Development of Highly Survivable Power and Communication System for NPP Instruments under Severe Accident

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1. Introduction

'Survivability of instrument' against to the extremely harsh environment under severe accident is one of the most important issues in nuclear power plant (NPP) instrument after the Fukushima nuclear accident. From the history of several severe accidents, it is found that the essential information such as temperature, pressure, and radioactivity in the containment and corium behavior is vital to maintain the soundness of NPPs under the severe accident [1].

According to the detail report from the Fukushima nuclear accident, the failure of conventional instruments is mainly due to the following reasons [2].

1) Insufficient backup battery capacity after the station black out (SBO)
2) The malfunction or damage of instruments due to the extremely harsh ambient condition after the severe accident
3) The cut-off of power and communication cable due to the physical shocks of hydrogen explosion after the severe accident

Since the current equipment qualification (EQ) for the NPP instruments is based on the design basis accident such as loss of coolant accident (LOCA), conventional instruments, which are examined under EQ condition, cannot guarantee their normal operation during the severe accident.

As a candidate of such problems, a methodology of wired and wireless multi power and communication system with a physical protection system for reliable instrument under the severe accident was proposed in [2], as shown in Fig. 1. A 7m-long-distance wireless power transfer and a radio frequency (RF) communication were introduced with conventional wired system to increase a redundancy. A heat isolation box and a harness are adopted to provide a protection from the expected physical shocks such as missiles and drastic increase of ambient temperature and pressure.

In this paper, the design principle of proposed highly survivable power and communication system, which was not covered in [2], is described in detail, and the performance of each sub-system is experimentally verified with fabricated prototype.

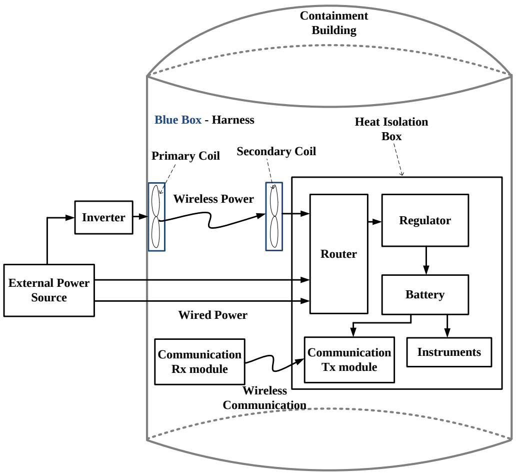


Fig. 1. Overall configuration of the proposed highly survivable power and communication system

2. Design of the Proposed System

The estimation of ambient temperature and pressure in the containment during the severe accident should be conducted before the design. From the collection of temperature and pressure simulation profiles for the variable locations in the containment after the severe accident, the most conservative temperature profile is selected, as shown in Fig. 2, where the maximum pressure is 60 psig.

Moreover, it is essential to evaluate the quantity and variety of physical shock from the hydrogen explosion to determine the system design requirements. According to [3], the estimated maximum pressure due to the hydrogen explosion is determined as 74.7 psig.

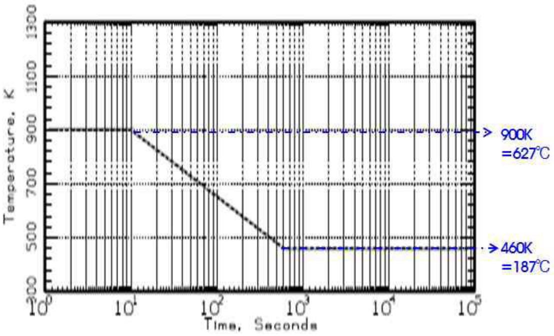


Fig. 2. Estimated ambient temperature and pressure profile in the containment.

As it is identified from the previous severe accidents, the initial countermeasure is the most important to mitigate the damage. The initial 72 hours after the sever accident, therefore, is targeted to evaluate the survivability of proposed system in this paper.

Throughout this chapter, the proposed highly survivable power and communication system is divided into 4 sub-systems such as a wireless power transfer, a wireless communication, a harness for the physical protection, and a router for the continuous power supply network. The design principle for each sub-system, moreover, is described in detail by considering the estimated environment conditions.

2.1 Wireless Power Transfer: 7m-long-distance Dipole Coil Resonant System (DCRS)

The following design requirements should be satisfied for the wireless power transfer.

1) Load power of 4 W, which is determined from the load estimation, as shown in Table I
2) Wireless power transfer distance of 7 m, as shown in Fig. 3
3) Higher Curie temperature of used ferromagnetic material than 600 ˚C
4) Structural integrity against the peak pressure condition of 74.7 psig (= 5 bar)
5) Robust power transfer regardless of explosion debris or high humidity condition

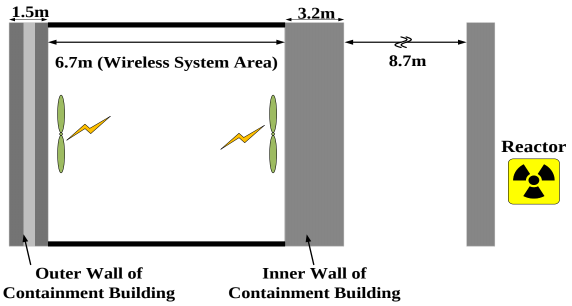


Fig. 3. Target area of the wireless power transfer.

Table I: Load Estimation for Wireless Power Transfer

	Maximum power consumption
MCU	1.20 W (Dspic30F6012A)
Communication module	0.75 W (RN-171XVWI/RM)
Instrumentation (Transducer)	0.90 W (Rosemount 1154)
* Total	2.85 $\times 10/7$ = **4.07 W**

* Where the used regulator efficiency is 70%.

A dipole coil resonant system (DCRS), which was introduced in [4] by KAIST, is nominated for the proposed wireless power transfer. The quality factor of DCRS is selected as low as 100 to avoid sensitive characteristic to the obstacles in the power transfer area. The soundness against physical shock is guaranteed by adopting a harness and a ferrite core, where the Curie temperature is 771 ˚C.

2.2 Wireless Communication: 7m Zigbee Type RF Communication

In a similar fashion with the previous section, the following design requirements should be satisfied for the wireless communication.

1) No error or data loss during initial 72 hours
2) Wireless communication distance of 7 m
3) Low Power consumption of the communication module
4) Structural integrity against the peak temperature condition of 600 ˚C and the peak pressure condition of 74.7 psig
5) Robust data transfer regardless of explosion debris or high humidity condition

A Zigbee type, which is generally used in the local area application, is nominated by considering its low power consumption of 0.75 W. The proposed Zigbee communication modules are in the heat isolation box, which maintain the inside temperature as low as 80 ˚C [2], and the harness for its protection from the harsh environment.

2.3 Harness: Glass Fiber Reinforced Plastic (GFRP)

In a similar fashion with the previous sections, the following design requirements should be satisfied for the harness.

1) Lower inside temperature than 180 ˚C during initial 72 hours
2) Structural integrity against the peak pressure condition of 74.7 psig (= 5 bar)
3) No effect on the performance of wireless power transfer or wireless communication

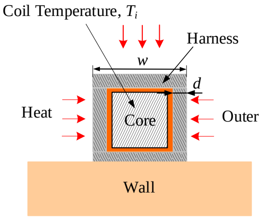
A glass fiber reinforced plastic (GFRP) with 1 cm thickness is selected as a design example for the wireless power transfer from (1) and (2), as shown in Fig. 4, where the heat generation from wireless power transfer coil is 100 W.

$$k\frac{A}{d}(T_o - T_i) + Q_g = cm\frac{dT_i}{dt} \tag{1}$$

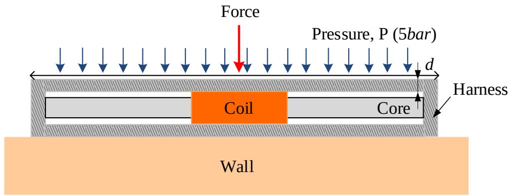
where k, A, d, T_o, T_i, c, m, and Q_g are the thermal conductivity of harness, the cross section area of heat conduction, the thickness of harness, the ambient temperature, the inside temperature, the specific heat, the mass, and internal heat generation, respectively.

$$d > \frac{w}{\sqrt{8\sigma/3P}} \tag{2}$$

where d, w, P, and σ are the thickness of the harness, the width of the harness, the forced pressure on the harness, and the ultimate strength of the harness, respectively.



(a) Side view



(b) Plan view

Fig. 4. Harness cross sectional diagrams of a design example for the wireless power.

2.4 Router: Passive Type Router with a Regulator

In a similar fashion with the previous sections, the following design requirements should be satisfied for the harness.

1) Continuous power supply via the selection of activated power between wired and wireless
2) Structural integrity against the peak temperature condition of 600 ˚C and the peak pressure condition of 74.7 psig
3) Robust operation regardless of high radiation environment
4) Constant DC output voltage of implemented regulator (ex. 10 V)
5) High efficiency of implemented regulator

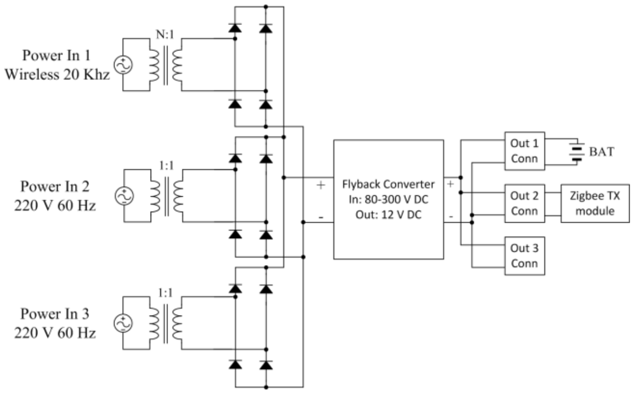


Fig. 5. An example of the passive type router.

Passive type router, which consists of sets of diode rectifiers, is nominated with a flyback type DC-DC regulator, as shown in Fig. 5. The active type router, which is composed of a microprocessor and conventionally used in the industry, is avoided due to the vulnerable characteristic to the radiation environment. The soft-switching technique is applied to the regulator to enhancing its efficiency, which is left for the further works [5]. Similar with the communication module design, the proposed router uses the harness as its protector against the harsh environment.

3. Fabrication of the Proposed System

The design principle of the previous chapter has been applied to the prototypes, as shown in Figs. 6, 7, and 8. 10 W of wireless power transfer was achieved over 7m distance, where the harness and router are implemented together, as shown in Fig. 6. The RF communication with no data loss for 72 hours was also verified with the fabricated Zigbee modules of Fig. 7. The negligible influence of the metal plates (1,000mm x 1,000mm x 1mm), which demonstrates the effect of debris, to the wireless power transfer was also well verified due to the low quality factor.

Fig. 6. DCRS wireless Power transfer GFRP harness.

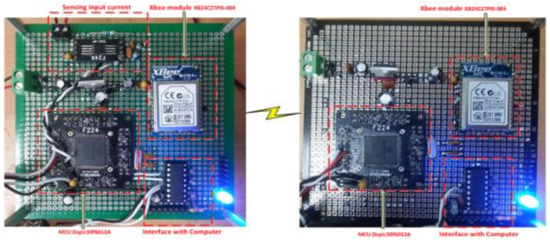


Fig. 7. Zigbee wireless communication.

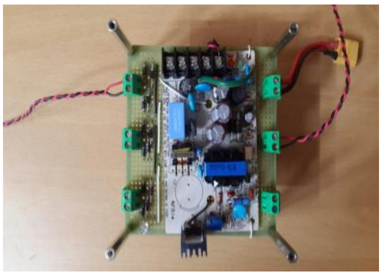


Fig. 8. Passive type router with the flyback type regulator.

4. Conclusions

A detail design principle of the highly survivable power and communication system, which has 4 sub-systems of a DCRS wireless power transfer, a Zigbee wireless communication, a GFRP harness, and a passive type router with a flyback regulator, has been presented in this paper. Each sub-system has been designed to have a robust operation characteristic regardless of the estimated physical shocks after the severe accident. The basic operations of the proposed power and communication system have been experimentally verified with the fabricated sub-systems. A detail performance evaluation and the system integration issues are left for the further works.

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