A Dependable Infrastructure of the Electric Network for E-textiles

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Abstract

Electronic textiles, known as computational fabrics, offer an emerging method for constructing wearable and large area applications. Because e-textiles are battery-driven and fault-prone systems, there is a need for developing a dependable infrastructure of the electric networks for e-textiles. In this paper, a new infrastructure of the power networks for e-textiles, Flexible Power Network (FPN), is presented. Instead of drawing power from a fixed battery as in the conventional electric networks, the power consuming nodes in a FPN can obtain power energy from one of the choices of batteries available with the help of the battery selectors. We also introduce the over current protectors into the battery nodes (BN) to protect the batteries from wasting the charge when short-circuit faults occur. The electric features of battery selectors and over current protectors, the two types of important electric devices used in FPNs, are illustrated in the paper. We have performed simulation experiments and the results show that our FPNs are more dependable than some common electric networks published before in the cases of short- and open-circuit faults.

1. Introduction

Electronic textiles are fabrics with electronic components, inter-connections and power supplies woven into them. They are an emerging approach for constructing wearable and large area applications [1-5]. Researchers in materials and textiles have presented new fibers, which can be used as speakers, durable wires and batteries [6]; new packaging technologies for electronic circuits give permission to manufacture practical electronic textiles [7]. Several prototypes based on e-textiles are documented in the papers and websites available [8-12].

As a kind of the novel computing substrates, e-textiles represent an extreme form of distributed computing [9] [14]. With lower communication bandwidth, all the electronic nodes in e-textiles are distributed in a relatively small space and they only have less available energy. In fact, e-textiles applications may be deployed in inaccessible terrains. In these cases they are isolated from permanent power sources and the amount of charge in batteries is limited. On other occasions, when they are tailored as a wearable garment or other applications, tear and wear are highly frequent. The factors potentially introduce some short- or open-circuit faults into the power network in the e-textiles. Short-circuit faults can result in the rapid leakage of the limited charge of the system. Some electronic components in the e-textiles may have to stop their work due to open-circuit faults. Thus, the performance of operations will be greatly affected. Because the system is failure prone, electronic textiles suffer from more stringent constraints on power consumption and management than other battery-driven systems do. It is necessary for the infrastructure of the power network embroidered in the textiles to support fault-tolerant power management schemes. These power management schemes should (a) protect the battery from being discharged by short-circuit faults and prevent power consuming components from being disabled by open-circuit faults; (b) have the ability to prolong the operation lifetime of the systems by making use of the limited charge as effective as possible. Obviously the former can be achieved during the design of the electric networks' infrastructure, while the latter is involved with the battery-efficient and power-aware policies.

The main contribution of this paper is related to (a). A new infrastructure of the electric network for e-textiles, *Flexible Power Network* (FPN), is developed, which has good fault-tolerance ability in the cases of short- and open-circuit faults. Because of the autonomous ability of the nodes in the FPN, the nodes in the power networks can self-adjust their own behaviors if necessary and avoid

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the damage of the faults introduced into the e-textiles. Many classes of battery lifetime maximization policies and approaches can be designed based on the FPN. This part of work is to address the problems in (b), which are in progress.

The remainder of this paper is organized as follows. Section 2 describes the related works on e-textiles. We also discuss some necessary background materials about analog switches and over current protection circuits which are used in our electric network. In section 3, we introduce original features of electronic elements, which are of great importance to implement the new power network for electronic textiles. The principles of battery selectors are also illustrated to explain how we achieve the objective of selecting one of the power sources or batteries available. The difference between FPN proposed in this paper with the existing electric networks for e-textiles are described in the section 4. To verify our design, we compare our FPN with some existing electric networks using Matlab/Simulink tools. Finally, section 5 concludes this paper and points out the future work.

2. Background

The main areas related to the FPN range from the fault-tolerant electric networks to the power management policies for e-textiles. The background materials of analog switches and over current protection circuits are also introduced in the following subsections.

2.1. Related Works

E-textiles consist of many computing and sensing elements distributed on the fabrics. While computing, communicating and sensing elements are interconnected by a fault-tolerant *data communicating networks* [15-16], the power management schemes of all power consuming elements in e-textiles depend on an *electric network* composed of the conducted wires, batteries and power consuming elements. There are two kinds of wires in the power networks: one is the positive power line and the other is the ground line. The research on the electric networks of the e-textiles is in its infancy, without specialized documents reported.

The majority of the earlier works on power management of e-textiles have the assumption that the elements obtain power energy from a fixed battery [9] [13] [14]. When implementing, previous prototypes based their power management policies on the “fixed” electric networks in which the interconnecting relations of the nodes and the batteries are “one to one”. That is, “one” power consuming node is connected to “one” and “only one” battery or group of battery cells. This relation is determined by the “fixed” connection between the batteries and the power consuming nodes in the phase of manufacturing and can not be changed dynamically. In this paper, we called the power networks with the “fixed” connection as the conventional electric networks for e-textiles. The fixed network was adopted in the e-textile developed in a research group in Virginia Tech where one or several groups of nodes in the fabrics are connected to one battery or a set of battery cells. Simulations and experiments were conducted to search the best electric network schemes with performance versus system lifetime tradeoff. When some faults are introduced, only a part of fabrics can work and the charge stored in the batteries of these faulty circuits will be wasted due to the “fixed” connection relations.

Another research group proposed a novel concept of *dynamic fault-tolerance management* (DFTM) for e-textiles [13]. DFTM aims to encompass a broader range of constraints besides power consumption for battery-driven and failure-prone systems. These constraints include utilizing variations in both application and environment, extending maximal application lifetime in the presence of both energy and reliability constraints, with a possible tradeoff for performance. Their work is also based on the conventional electric network of “fixed” relation between batteries and power consuming electronic nodes.

As mentioned above, the capacity of a specific battery is limited and predetermined. Given that the electronic components are linked to a fixed power source, device failure is a regular event due to energy depletion or other faults of either wires or electronic components. To enhance the fault-tolerant ability of the electric network for e-textiles, we present a flexible power networks (FPN) in this paper. By introducing analog switches and over current protection elements into the nodes of e-textiles, we develop battery nodes (BNs) whose main parts are batteries with over current protectors, and design power consuming nodes (PCNs) whose main parts are computing/communicating components with both battery selectors and over current protectors. With the battery selectors, a PCN in e-textiles can attain power energy from one of the multiple batteries available in the electric network, which are connected to the PCNs by the redundancy of the power lines. The PCNs and BNs therefore become more autonomous than those in the previous works and are able to adapt their own behavior in the power network to avoid the influence of the faults.

2.2. Analog Switch and Over Current Protectors

An *analog switch*, the most ubiquitous integrated circuits (IC) in electronic systems, is a digitally controlled switch that provides a conductive path for a linear or

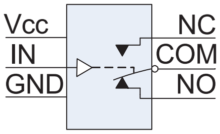

Figure 1. SPDT Analog Switch

analog voltage in its ON state. The most common analog switch, shown in Figure 1, is a single-pole dual-throw (SPDT) device that offers two separate choices of port NO or NC to the port COM for output. And the port IN is digitally controlled following the command from a microprocessor. Some of the newest precision analog switches can operate with power supplies between ±1.5V to ±12V, housed in SOT-23 packages, with ultra low power consumption at the scale of μW, and with fast switching response times (i.e., Turn-on and Turn-off times)[17]. The switch response times are a pair of significant parameters because in these critical intervals the processor in a PCN is selecting the appropriate power source and demanding the corresponding analog switches to perform this task fast.

Over current protection protectors are of great significance to protect the batteries from the rapid leakage of the charge when the short-current faults occur. With the advantages of low power consumption and small footprints, poly resettable fuses are chosen as the over current protectors to stop the leakage of the charge when the electric current is over the predetermined maximum value. And once the current is lower than the threshold, the fuse will recover and connect the components to the circuit. From the power consuming components' standpoint, the protected circuits will segregate the fault component from the circuit. Otherwise, this components with short-circuit faults will bring its faults to the power network.

3. The Flexible Power Network

The FPN is implemented as X-Y layout of a fabric for the reasons of its implementing on a textile backplane. The nodes in the FPN are classified into two classes: power consuming nodes (i.e., PCNs), and power providing nodes (i.e., battery nodes, BNs). With the redundancy of the power lines, these two kinds of nodes are interconnected into the new dependable infrastructure of the electric networks for e-textile applications. By adding the analogue switches or over current protectors to the nodes, we design the new Flexible Power Networks (FPN) with high fault-tolerant ability.

Power consuming components in e-textiles benefit greatly from the convenience of analog switches, the power lines redundancy and the over current protectors. By introducing the multi-throw analogue switches and over current protectors into processing/communication nodes in the e-textiles, their ability of self-management and adaptation is greatly improved. As illustrated in Figure 2, four PCNs and three BNs are interconnected as a part of the FPN which has n groups of PCNs and m BNs. Each PCN is connected to the m battery channels by the multi-throw analog switches in its battery selector. And each channel derives from one battery node, which is equivalent to the "fixed" power supply in the conventional electric networks. On the other hand, each BN offers a BN channel for every group of PCNs. That is, a PCN in the FPN can attain power energy from one of the m battery channels, while a BN provides its power energy to n group of PCNs by the new power network.

In the FPN, with the introduction of some open-circuit faults, the PCN in the fault loop can select another battery channel to obtain power energy and thus avoid the failure of being disabled. While short-circuit faults occurs in a

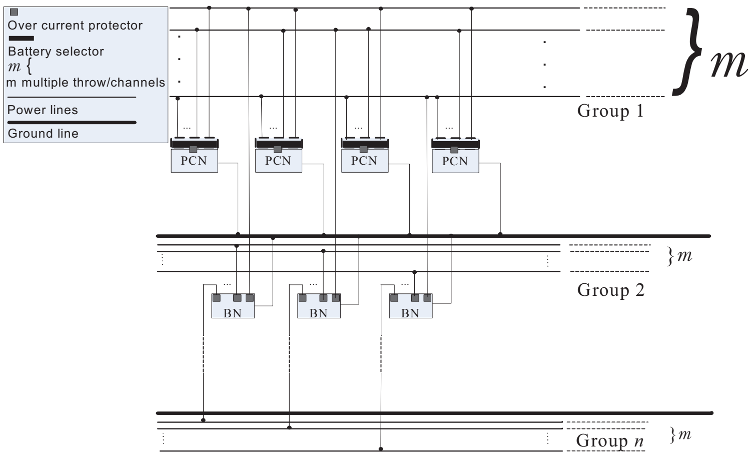

Figure 2. Topology of Flexible Power Network

PCN, the over current protector of the PCN will disconnect the PCN from the FPN. The short-circuit fault will be removed. From the point of the BN, when short-circuit faults occur between the pair of wires in one of its *n* channels, the corresponding BN will be isolated by one of the over current protectors within the current BN. The charge stored in the battery are protected from be wasting by the short-circuit faults. Due to the redundancy of the power lines in the FPN, a BN still can provide its energy to some PCNs unless all the power lines derived from this BN are open. Consequently, the FPN will be more dependable than the conventional electric networks.

3.1. Power Consuming Nodes with Battery Selectors and Over Current Protectors

The power consumption nodes of e-textiles are typically connected with each other by power lines (in electric networks) or communication digital wires (in communication networks). By a power consuming node (PCN), we mean the center power consumption element f an independent function cluster, which has the ability to control power modes, either of its own or of interconnecting elements in this cluster. An illustration of a PCN is shown in Figure 3. The part in the eclipse is a PCN with battery selectors of *m* battery choices. *m* is a number not larger than the total sum of the battery channels in the FPN, which is also decided by the multi-throw analog switches in the battery selector. A PCN consists of a conventional processing & communicating node, a DC-DC converter, an over current protector and battery selectors. The former two parts are the normal components for a node in conventional electric networks, while the latter two are introduced newly by the FPN.

DC-DC Converter. The state of charge and chemistry of a battery determine its output voltage, which is not well controlled during operation. Consequently, a battery cell can not be connected directly to the power consuming component, but it requires a DC-DC converter for stabilizing and shifting the voltage supply. With the DC-DC converter, a PCN can obtain stable power supply from the electric network.

Over Current Protectors. The over current protector in the PCN can monitor the current flowing through this node. Once the node fails with a short-circuit fault that leads to one channel of the corresponding battery in a short-circuit loop, the over current protector will disconnect the node from the connection to the battery and thus remove the short-circuit fault from the loop to prevent the charge of the battery being wasted. After the failure is removed from the node (if it can be removed), the over current protector will recover from the faults and reconnect the PCN to the circuit.

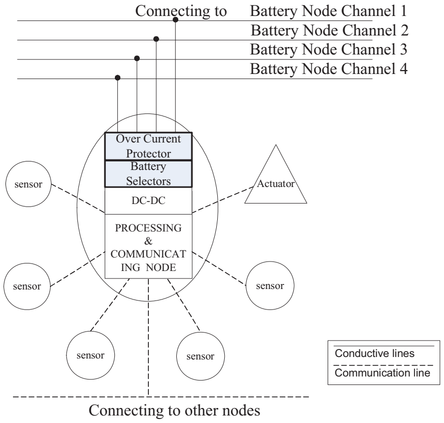

Figure 3. Power Consuming Node with battery selectors of 4 battery choices

Some system power management schemes depend on a few specific or common nodes to decide the connection choices of all nodes in e-textiles. Because of the high frequency of the faults in e-textiles, these schemes are less practical. The reasons for this are that some faults in those nodes taking charge of system power management will lead to the collapse of some fabric parts in e-textiles, even the whole system. A *power consuming node*, on the other hand, should be of enough intelligence to choose an appropriate battery from all battery candidates. In other words, we should enhance the ability of the nodes to perform some power management autonomously. It is the battery selector in each PCN that implements this goal. The most important modules in battery selectors are the *analogue switches* and its *self power circuits*.

Battery Selectors. As the critical part of battery selectors, multi-throw analog switches are introduced into the PCN in the power networks of e-textiles with the redundancy in number of power lines. The PCNs have the ability to select one battery from the *m* BN channels, since each power line is responsible to route the power energy from a single power supply (i.e., a BN Channel). The key problem in implementing this selector is how to design the self power circuit. Without this self power circuit, a PCN cannot fulfill the battery selection task if the PCN only relies on the analogue switches during the absence of the power supply. When a PCN connects to a battery and is in its stable working states, the self power circuit is charged to store enough energy. And while the PCN selects another power source and is disconnected from a battery, the self power circuit is discharged to offer the PCN power energy.

A simplified approach to implement the battery selector is shown in Figure 4. The processor monitors the

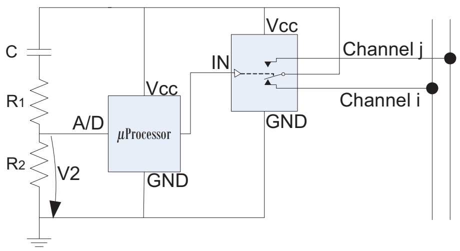

Figure 4. Simplified Circuits of Battery Selector

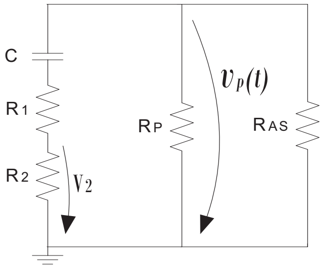

Figure 5. Equivalent Circuit of Simplified Battery Selector

state of the node (steady working or selecting battery) by detecting the voltage value V_2 across the ends of R_2 .The capacitance C is fully charged in the phase of proper working state when the node gets power energy from some battery with the index i among the choices available and the voltage value V_2 equals zero. When the PCN switches from battery channel i to j for some reasons, the capacitance C is discharged to provide power energy to the power consuming components in the node. There are two kinds of occasions on which a PCN wants to or has to perform battery channel switching. The first one is the depletion of the current battery channel; the second one is the introduction of the open-circuit faults in the loop on which the PCN has to perform the switching task. And the third one is the demand of some power management schemes on which the PCN is active. What the PCN need do on the last case is to obtain power energy from the self power circuit, while on the former two cases the PCN first need to determine when it should perform the switching task with some detecting mechanism. The detecting mechanism is a simple A/D converter circuit of the value of V_2 . When the PCN are in steady working state of obtaining power energy from some battery channel, V_2 equals zero. And while the battery is reaching its exhaustive point, the supply voltage will decrease lower than the proper battery voltage. Or for an open-circuit fault in the loop, the PCN is disconnected from the BN channel i. At this time, the energy stored in the capacitance is released. V_2 should be a negative value. The processor detects this phenomenon and then sends a control pulse that requires the battery selector to switch to the channel j from the current battery channel i according to some battery selection algorithm. The simplified circuit in Figure 4 is equivalent to the situation in Figure 5, a typical RC circuit.

Then the time constant T_0 in this circuits can be calculated as follows:

$$T_0 = (R_1 + R_2 + \frac{R_P R_{AS}}{R_P + R_{AS}}) \cdot C \tag{1}$$

where R_1 and R_2 denote the resistance value of R_1 and R_2 , respectively; R_P and R_{AS} represents the equivalent resistance value of processor with its necessary peripheral circuits in the node and the analog switches in the RC circuit, respectively. The values of R_1 , R_2 and C depend on electronic properties of the micro-processor and analogue switch chips. Firstly, the discharge stored in the capacitor C should be sufficient to support the operations of battery selection. Secondly, higher values of R_1 and R_2 can provide a larger time constant, thus a discharge current of greater stability. For simplicity, we denote $R_{P\,|\,AS}$ as in equation 2.

$$R_{P\,|\,AS} = \frac{R_P R_{AS}}{R_P + R_{AS}} \tag{2}$$

And we also define the following symbols as time tags: T_{start}^{ij} is the instant when a command pulse is sent to the control port of the analog switch for beginning a selection task. T_{end}^{ij} is the instant when the feedback signal, V_2 (i.e. the voltage value across R_2), reaches zero. Now, the critical switching interval Δt_s^{ij} from channel i to channel j can be obtained by the following equation.

$$\Delta t_s^{ij} = T_{end}^{ij} - T_{start}^{ij} \text{ , for } i \neq j \tag{3}$$

where $i, j \in \{1, 2, ..., m\}$; and m is the total number of battery channels available in the current PCN node. The intrinsic meaning of Δt_s^{ij} is the interval for a node switching from the previous steady working state to another steady one with the variation of connected battery. The steady working state is reached when V_2 equals zero, which also means the completion of charging of capacitance C and the stabilization of the circuit. Δt_s^{ij} mainly depends on the performance features of the analog switch, both the turn-on time and turn-off time. Here, we use the sum of the turn-on time and turn-off time as the approximate value for Δt_s^{ij} . Thus once the type of the analog switch is determined in design phase, Δt_s^{ij} is a constant.

From equation 2, 3 and Figure 4, the time-changing value $v_p(t)$ of voltage posed across the processor and the analog switch can be achieved by equation 4.

$$v_p(t) = \frac{R_{P\,|\,AS}}{R_1 + R_2 + R_{P\,|\,AS}} V_0 e^{-t/T_0} \qquad (4)$$

Where V_0 represents the voltage value across the two ends of capacitance C at the instant T^{ij}_{start}. Based on the analysis above, for enough self energy supply, it is necessary to hold the condition of inequality 5 during the switching state.

$$v_p(t) \ge V_c = \max\{V_{Processor}, V_{AS}\},$$

$$\text{for } T^{ij}_{start} \le t \le T^{ij}_{end} \qquad (5)$$

Then we can derive inequality 6 from equation 4 and 5, representing the necessary condition for one execution of battery selection task.

$$v_p(T^{ij}_{start}) \ge V_c e^{\Delta t^{ij}_s / T_0} \qquad (6)$$

For a node without its own faults, the inequality 6 is also the sufficient condition for an operation of the battery selection. With the appropriate values of R_1, R_2 and C, we can make the node meet this necessary & sufficient condition in design phase. Thus, the PCNs in the FPN can control their own behavior of selecting the battery channel on runtime occasions and the interconnecting relation of the BNs and PCNs can be dynamically adjusted.

3.2. Battery Nodes with multiple over current protectors

Besides the power-consumption nodes in the system, there is another kind of nodes, battery nodes, which consist of the battery and over current protectors. Similar to a PCN, a BN has multiple wires connecting to its two poles but without the analog switches. Figure 6 shows a battery node of the index i. It is connecting to n groups of PCNs because this BN has a number of *n* over current protectors.

For some kind of reasons, the positive pole may be directly connected to the negative one by some wires in the loop of current circuits or disabled PCNs. As a result, short-circuit faults are introduced to the loop, leading to the over current accidents. Given no protection measures, the energy in the corresponding battery will exhaust in a short time. Because the power energy is of great importance to e-textiles applications, the nodes should have the fault-tolerant ability to avoid this result. With the over current protector connected to the end of each positive wires, the battery nodes will be cut off from the short-circuit loop. It should be noted that operations of the over current protector only cut off the load of the short-circuit loop, having no effect on other groups of the PCNs connected to other over circuit protectors in the BN. Thanks to the characteristics of the poly resettable fuse in the module, the disconnected circuit with short-circuit fault will make a recovery from the open state after the current becomes lower than the cut-off voltage threshold.

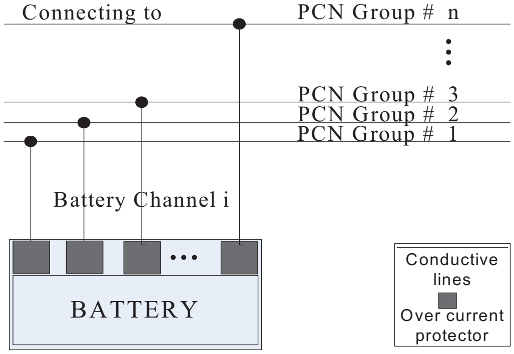

Figure 6. A battery node of the index i connecting to n groups of PCNs with a number of n over current selectors

4. Flexible Power Networks vs. Conventional Electric Networks for E-Textiles

It is clear to observe the difference between the power routing network proposed in this paper and the traditional power networks in e-textile applications. By using analog switches, over current protectors and the redundancy in channels of power wires, the new power network has the ability to adjust the topology dynamically. PCNs and BNs can change their own connecting relations autonomously. This feature of the FPN can have positive effect on fault tolerance ability of e-textiles systems.

4.1. Enhanced Fault Tolerance ability

From the development experience of various applications on e-textiles investigated [5] [8] [9], it is reported that the short- and open- circuits are highly frequent faults. Consider introducing the open-circuit faults to the FPN, due to the ability of the nodes to select another battery, the PCNs in the open circuit can still attain power energy unless all the choices available are in open loops. With the same faults in the common electric networks, the PCNs in this circuit are not able to work due to the nodes have only one choice of the power supply. The FPN gains the advantage over the traditional power networks because each PCN has the ability to select an appropriate battery channel in several choices. In addition, a short-circuit fault can be introduced into the loop by the wires or the PCNs. (a) When short-circuit faults are caused by wires, the BN will disconnect itself from the loop with the fault. The battery selector of the PCN in the same loop will then detect that the node is lack of power supply for the faults and make a switch off-and-on by a simple selection algorithm. After all the series of action, the node will be in a proper working circuit again. And the charge of the battery is protected from the direct discharging by the short-circuit faults. (b) When short-circuit is caused by a PCN, the over current protector of the PCN itself will first detected the fault. Then the PCN will cut off its connection to the battery channel. In the common electric networks, either (a) or (b) will lead to the critical result: the battery in the loop is directly discharged and all the power consuming elements in the loop can not work for the lack of power energy.

4.2. Overheads

To implement the enhanced fault-tolerant ability, the FPN has its own physical and electrical overheads. Redundancy of the conductive strands is the necessary condition to route the power energy of the variable batteries to the PCN groups. For the wires are much heavier than the threads, the FPN will attach additional weight to the e-textiles. And the cost of the nodes in FPN is more expensive than those in the traditional electric networks for the added analogue switches, resistances, capacities and fuses.

The analogue switches, the self-power circuit and the over-current protectors have additional power consumption. For the current flowing through the PCNs is the direct current, the capacitor C , the resistance R_1 and R_2 in Figure 5 do not consume any power energy in the proper working state of the PCN. Therefore, the additional power consumption for a switch task can be approximately evaluated by the following equation:

$$W_{add} = P_{add} \cdot \Delta t_s^{ij} \approx \frac{(R_1 + R_2) \cdot (P_{\mu P} + P_{AS})}{R_{P \mid AS}} \cdot \Delta t_s^{ij} \tag{7}$$

Where P_{add} is the additional power of the battery selector. $P_{\mu P}$ and P_{AS} represent the maximum power of the micro-processor and the analogue switches with their peripheral circuits. A minimum of these peripheral circuits is in work while the FPN are performing the battery selection. The duration of the battery selection, Δt_s^{ij} , is a parameter of millisecond. Furthermore, due to the small resistance of the fuse is in the milliohm range, the amount of power energy dissipated by the fuse is negligible.

4.3. Simulation Results

Experiments have been conducted in order to evaluate the effectiveness of fault-tolerance of the proposed power networks, FPN. We choose MatLab/Simulink as the simulation environment. To compare our power routing networks with the typical power supply schemes presented in [9] [14], we set the nodes in four configurations as shown in Figure 7 (8 PCNs, 4 batteries):

- case 1: one single battery for four fabrics
- case 2: two batteries for each pair fabrics
- case 3: individual battery for each fabrics
- case 4: a Flexible Power Network of eight PCNs and four BNs

Note that ground lines are not shown in case 1, 2 and 3 for the clarity in the Figure 7 and Figure 8. To simplify the problem, we assume that the batteries in the experiments are ideal and the stationary load of every node is equal. Nonlinear behavior of the batteries is not considered. Thus, the capacity of the battery obeys to the following equation:

$$C(t) = C_0 - I \cdot t \tag{8}$$

where C_0 is the open-circuit capacity of the battery, I represents the load, and t is the discharge time of the battery. The total charges of the four configurations are equal and it is $4C_0$.

From left to right, in Figure 7, the four fabrics are indexed as fabric 1, fabric 2, fabric 3, and fabric 4, while the four batteries are denoted as battery 1, battery 2, battery 3 and battery 4.

We consider the Poisson process as a model for the errors on the wire segment. Due to the paper limit, we are not able to model all the factors that are related to the faults in the electric network. Consequently, we only consider the fault occurrences on a special segment, illustrated in Figure 8, which is the dot-line segment labeled by a red square. This method can be expanded to a complete analysis for the fault tolerance ability of FPN by considering fault occurrence on all the line segments in the network.

The number of the short-circuit errors on the segment varies with the working time of the e-textile systems. Let $N_{short}(t)$ denote the number of short-circuit errors and let us assume the Poisson process has a rate of λ_{short} . Similarly, let $N_{open}(t)$ with the rate of λ_{open} represent the number of the short-circuit errors on the segment. It is reasonable to assume that the rate of $N_{short}(t)$ or $N_{open}(t)$ is linearly proportional to the length of a wire segment. In our experiments, we assume the length values of the special wire segment have the following approximate relations:

$$l_{case1} : l_{case2} : l_{case3} : l_{case4} = 2 : 2 : 1 : 4 \tag{9}$$

Our goal is to analyze the effect of the same faults on the electric networks of four cases. More specifically we will analyze the expected "lost" capacity in the electric network and the set of disabled nodes.

With the open-circuit error only on the segment discussed in Figure 8, the "lost" capacity caused by the open-circuit error is zero in case 1, 2 and 4. Because in these cases, all the four batteries are still connected to the electric networks and other proper nodes can drain power energy from them. While in the case of 3, the expected value of the "lost" capacity at the time t can be evaluated by $(1-e^{-t\cdot\lambda_{open}})\cdot(C_0-I\cdot t)$. Once the open-circuit error occurs in case 1, the four nodes in the fabric 1 and 2 are disconnected from the power network, and are disabled for the absence of power energy. The nodes affected by the open-circuit error in case 2 and 3 are the same as those in fabric 1. While in the case of the FPN, all nodes can still perform their task properly. Those nodes (among the nodes of the top row in the FPN of Figure 8), which are obtaining power from battery channel 1 when the open-circuit faults happen, have to pay a small quality of the energy penalty for switching from the faulty channel to another one connected to the distributed battery 2 or 3 or 4.

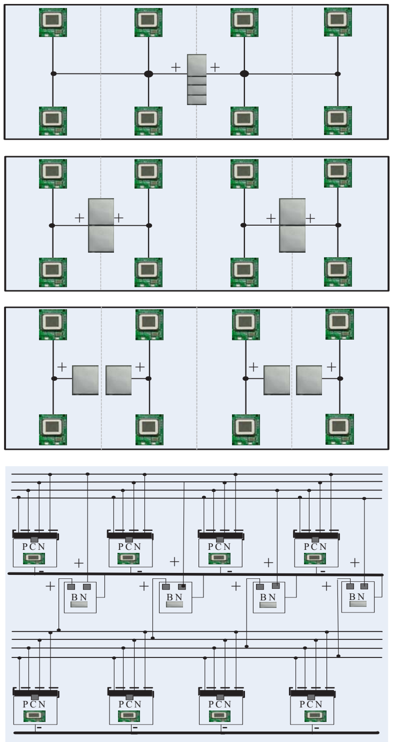

Figure 7. Four configurations of the power supply networks

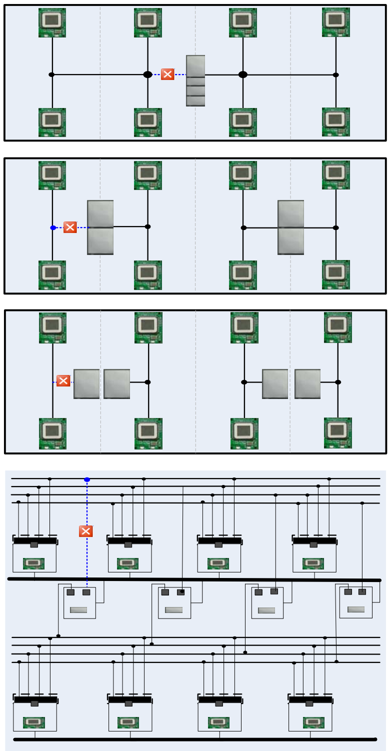

Figure 8. Faults introduced into the power supply networks

If there are short-circuit faults on the segments denoted in Figure 8, the capacity of some batteries will leak quickly. In case 1, all the power energy in the system will be wasted and the PCNs have to stop their work. Thus the whole system collapses since the instant when the battery is discharged by the short circuit. In case 2, the faults affect only the left set of the batteries and the nodes in fabric 1 and 2 are disabled. For case 3, because only one battery is connected to the fault segment and only two nodes in fabric 1 are powered by this battery, the results are more optimistic than the former two cases. In the case of the FPN, the resettable fuse in the battery will break off the interconnection between the battery node and the wire segment with the faults. Because the battery 1 is also connected to the battery channel for the bottom group of the PCNs, the capacity stored in the battery 1 can still serve these nodes. For the PCNs in the top group, occasions are the same as those with the open-circuit faults on the wire segment. Those that are working and connecting to the battery 1, have to switch from battery channel 1 to another one. Thus the energy overhead of performing switching tasks is incurred. The nodes in the top group have to get power energy limited to the battery 2 or 3 or 4.

The capacity of the simulated battery has the parameter C_0 equal to 800mA*Hour. The electric currents flowing through the labeled segment in case 1, 2, 3, 4 are 400mA, 200mA, 200mA and 400mA respectively, which are determined by the loads in the network. In case 3, with

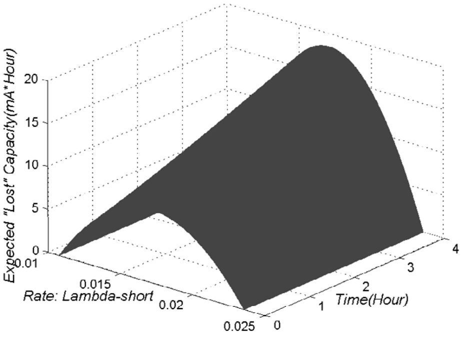

Figure 9. The expected value of the wasted capacity in case 3

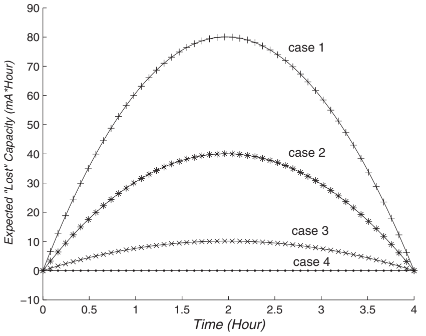

Figure 10. Simulation results of the four cases

the wire segment of the shortest length and the battery of the minimum capacity C_0, the operation period without any rest time is 4 hours. If we assume $0.91 \le p[N_{short}(4) \ge 1] \le 0.95$ or $0.01282 \le \lambda_{short} \le 0.02356$, then the expected "lost" capacity during the operations of the system is shown in Figure 9. The simulation results of the case 2 or 3 have the similar relation of the "lost" capacity, λ_{short} and the operation time. In particular, when the probability $p[N_{short}(4) \ge 1] = 0.95$ in case 3, based on the Equation 8 and the assumption that the rate is linearly proportional to the length of the segment, we have gotten the curves of the expected "lost" capacity during the operation time of the system, as illustrated in Figure 10. Though the probability of $p[N_{short}(t)]$ increases with the operation time, the wasted capacity by the short-circuit faults achieves the extremum at the instant near the mean time. The "lost" capacity is highest in case 1 because all the power energy is centralized at single point. The factor makes the system more prone to be affected by the short-circuit faults. On the other hand, the over current protectors in the FPN decrease the loss of the capacity and the redundancy of the lines contribute to the routing the power dynamically, enhancing the fault-tolerance ability of the electric network.

5. Conclusion and Future Work

The paper has presented a Flexible Power Network (FPN) with enhanced fault-tolerance ability for e-textiles. The proposed FPN is based on the new features of power consuming nodes (PCNs) and battery nodes (BNs) in e-textiles. This proposed FPN can be used to protect the power energy in the system from being wasted by the open-circuit or short-circuit faults. Meanwhile, it has advantages of dynamically routing power energy for the PCNs over the traditional electric networks for e-textiles. The requisite conditions are nodes in the new power network must have the equipment of battery selectors and the over current protectors described in the previous sections. The behavior of the battery selectors has been described in the paper. Experiments have been conducted to compare our FPN with some common fixed networks and the results show that our FPN has higher dependability when there is short-circuit faults and open-circuit faults.

Our further work includes designing battery selection algorithms to prolong the lifetime of the system and expand the fault analysis method for FPNs by considering more factors in the networks and fault occurrence on all the line segments in the network.

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