A Novel Design for HEMS consisting of Sensor Network Nodes with Energy Harvesting and Wireless Power Transmission

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Abstract: The HEMS is expected as one of the promising technologies to satisfy the demand for energy saving. Though it is understood useful and really used on some situations, it has not prevailed well into the public. The reason is considered to be the high initial cost of the equipment, low mobility of the system and regrettable unconcern for saving energy. In order to change the present situation, we have proposed to introduce a sensor network system into HEMS. The distributed sensors are easy to change their location and number as we like. Moreover, we have proposed to employ the energy harvesting and power transfer technology. This architecture will provide the basis for the system operation with no power supply and no maintenance. In this paper we will study the grand design for the sensor network HEMS mentioned above. As a result, we've concluded the sensor network node can continue to work with energy harvesting and wireless power supply. Still we've clarified the fact that our method of wireless power transmission could transmit power by more than 1m. These results would provide great progress for future HEMS.

Keywords: HEMS, Sensor Network, Energy Harvesting, Wireless Power Transmission

Introduction

We have studied HEMS (Home Energy Management System) consisting of the sensor network. Because the sensor network nodes has the feature of portability and low cost it is helpful for widely spreading for people. But since the sensor network has the problems of the battery changing maintenance or using AC power supply cable, it is quite hard to be used for HEMS. Then we have proposed sensor network HEMS with energy harvesting and wireless power transmission. It needs delicate power balance between generated power and consuming power referring to HEMS. Then we have studied from the elemental technologies to the grand design based on that.

The power converting transition of our sensor network HEMS with the energy harvesting and the wireless power transmission is shown in Fig.1. The power resources are harvesting power P_{GE} multiplied by the power generating duty ratio D_E and the transmitting power P_{GT} multiplied by the power generating duty ratio D_T, and the consuming power consists of the energy converting device power consumption and the capacitor leakage power and HEMS communication and sensing power consumption. The relation between the generated power and the consumption power is shown by following equation (1). We have to design the system to satisfy the equation (1).

$$P_{GT} D_T + P_{GE} D_E = P_{CH} / \eta_C + P_{CD} \quad (1)$$

HEMS Modeling referring to the sensor network consuming power

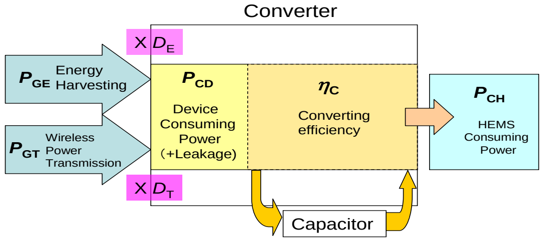

Fig.1 The power converting transition of the sensor network HEMS with the energy harvesting and the wireless power transmission.

We have studied how much power is required for the HEMS. Its characteristic varies according to the kind of service. Thus, we have classified HEMS according to the content of each service (Table I.).

Table I. HEMS model and for its power consumption

Monitoring HEMS	I 7uW	Surroundings Monitoring Pre-HEMS (pHEMS)	II 10uW	+Energy Consumption Monitoring (mHEMS)	III 10uW	+Human Vital Monitoring (vHEMS)
Control HEMS	IV 19uW	+Controlling Electric apparatus (cHEMS)	V 19uW 23uW	+Controlling with Fixed and Vital status (cvHEMS)	VI 48uW 35uW	+High Duty Customize control (ccHEMS)

Table I. shows the meaning of each HEMS from I to VI and the consuming power value for each HEMS node under Roman numerals. We have estimated the power consumption based on the sensor variation and the duty ratio of the wireless data communication and the sensing for each HEMS model. This value is the average power consumption and corresponds to P_{CH}. In general, monitoring HEMS (only monitoring) needs less power than control HEMS (the monitoring and controlling electric apparatus) because the data communication duty ratio for monitoring HEMS is shorter. And in account for other respect, there are fixed HEMS and human vital HEMS. Fixed HEMS is expressed which node is never moved, while human vital HEMS is expressed which node is basically portable or wearable HEMS. Human vital HEMS needs much power because it demands higher sensing duty ratio.

Energy Harvesting

We have focused on the illumination energy and the thermal energy and the vibration energy as the energy harvesting resource suitable for the home environment.

Our aim in this section is to estimate the generating power for each harvesting element. In general, the harvesting energy becomes larger by bigger scale equipment for the harvesting element is used. Then we have defined the restriction that the dimension of the sensor network node has to be less than x10cm corresponding to the practical operation.

Illumination energy

Considering the power generation using room light, amorphous silicon solar cell (a-Si solar cell) is very useful having high converting efficiency under the room illumination (less than 500lx) and good durability and the low price.

We have measured the fundamental performance for 5cm square a-Si solar cell under 500lx condition. We have gotten the result that a-Si solar cell can generate the power P_{GE} as 320uW. Referring to the ordinary life style, we have modeled the illuminated duration such as 4 hours a day and 5 day a week (two days are totally black). In this life model, the illuminated duty ratio D_E is calculated as 11%, namely the generating average power is estimated as 35uW.

Thermal energy

We can obtain the thermal energy from the temperature difference between human body and room by using Peltier element. The average temperature difference between the human body and the room is estimated as from 5 to 10 degree.

The thermal power generation using Bi-Te type Peltier element is promising for obtaining the considerable power even if the temperature difference between the hot side and the cool side of Peltier element is less than 10 degree.

Though common commercialized Peltier element can generate more than 1mW/cm^2 under the temperature difference condition of 10 degree, it is actually very hard to get the same temperature difference between both sides of Peltier element as the giving temperature difference. Because Peltier element is too thin to avoid thermal conduction. In our experiment avoiding the heat conduction[1] between each surface the ability of the power generation is estimated 35uW with 5cm square Bi-Te Peltier element.

Vibration energy

We can get the vibration energy from the human walking movement wearing any kinds of generating equipment.

Piezoelectric element or the electromagnetic induction element or the electret element is used for the vibration power generation. The generated power by the vibration largely depends on the frequency, acceleration, mass and stroke, while less influenced by the kinds of generation element.

As one example, the calculation of power generation for the electromagnetic induction is shown eq. (2). P_{max} is maximum power under the impedance matching condition.

$$P_{max} = N^2 \omega^2 (BA)^2 / 4R \qquad (2)$$

Here N=100(the number of turns), ω=2π[rad/s] (angular frequency), B=1[T] (magnetic flux density), A=0.022π (Coil cross section :diameter is 4cm), R=50[Ω] assuming that the human step is with 1 [Hz] and enough acceleration[2].

Calculating eq.(2), generated power is obtained as 3mW. Assuming walking time as 45 min. per day, the duty ratio D_H is about 3%, so generated the average power is estimated as 90μW.

Wireless Power Transmission

Since the validity of the resonant-type wireless power transmission was reported by MIT[3] in 2007, many researchers have started the study on the relating technologies.

This technology is expected to transmit higher power for larger distance than the conventional technology that can transmit by less than few [mm] or [cm] by the electromagnetic induction.

We have studied to introduce a resonant-type wireless power transmission into HEMS. Our aim is to ensure the feasibility of a practical HEMS system.

To attain it, we have measured the power transmitting characteristics in the case of 100mm diameter coil Measurement system is drawn in Fig.2. This system consists of four coils, that is, two resonant coils and two exciting coils. The resonant coils are 100[mm] diameter loops by ϕ1.6 wire with 220pF mica capacitor at the loop end. Two resonant coils make a reciprocal transmitter and receiver located with the distance *D*.

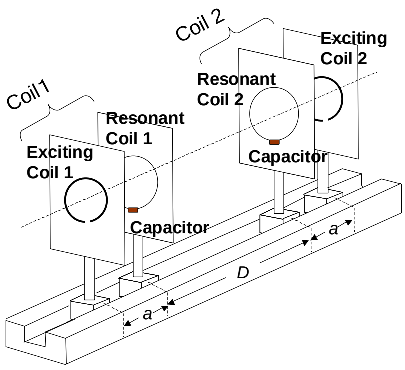

Fig.2. Resonant-type WPT measurement system

And the exciting coils are adjusted by the distance *a* to attain the circuit matching based on the band pass filter theory[4].

The measurement is performed for various distance *D*=0.05m, 0.1m, 0.15m, 0.2m by sliding the coil along to the optical stage. In addition to the experiment we performed the calculation with the equivalent circuit and numerical method by WIPL-D. In equivalent circuit calculation we have derived the equation of S_{21} as eqs.(3) based on the equivalent circuit (Fig.3). M and L is calculated by circular formulas[5]. The measured and the calculated results are shown in Fig.4.

$$S_{21} = \frac{K_1}{K_2 K_3 + K_3} \tag{3}$$

$$K_1 = -2j\omega^3 \sqrt{Z_{01} Z_{02}} MM_1 M_2 (Z_1 Z_2 + \omega^2 M^2)$$
$$K_2 = (Z_{01} + j\omega L_0 + R_0)(Z_1 Z_2 + \omega^2 M^2) + \omega^2 M_1^2 Z_2 \tag{4}$$
$$K_3 = (Z_{02} + j\omega L_0 + R_0)(Z_1 Z_2 + \omega^2 M^2) + \omega^2 M_2^2 Z_1$$
$$K_4 = \omega^6 M^2 M_1^2 M_2^2$$

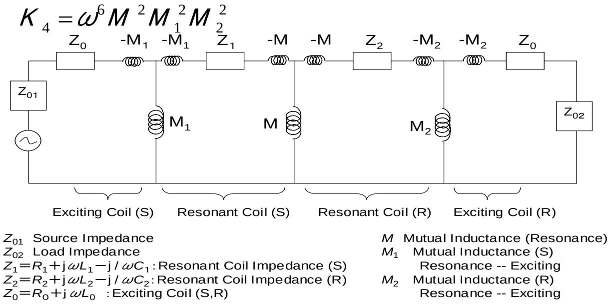

Fig.3. Equivalent Circuit of Resonant-type WPT

The numerical calculation results in Fig.4(c) are in good agreement with the experimental results in Fig.4(a).

But as shown in Fig.4(d), the calculated results with the equivalent circuit in Fig.4(b) are slightly larger than the experimental results in higher frequency range. This is because we can only consider uniform eddy current along the circumference of the coil wire in the equivalent circuit calculation but it is not uniform under higher frequency range actually.

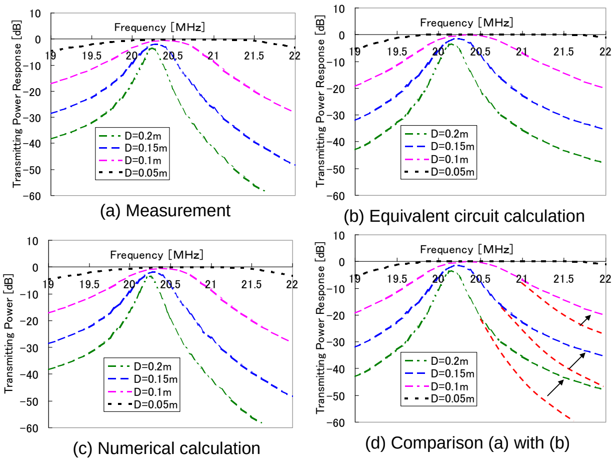

Fig.4. Experimental and calculated transmitting response

As we have confirm the validity of our calculation method, we calculated the transmitting efficiency accounting for the farther distance transmission with the equivalent circuit method. The result is shown in Fig.5.

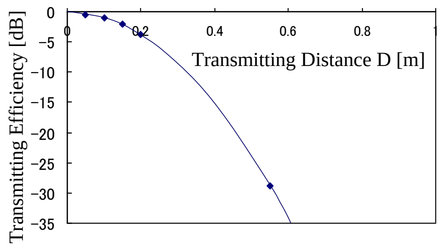

Fig.5. Farther transmitting calculation

Fig.5 shows the transmitting efficiency is drastically reduced according to the distance. If we want farther distance transmission more than 1m, two resonant coils are not enough.

In that case, one or two extra resonant coil (repeating coil) must be inserted between initial two resonant coils[6], and the calculated results are shown in Fig.6.

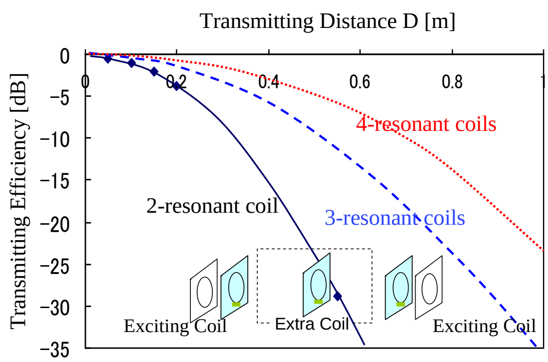

Fig.6. Transmitting characteristics in the case of inserting extra resonant coil

Converting and charging energy method

Converting method is so important for reducing energy consumption as mentioned in section I. We have examined the charge pump and the series regulator and the switching regulator. There is any predominance among them. We have to choose the most proper converter referring to converting voltage or working duty cycle and so on. In our experience, the efficiency of the converter is less than 65% in this very small energy region of μW order, and the consuming power of the converter itself is regarded less than 10μW in this low power region. In our prototyping case[1] $\eta_C = 0.6$ and P_{CD} = 20μW which consists of following power consumption as leakage current, pre-converter adjusting voltage from input to the dump capacitor and the post-converter adjusting voltage from the dump capacitor to output.

While in the case of AC power is generated as the vibration or the wireless power transmission, the rectifier (AC-DC conversion) is necessary.

We have made the experiment in which we examine the converting efficiency of the rectifier consists of four diode and smoothing capacitor shown in Fig.7.

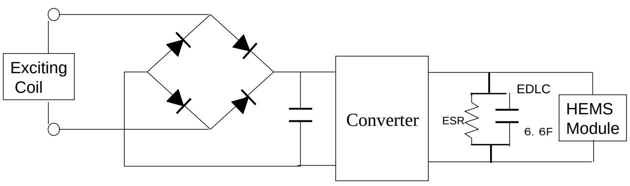

Fig.7. Electrical circuit for energy charging from the wirelessly transmitted AC power through the Rectifier

As the result we can obtain the AC to DC converting efficiency as about 60% at 2.5V 10mA condition.

Grand design

Through the section II to V we can get the value for the parameters used in eq. (1). Now Fig.1 is rearranged into Fig.8 summarizing the results through section V.

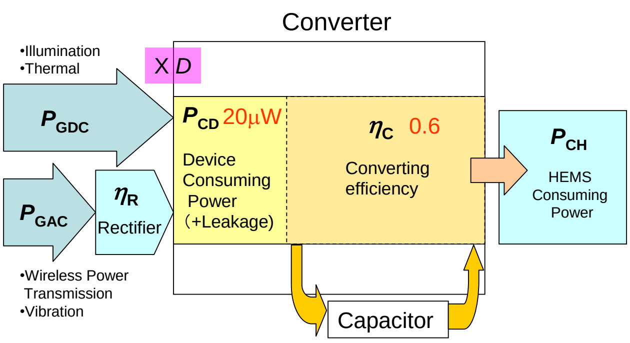

Fig.8. Energy conversion flow of sensor network HEMS

Eq.1 is converted into (1)' as follows,

$$P_{GDC} D + P_{GAC} D \eta_R = P_{CH} / 0.6 + 20\times10^{-6} \qquad (1)'.$$

HEMS true power consumption in Table I. is converted to equivalent input power by calculating the right hand side of eq.(1)' accounting for each HEMS model. By calculating equivalent input power, we can find how much power should we get by the energy harvesting or the wireless power transmission.

Table II. Equivalent input power for each HEMS

Monitoring HEMS	I 31uW	Surroundings Monitoring Pre-HEMS (pHEMS)	II 37uW	+Energy Consumption Monitoring (mHEMS)	III 37uW	+Human Vital Monitoring (vHEMS)
Control HEMS	IV 52uW	+Controlling Electric apparatus (cHEMS)	V 52uW 58uW	+Controlling with Fixed and Vital status (cvHEMS)	VI 100uW 78uW	+High Duty Customize control (ccHEMS)

Then referring to the results in Section III and Section V, input energy by energy harvesting is shown in Table III.

Table III. HEMS generated average power by energy harvesting

	Generated power	Duty	Rectifier	Average Power
Illumination	320uW	11%	-	35uW
Thermal	35uW	100%	-	35uW
Vibration	3mW	3%	60%	54uW

Referring to Table II and Table III, monitoring HEMS could work by only one kind of energy harvesting. We have already succeeded in the trial experiment for HEMS model I with only illuminated power source[1]. But control HEMS need two or more kinds of energy harvesting.

Moreover in the environment where we can get enough harvesting energy, wireless power transmission is helpful.

Transmitting power in air must be less than 75mW (in the case of coil diameter is 10cm.) referring to the electromagnetic protective guideline. If we want to get more than 100μW at receiving coil, the wireless transmitting efficiency must be higher than 0.13% (-29dB). Referring to Fig.5 under such consideration 100μW can be transmitted in the extent of 55cm distance (transmitting efficiency is -29dB point). Furthermore referring to Fig.6 transmitting distance is extended to be more than 1m, adding two extra resonance coils.

In this way, sensor network HEMS could be designed for working permanently at the specific location by the energy harvesting and the wireless power transmission.

Conclusion

We have proposed a new concept for HEMS based on sensor network with energy harvesting and wireless power transmission. This concept is a quite new approach, therefore grand design is necessary. In order to design the power balance of sensor network HEMS we have categorized HEMS accounting for its function at first.

Next we have clarified the generated and consuming power as the illumination generated power, vibration generated power, thermal generated power, wireless power transmitting power along the distance, and the consuming power of sensor nodes and converter.

Finally, we have shown sensor network HEMS possibility for each model (monitoring HEMS, control HEMS) referring to the generated power and the consuming power.

Moreover, remarkably, we have shown the calculated result that the transmitting distance by the wireless power transmission can be more than 1m with extra two resonance coil.

This way of the design is still the first step, and the element technologies consisting sensor network HEMS are growing day by day. Thus, we will continue to reconstruct every parameter and plan to develop the hybrid HEMS node equipping with many kinds of energy harvesting element and the wireless power transmitting coil in near future.

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