

Passive Telemetry Sensor System using RLSE Based Real Time Estimation Technique with Optimal Forgetting Factor

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Abstract

In this paper, a passive telemetry RF capacitive humidity sensor system using a RLSE(Recursive Least Square Estimation) technique is proposed. To overcome these trouble problems such as a power limitation and a estimation complexity that the general passive telemetry sensor system including IC chip has, the principle of inductive coupling was applied to the modeling of a passive telemetry RF capacitive humidity sensor system and its capacitance was estimated by the RLSE algorithm. Specially, by introducing the optimal forgetting factor, we showed that the accuracy of its estimation was improved even in the time varying system and also the convergence time was reduced.

1. INTRODUCTION

A sensor can be regarded as a device that transforms a physical quantity to be measured into information that can be further processed. Traditionally, a sensor should be powered by an external supply or a battery. But, passive sensors have no extra power source or battery, but also use back scattering for RF communication [1,4].

Therefore, principal concept of RF identification system allows the sensor to be operated without external power supply. Wireless RF sensors are also divided according to the type of electromagnetic coupling; those are, *Inductive type* is used in magnetic field, *Capacitive type* is used in electric field and *Radiating type* is used in radiating field [2].

In this paper, we want to focus on the fact that low-frequency inductively coupled systems are in widespread use in RF identification. The passive sensors require in practice a very short distance, near contact, in fact, between the sensor and the reader head, and have therefore given way to inductive and radiating systems [4]. When properly designed, the production costs of these sensors might be very low. Sensors using Bluetooth or GSM technology can be called, according to these definitions, radiating active sensors.

In this article we focus mainly on radiating passive sensors. The simplest and cheapest wireless sensor is based on an inductor- capacitor resonator. The functionality of this sensor is, however, limited. Data can only be coded into the resonant frequency or the Q-value of the resonance. If an integrated circuit (IC)

chip is connected to an antenna, the wireless sensor can have much more complicated functions, because the IC is like a small micro-controller that communicates in both directions wirelessly. If this kind of system tries to be implanted in human body for the purpose of medical care, the power must be limited to $10[mW/cm^2]$ and the size has to be as small as possible [1].

So, in order to solve these problems of the traditional passive telemetry sensor system, we propose the passive telemetry RF capacitive humidity sensor system to measure the capacitance of implanted capacitive humidity sensor using RLSE algorithm with an optimal forgetting factor. The optimal choice of forgetting factor is usually performed empirically on some development data, and no optimality criterion is used. In this paper we introduce a framework for obtaining an optimal forgetting factor. This technique will make it possible to realize the new measurement technique and to reduce the installation costs of the sensors.

2. CAPACITIVE HUMIDITY SENSOR

In general, the material of RF humidity sensor is made of ceramic, polyamide and so on. Especially, the polyamide is a dielectric material, changing its permittivity with respect to humidity. As humidity increases, the permittivity increases. This characteristic results in the development of a capacitive-type humidity sensor [5]. And capacitive humidity sensor made of polyamide has proper linearity and hysteresis to be used

as a sensor. Hence, in this paper, in order to implement the passive telemetry capacitive humidity sensor system, capacitive humidity sensor is selected as time varying capacitance used in sensor part. According to the characteristic of humidity sensor shown in Eq. (1) and Fig. 1, the relation between capacitance C_2 and relative humidity RH can be obtained [5] as

$$C_2 = 0.0000225RH^3 - 0.002448RH^2 + 0.3942RH + 162[pF] \quad (1)$$

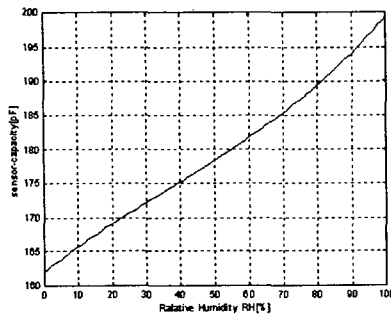


Fig.1 Characteristics of Humidity Sensor

3. PASSIVE TELEMETRY RF CAPACITIVE HUMIDITY SENSOR SYSTEM

General passive telemetry RF sensor system including IC chip is operated as following block diagram.

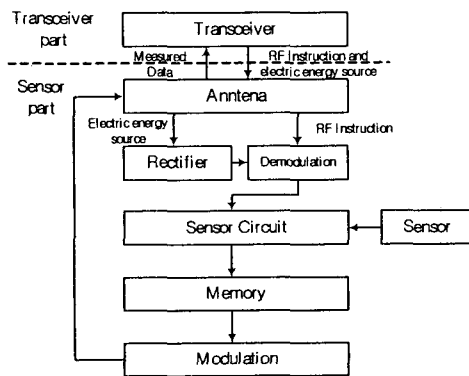


Fig. 2 Block Diagram of the Traditional Passive Telemetry RF Sensor System

This system also contains a circuit, like a voltage rectifier, that derives power for the sensor from the field of the transceiver. Fig. 2 shows the concept of a traditional passive wireless RF sensor system. The antenna of a wireless sensor which transmits and receives RF signals is fabricated on a laminate or a printed circuit board. Because the power available from this supply gets less when the distance between the base station and sensor increases, the power consumption must be very little if long operation distances are required.

A transceiver sends out a RF instruction signal for measurement, and supplies electric energy sources by giving a regular RF signal. The measured value is transformed into the digital signal, and stored in the RAM. After then, this

transformed signal is instantly re-transmitted through an antenna. However, typical passive telemetry sensor system encounters the limits in complication, power consumption, and size in application field. Hence, the system to overcome the limits is need and this paper proposes the passive telemetry humidity sensor system.

4. MODELING OF PASSIVE TELEMETRY RF CAPACITIVE HUMIDITY SENSOR SYSTEM

4.1 Equivalent Circuit of Passive Telemetry RF Capacitive Humidity Sensor System

The proposed passive telemetry RF capacitive humidity sensor system is divided into two parts; transceiver and sensor part as Fig. 3. First, the sensor part, comparing to typical passive telemetry RF sensor system, doesn't have any active components like logic circuit for modulation and demodulation nor memory in order to store the measured data (ie. humidity, pressure, temperature, etc.) inside. Also, it consists of only R, L and C components. So, sensor part to be implanted is very simple. And the transceiver part of the proposed passive telemetry RF capacitive humidity sensor system plays a role, like AD converting and so on, of the sensor circuit of typical passive telemetry sensor system. So, the sensor part of the proposed passive telemetry RF capacitive humidity sensor system can be smaller than typical one [1]. Because the capacitance C_2 shown in Fig. 3 is estimated by applying the principle of inductive coupling, this proposed system can be implemented very simply.

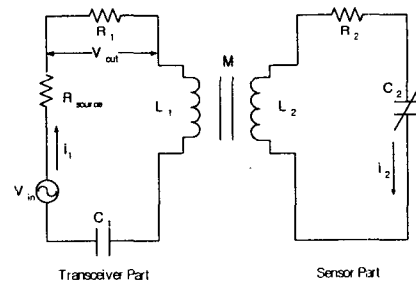


Fig.3 Principle of Passive Telemetry RF Capacitive Humidity Sensor System

Because of the RF source signal V_{in} , the alternating current i_1 is flowing through the primary source resistance R_{source} , the line resistance R_1 , the line capacitance C_1 and the inductance L_1 in transceiver side for the purpose of inductive coupling. Hence the secondary electric motive force is induced across the coil inductance L_2 of sensor side by the linkage flux Mi_1 . In this case, because we cannot observe the secondary electric motive force, we must measure the voltage V_{out} across R_1 . But, the capacitance of passive telemetry sensor gets continuously changed, the impedance of sensor part also various. This means that

the reflected impedance equivalent with the impedance of sensor part various too. But the capacitance of sensor can be estimated by monitoring the continuous variation of impedance. Fig. 4 is the transferred equivalent circuit of Fig. 3.

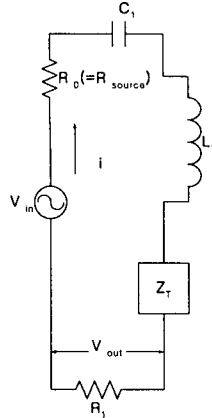


Fig.4 Equivalent Circuit Model of the Proposed Passive Telemetry RF Capacitive Humidity Sensor System

4.2. Mathematical Modeling of the Proposed Passive Telemetry RF Capacitive Humidity Sensor System

In Fig. 4, transceiver part and sensor part are coupled inductively with mutual inductance M and impedance of sensor part Z_{sensor} is included in reflected impedance Z_T .

$$Z_T = \frac{(\omega M)^2}{Z_{sensor}} = \frac{\omega^2 M^2}{(j\omega L_2 + R_2 + 1/j\omega C_2)} \quad (2)$$

where, ω means an angular velocity[rad/sec]. The transfer ratio between the RF input voltage V_{in} and the measured voltage V_{out} across R_1 is equal to Eq. (3). Where, M and C_2 are unknown. RLSE is introduced to estimate the variables M and C_2 . In order to simplify this model, Eq. (4) can be rearranged as Eq. (5) and (6).

$$G(j\omega) = \frac{V_{out}}{V_{in}} = \frac{R_1}{(R_1 + R_0) + j(\omega L_1 - 1/\omega C_1) - (\omega^2 M^2 / (R_2 + j(\omega L_2 - 1/\omega C_2)))} \quad (3)$$

$$\frac{1}{G(j\omega)} = y_1 + jy_2 \quad (4)$$

$$y_1 = \frac{(R_1 + R_0)}{R_1} - \frac{\omega^2 R_2 x_2 / R_1}{R_2^2 + (\omega L_2)^2 - 2L_2 x_1 + x_1^2 / \omega^2} \quad (5)$$

$$y_2 = \frac{\omega L_1 - 1/\omega C_1}{R_1} + \frac{(\omega^2 / R_1) x_2 (\omega L_2 - x_1 / \omega)}{R_2^2 + (\omega L_2)^2 - 2L_2 x_1 + (x_1 / \omega)^2} \quad (6)$$

where, $x_1 @ \frac{1}{C_2}$, $x_2 @ M^2$

where, y_1 and y_2 can be obtained through the magnitude and the phase of $G(j\omega)$.

$$y_1 + jy_2 = \frac{1}{|G(j\omega)|} (\cos\theta + j \sin\theta) \quad (7)$$

where, θ is equal to $-\angle G(j\omega)$. For the vector type presentation of Eq.(5) and (6), parameters are set as

$$x_3 = x_1^2 \text{ and } x_4 = x_1 x_2.$$

$$\phi_1 x_1 + \phi_2 x_2 + \phi_3 x_3 + \phi_4 x_4 = z_1 \quad (8)$$

$$\phi_5 x_1 + \phi_6 x_2 + \phi_7 x_3 + \phi_8 x_4 = z_2 \quad (9)$$

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ \phi_5 & \phi_6 & \phi_7 & \phi_8 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

or

$$\mathbf{Z} = \Phi \mathbf{X} \quad (10)$$

where, \mathbf{Z} and Φ means the outputs of this model and regression variables respectively and will be defined in following chapter 5 in detail.

5. ESTIMATIONS OF VARIABLES AND OUTPUTS BY RLSE WITH OPTIMAL FORGETTING FACTOR

These recursive variables $\phi_1 : \phi_8$ are varied with the applied input frequency ω . See Table 1. And four variables $x_1 : x_4$ are estimated by RLSE with forgetting factor λ . The data pairs for the estimation of variables are obtained from gain $|G(j\omega)|$ and the phase argument $\angle G(j\omega)$.

Table 1. Regression Variables Φ and Outputs \mathbf{Z}

ϕ_1	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) 2L_1$	ϕ_2	$-\omega^2 R_2 / R_1$
ϕ_3	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) \frac{1}{\omega^2}$	ϕ_4	0
ϕ_5	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) 2L_2$	ϕ_6	$\omega^3 L_2 / R_1$
ϕ_7	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) \frac{1}{\omega^2}$	ϕ_8	$-\omega / R_1$
z_1	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) (R_2^2 + (\omega L_2)^2)$		
z_2	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) (R_2^2 + (\omega L_2)^2)$		

The estimation vector $\hat{\mathbf{X}}(k) = [\hat{x}_1 \hat{x}_2 \hat{x}_3 \hat{x}_4]$ is updated with the correction factor $\mathbf{K}(k)$. The estimated output $\hat{\mathbf{Z}}(k) = [\hat{z}_1 \hat{z}_2]$ approaches to the measured output $\mathbf{Z}(k) = [z_1 z_2]$ with little deviation. Because this calculation procedure is recursively achieved, this estimation technique can be applied to the online modes [3.6]. In general, they are described as

$$\hat{\mathbf{X}}(k) = \hat{\mathbf{X}}(k-1) + \mathbf{K}(k)(\mathbf{Z}(k) - \Phi(k)\hat{\mathbf{X}}(k-1)) \quad (11)$$

$$\mathbf{K}(k) = \mathbf{P}(k-1)\Phi^T(k)(\lambda\mathbf{I} + \Phi(k)\mathbf{P}(k-1)\Phi^T(k))^{-1} \quad (12)$$

$$\mathbf{P}(k) = (\mathbf{I} - \mathbf{K}(k)\Phi(k))\mathbf{P}(k-1) / \lambda \quad (13)$$

where, the forgetting factor λ is used in estimating the time varying variables $\hat{X}(k)$ and $P(k)$ is defined as

$$P(k) \cong \left[\sum_{i=1}^k \lambda^{k-i} \Phi(k) \Phi^T(k) \right]^{-1}$$

Usually, trial and error method can be used to search for the good λ values, which may not be optimal and the process can be very burdensome. Furthermore, the optimal value of λ can be dependent on the instantaneous dynamics of the noisy time varying system. Over a long time interval, the exponential forgetting factor with a constant λ is used in the estimating algorithm method. Therefore, in order to get the optimal forgetting factor, at first, we can rewrite Eq. (13) as.

$$P(k) = (I - K(k)\Phi^T(k))P(k-1) / \lambda(k) \quad (14)$$

And we can postulate that the estimation error at k is considered to be deterministic and is defined as

$$\varepsilon(k) = Z(k) - \hat{Z}(k) = Z(k) - \Phi(k)\hat{X}(k-1) \quad (15)$$

The weighted squared error as the cost function

$$J(k) = \sum_{i=0}^k \lambda^{k-i} \varepsilon^T(k) \varepsilon(k) \quad (16)$$

must be minimized. The forgetting factor, λ^{k-i} is exponentially decreasing for the time varying system.

However, if we define the normalized variance with respect to σ_ω^2 as

$$\begin{aligned} E[\varepsilon^T(k)\varepsilon(k)] &= \sigma_\omega^2 S(k) \\ S(k) &= 1 + \Phi^T(k)P(k-1)\Phi(k) \end{aligned} \quad (17)$$

then the autocorrelation function of the estimation error can be derived as

$$\begin{aligned} R(j) &= E[\varepsilon^T(k)\varepsilon(k)] \\ &= \sigma_\omega^2 \Phi^T(k+j) \left[\prod_{i=0}^j (1 - K(k+i)\Phi^T(k+i)) (\lambda^1(k)P(k-1)\Phi(k) - K(k)S(k)) \right] \end{aligned} \quad (18)$$

From the above equation, we can choose the last term be zero as

$$\lambda^{-1}(k)P(k-1)\Phi(k) - K(k)S(k) = 0 \quad (19)$$

When the gain $K(k)$ is optimal, the corresponding optimal forgetting factor for the time varying system is given as

$$\lambda(k) = \frac{\lambda(k-1)[1 + \Phi^T(k)P(k-1)\Phi(k)]}{S(k)} \quad (20)$$

The initial guessing values of $\hat{X}(k)$ and $P(k)$ are chosen as $\mathbf{0}$ and δI . The variation of λ , is limited according to the following rule:

$$\lambda(k) = \lambda(k-1) + \mu \cdot \text{sgn}(\lambda(k) - \lambda(k-1)) \quad (21)$$

where, $\text{sgn}(\cdot)$ is the signum function and μ is called as update rate and means the step size whose value should be proportional to SNR value of the received signal[7]. By considering the above equations, the summarized estimation model can be depicted as Fig. 5.

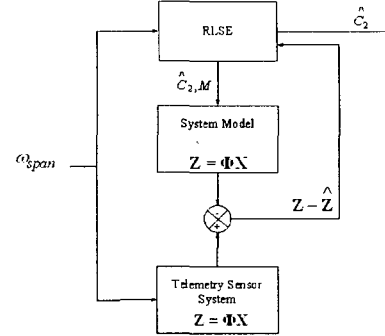


Fig. 5 Block Diagram of RLSE System

where, $\omega_{span}[\text{rad/sec}]$ means the angular frequency area between the starting frequency $\omega_{start}[\text{rad/sec}]$ and the stopping frequency $\omega_{stop}[\text{rad/sec}]$. And \hat{C}_2 is the estimated value of C_2 which is obtained in resonant frequency $\omega_0 = 2\pi f_0[\text{rad/sec}]$.

6. SIMULATION RESULTS

In this section, the simulations for the proposed system are performed to prove the availability of proposed passive telemetry RF capacitive humidity sensor system.

Table 2 shows the values of each component used in the proposed telemetry RF humidity sensor system like Fig. 3. These parameters are setup according to the resonance frequency of this proposed system and implementation. When the capacitance of RF humidity sensor is time invariant, the forgetting factor is set as $\lambda = 1$.

Table 2. Passive Telemetry Capacitive Humidity Sensor System Parameters

Parameter	Value	Parameter	Value
L_1	700[H]	Initial value of C_2	4000[pF]
C_1	80[pF]	M	8.2[H]
L_2	50[H]	R_{source}	30[Ω]
C_2	160, 180, 200 [pF]	R_2	10[Ω]
$R1$	5[Ω]	$span$	1[kHz] ~ 2[MHz]
λ	1	Distance between two coils	2.5[cm]

When the capacitances of RF humidity sensor in the proposed system are assumed as $C_2 = 160[pF], 180[pF]$ and $200[pF]$, Fig. 6(a) shows the

convergence pattern for $C_2 = [180 pF]$, and Fig. 6(b) and (c) show the gain and the phase of the sensor system for each C_2 according to the above mentioned block diagram of RLSE system .

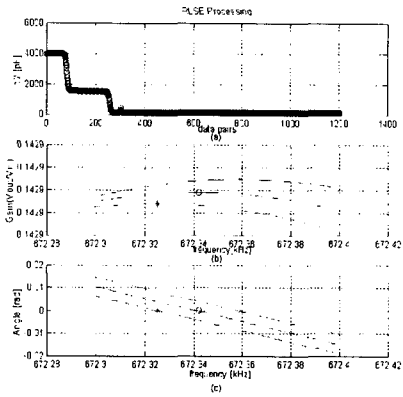


Fig. 6 Convergence Patterns, Gain and Phase Diagrams by RLSE

The capacitance of estimated RF humidity sensor \hat{C}_2 using RLSE algorithm with the optimal forgetting factor is converged to the desired value with a few errors at the 260th data pair as Fig. 6(a). The notations for '*' , 'o' and 'x' marked in Fig. 6(b) and Fig. 6(c) are denoted as the resonant frequency in $C_2 = 160[pF], 180[pF]$ and $200[pF]$ respectively. Fig. 7 shows the relation between the resonant frequency

$$f_0 = \frac{\omega_0}{2\pi} [Hz] \text{ and the calculated capacitance } C_2 .$$

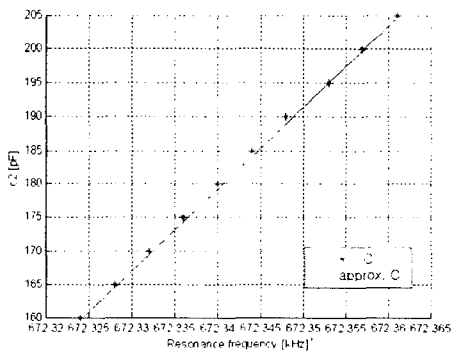


Fig. 7 Resonant Frequency vs C_2

The Fig. 8 depicts the convergence pattern when the forgetting factor λ is changed from 0.4 to 0.7. Based on this graph, the forgetting factor is set to 0.6.

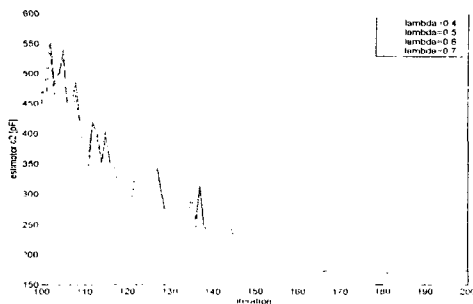


Fig.8 Convergence patterns according to forgetting factor

Fig. 9 (a) shows the estimation performances of RLSE algorithm when the capacitance of capacitive humidity sensor C_2 is varying with 100[Hz]. The notation for '-' and 'o' shown in Fig. 8 (a) mean the change of C_2 and

its estimated \hat{C}_2 respectively and the '*' marked value in Fig. 8 (b) means its estimation errors.

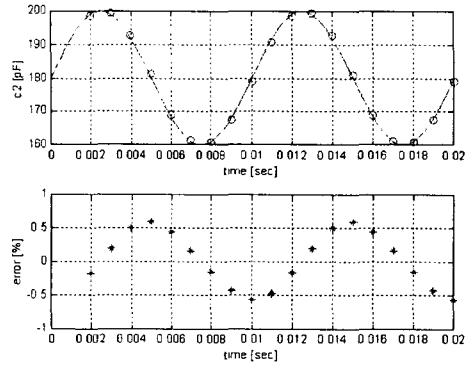


Fig. 9 Simulation for Parameter Estimation for the Time Varying C_2 with 100 [Hz]

While Fig. 6, Fig. 8, Fig. 9 result from RLSE Algorithm with the unchanged forgetting factor, Fig. 10 shows the estimating results of the variable forgetting factor using the adaptive algorithm. Specially, the convergence pattern of estimated C_2 and its contour according to μ is illustrated through Fig. 10.

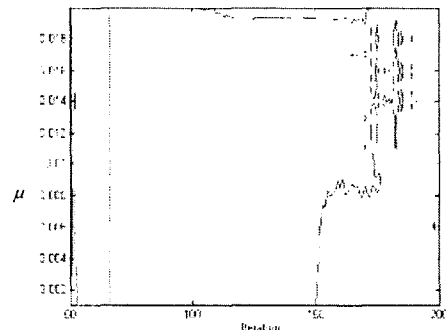


Fig. 10 Contour of Convergence Pattern of Fig.

Fig. 11 shows the comparison of the results to be obtained with the fixed forgetting factor and variable forgetting factor. According to Fig. 10, μ is set to 0.015. 'o' means the results to be used with the variable forgetting factor, and '*' means the results to be used with the fixed forgetting factor. The graph of Fig. 11 shows that the estimating results with variable forgetting factor are better than estimating ones with the fixed forgetting factor.

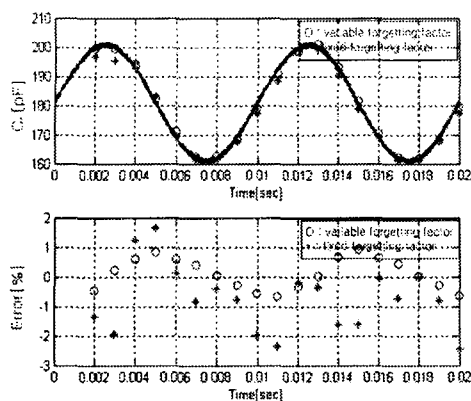


Fig. 11 The comparison of the estimating results to be used with the variable forgetting factor and the fixed forgetting factor.

7. CONCLUSION

Wireless measurements are very important in many application fields where measurements should be made through the impenetrable material. In this paper, the capacitance of passive telemetry RF capacitive humidity sensor system with noise input was estimated with mean error 0.558553[%] using RLSE with the fixed forgetting factor. However, in case of using the variable forgetting factor, mean error is reduced up to 0.140902[%]. In this paper, it is preferred to use the variable forgetting factor than to use the fixed forgetting factor in part of passive telemetry RF capacitive humidity sensor system. Introduction of an optimal forgetting factor with the update rate μ to RLSE algorithm made the estimation time shorten and also the estimation error reducible substantially. On the other side, this proposed system has some disadvantages that it cannot be used if it is embedded in a medium material which the RF field can not penetrate such as thick layers of water or some weakly conductive materials.

Nonetheless of that defect, the proposed estimation system shall be applicable to the similar implanted sensor system.

8. REFERENCES

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