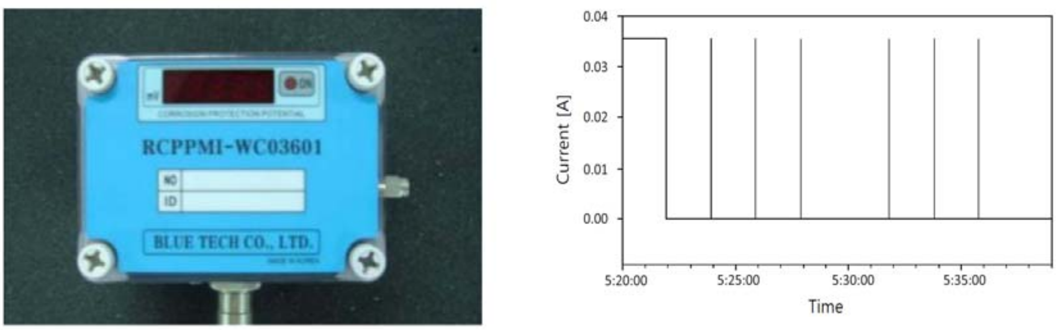


Fig. 3 System block diagram for an ultra-low power consumption harvester

3.1 Hysteresis charging scheme

The minimum conversion voltage (*V*conv, min) of a boost-up dc-dc converter is to be 0.7 V to date (Zhu *et al*. 2009). However, the efficiency of the input voltage, 0.7 V is under 30 % at the output voltage is 3 V. This is because most dc-dc converters operate most efficiently when the input and output voltages are similar. To ensure the efficiency of more than 75% and consider the minimum voltage of the ambient source of RCM systems, it would be better to fix input voltage of the charger by 0.9 V. As shown in Fig. 3, the power of the ambient source of RCM systems is 3 mW (i.e, 3 mA at 1 V), considering the charger efficiency of 75%, the output current from the charger is 0.75 mA. According to many references in the literature on supercapacitors, the leakage power of supercapacitors increases exponentially to the size and to the charged voltage of the supercapacitors. Accordingly, the leakage current of supercapacitors, in particular near the rated voltage, (e.g., 2.3 or 2.7 V) can be a main disadvantage. For instance, the leakage current of 300-F supercapacitors is around 15 mA at 2.5 V. Therefore, it is a challenge to charge the large capacitance supercapacitors up to 2.4 V using the low-power ambient sources. With the charging current of 0.75 mA, a 10-F supercapacitor can be the maximum size to charge up to 2.4 V. To overcome the high leakage issue, as well as to increase chargeable size of supercapacitors, we propose the new charging scheme: the ambient source, first, charges the small capacitance of input supercapacitor. When the charging voltage of the input supercapacitor approaches to preset voltage (1 V), the charger is turned on and then starts to transfer the stored energy to the reservoir supercapacitor (350 F) until the voltage of the input-supercapacitor drops to 0.1 V, which is in the hysteresis range. This is a useful technique to ensure the efficiency of the charger remains above 75 % by fixing the input voltage of the charging between 0.9 V and 1 V. Furthermore, the scheme can transfer higher current than the leakage current of reservoir supercapacitors so that it can be helpful in charging larger supercapacitors than typical capacitance charged by the conventional charging scheme.



(a) Corrosion monitoring node (b) Measured current of the node @ 3.6 V

Fig. 4 RCM node and its power consumption measurement

3.2 Discharging control

On account of the low nominal rated voltage of supercapacitors (e.g., 2.3 V or 2.7 V), most supercapacitors-base harvesters need to be equipped with a dc-dc converter, which can supply the specified voltage of the target embedded system. Buck/boost regulators are commonly used for converting a lower voltage of supercapacitors to the given target voltage. The embedded target system typically has two power consumption modes: active mode and sleep mode. The range of power consumption in active mode is from 100 to 150 mW (e.g., Mica2 at 3.3 V/16 mA (Crossbow 2004); iMote at 2.5 V/60 mA (Rice and B. F. Spencer 2008); Eco node at 3.3 V/30.8 mA (Chou 2011)) and that of sleep mode is from 1.8mW (3.6 V/0.5 mA) to 12.5 mW (5 V/2.5 mA). Assume the power consumption in sleep mode 1.8mW (3.6V/0.5mA), the efficiency of a load-side dc-dc converter drops to 5% at 3.6Vout. This means 36 mW is drawn from a reservoir supercapacitor to supply 1.8 mW to the target embedded loads. In other words, the efficiency of the load-side dc-dc converter can be a crucial problem when the target load is in sleep mode. Therefore, a key question to address the issue is how to efficiently use the stored energy of a reservoir supercapacitor during sleep mode.

We add additional energy storage elements (ESEs) to the output port of the load-side dc-dc converter, which is in charge of supplying power to the target loads in sleep mode. According to Fig. 3, the current sensor detects whether the target embedded load is in active mode or in sleep mode. When it is in sleep mode, the output of the current sensor goes to low level (Logic = ‘0’), which disables the load-side dc-dc converter during sleep mode. When either the current sensor detects the high current in active mode or the voltage of the additional ESEs drops to the required range of the target embedded loads, the load-side dc-dc converter is turned on. This discharging scheme can be helpful to address the inefficient operation of the load-side dc-dc converter during sleep mode of target embedded loads.

(a) Prototype board (b) Harvester w/enclosure

Fig. 5 Prototype harvesting system for an RCM node

3.3 Implementation

This section presents the prototype harvesting system for RCM systems. First, the power condition of the ambient source of the RCM systems and the power consumption of the RCM node are as follows:

Ambient Source Conditions: The potential on the conductive wire has a minimal of – 850 mV relative to a CuCuSO4 reference electrode, and the current density from reference electrode is 2~4 mA depending on the soil condition surrounding a single reference electrode.

In this reason, the overhead of harvesting circuitry should be less than 1 mW, therefore it is necessary to develop the low overhead charging circuitry to charge the ESEs of harvesters.

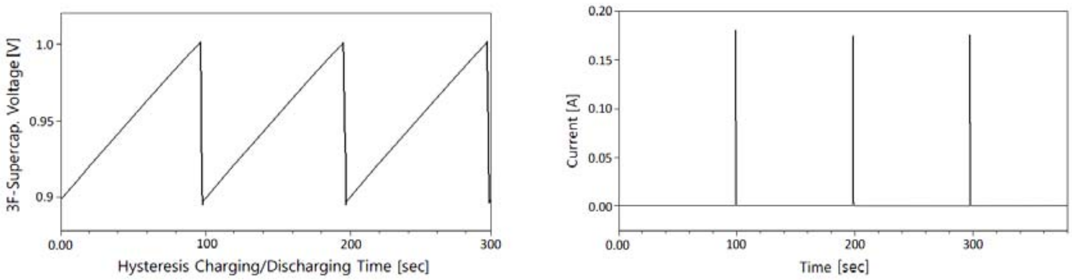
Power Consumption of an RCM node: Fig. 4 shows an RCM node and the current measurement result at 3.6 V in both active mode and sleep mode. The power consumption of the RCM node is 126 mW in active mode, and 1.1 mW in sleep mode. In fact, the 0.3 mA is the *root mean square* (RMS) current because the sleep mode consists of periodical catnap signal as shown in Fig. 4(b). The duty cycle to monitor the potential between a wire connected to pipelines and a CuCuSO4 reference electrode is 2 %.

Based on the characteristics of the ambient source and operational conditions of the RCM node, the proposed hysteresis charging and discharging schemes are implemented using COTS parts as shown Fig. 5. The boost converter (i.e., TPS61200) has built-in hysteresis function and ultra-low quiescent current (IQ) of less than 55 uA. The hysteresis band can be extended by adjusting external resistive voltage divider resulting in the lower boundary voltage of 0.9 V and high boundary voltage of 1 V. As mentioned in Section 1.2, the voltage and the current of the ambient sources from corrosion monitoring systems could be varying depending on soil conditions, thus the charger needs to track the maximum power point (PMPP) from RCM environments. In other words, the microcontroller unit (MCU) detects the change of the open circuit voltage between an anode and a reference electrode. If the range of voltage variation goes over 0.2 V, the MCU is awakened by the interrupt routine, and then moves the center voltage of the hysteresis band by adjusting the digital potentiometer on the resistive voltage divider. As a result, the hysteresis band can be placed between 1.1 V and 1.2 V, Consequently, the efficiency of the boost converter can be increased.

In addition, the current sensor monitors the load current to detect whether the power modes of the RCM node is in active or in sleep mode. According to the Table 1, the overall power consumption of the proposed harvester is 0.59 mW with 2% duty-cycled operation.

Table 1 Power consumption for each component

	Status	Power Consumption	Part Number
MCU	Active	4 mA@3 V	C8051F960
	Sleep	600 nA@3 V	
Boost Converter	Quiescent Current	55 uA	TPS61200
Hys. & MPPT	Quiescent Current	3.3 uA	AD8603, LT6656
	Shutdown Current	< 1 uA	
Current Sensor	Supply Current	0.75 uA	MAX9610



(a) Hysteresis band (b) Transferred current

Fig. 6 Hysteresis operation during charging phase

Considering deployment to the harsh environmental conditions, both the NEMA 4+ enclosure and the conformal coating made of modified polyurethane resins (PUR) are applied to the harvester for the RCM system. The enclosure would be helpful to protect the harvester against heavy rain, high humidity, and high temperature, while the conformal coating is useful to insulate the assembled printed circuit boards (PCBs) from the harsh environmental conditions.

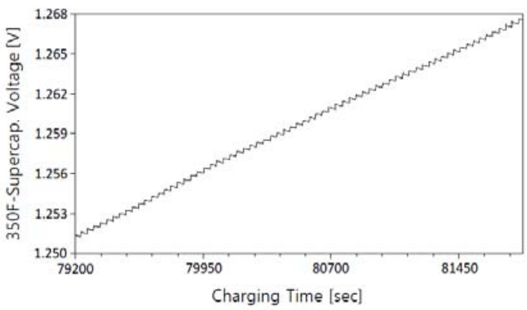
4. Experimental results

To validate the proposed charging scheme, we setup the experiment using a 3-F input supercapacitor and a 350F-reservoir supercapacitor (BCAP0350). The power condition of ambient source is simulated by 3 mW(i.e., 1 V/3 mA) using a power supply. The hysteresis window size is 100 mV; that is, the hysteresis range is preset from 1 V to 0.9 V of the 3-F input supercapacitor.

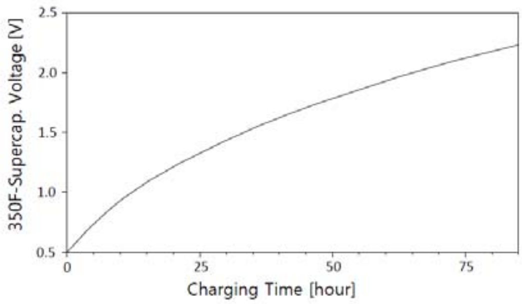
4.1 Hysteresis operation

The typical supercapacitor charger continuously transfers the stored energy of an input ceramic capacitor to either loads or ESEs. Since the value of the input capacitor is related to the efficiency and the amount of ripple of the charger, tens or hundreds of microfarad is usually suitable to the input capacitance. However, considering supercapacitors as a reservoir ESE (i.e., primary energy buffer), in case of low ambient power condition, it is difficult to charge the large capacitance of supercapacitors due to its high leakage current. In order to compensate or overcome the high leakage current of supercapacitors, we replace the input ceramic capacitor with a 3-F supercapacitor. In this experiment, we assume ambient source has the power condition of 3 mW, therefore, maximum power point of the ambient source can be 0.95V considering the built-in hysteresis band of 100 mV. The MPPT tracker adjusts the center voltage of hysteresis comparator to *V*MPP of 0.95 V.

Once the voltage of the 3-F supercapacitor approaches to *V*MPP+*V*Hysteresis (≈ 1 V), the hysteresis controller turns on the boost converter, and then transfers stored energy to the 350-F reservoir supercapacitor. Just after transferring the stored energy, the voltage of 3-F supercapacitor drops to *V*MPP-*V*Hysteresis (≈ 0.9 V). At that point, the hysteresis controller turns off the boost converter. As a result, the energy of ambient source starts to accumulate at the 3-F supercapacitor until its voltage is higher than *V*MPP+*V*Hysteresis. Fig. 6 summarizes how hysteresis operation works on the prototype energy harvester. The charger transfers the stored energy from the 3-F input supercapacitor to the 350-F reservoir supercapacitor at the rate of 175 mA for 98 seconds. The delivered current of 175 mA is much higher than the leakage current of the 350-F supercapacitor.



(a) Zoom-in the measured voltage



(b) Reservoir scap. charging

Fig. 7 Measured Charging Voltage of 350F

175mA for 98 seconds. The delivered current of 175 mA is much higher than the leakage current of the 350-F supercapacitor.

4.2 Charging phase

According to the data sheet of the BCAP0350, the leakage current of the 350-F supercapacitor is 0.30 mA. However, this leakage current is measured after 72 hours at 25°C and rated voltage. Therefore, the initial leakage current can be around 1 mA at 2.2 V. In Fig 6, the hysteresis charging scheme can deliver 175 mA at every 98 seconds, while the total leakage current during 98 seconds is about 98 mA. Therefore, during one charging cycle, the proposed hysteresis charging scheme is able to charge the 350-F reservoir supercapacitor under the low ambient-power source of 1 V/3 mA by using the proposed charging scheme. This is because the charging current is 77 mA, which can be overcome the leakage rate of the 350 F-reservoir at the rated voltage.

Fig. 7(a) reveals the 350 F-reservoir supercapacitor is eventually charged while repeating between a higher charging rate and a lower self-discharging rate. The leakage current is rapidly increasing near the rated voltage of the supercapacitor and as the voltage of the supercapacitor approaches the rated voltage, the charge rate decreases. Fig. 7(b) shows the measured voltage based on the combination of a 3-F input supercapacitor and a 350 F-reservoir supercapacitor. The 350-F supercapacitor has been charged to 2.0 V after 3 days using the hysteresis charging scheme.

5. Conclusions

In this study, it has been validated for our proposed supercapacitor-charging scheme to be feasible to harvest energy from RCM environments. We first define the requirements to design harvesting system design, and then prove its operational functions such as hysteresis, current delivery, and charging capability by the laboratory experiment. The experimental results show that the proposed scheme can charge supercapacitors of up to 350-F, which is larger than upper bound achieved by all previous COTS supercapacitor. In more detail, this scheme makes it possible to implement the supercapacitor-based energy harvester chargers at this very low power level; that is, the proposed scheme enables supercapacitors to use reservoir ESEs (i.e., primary energy buffers) because it can charge larger capacitance-supercapacitors by overcoming the limitation of the previous COTS charger, which can charge only 1-F supercapacitor at this very low power level. In short, the proposed harvesting circuitry will enhance the charging ability under the low-power ambient source and improve the efficiency of the harvester systems.

Further study includes system-level optimizations and real-world evaluations. The dedicated MCU of the prototype harvester can be eliminated by moving its functions to an existing MCU, such as the one on an RCM node. It will save component cost while adding little software overhead, especially if the MCU is under-utilized in the first place. We are planning to deploy our proposed harvesting system to verify its performance in the real-field application for RCM systems.

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