Automatic frequency control of the magnetron system for medical linear accelerator using fuzzy logic control

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Abstract

The Medical Linear Accelerator (MedLINAC) at Synchrotron Light Research Institute (SLRI) in Thailand is the first machine prototype that has been successfully installed and commissioned. The MedLINAC provides the radiation effect of X-RAY for cancer treatment. The control system of the MedLINAC is currently manually controlled by Users, adjusting the microwave power, provided by a magnetron, through the Graphical User Interface (GUI). The magnetron system includes the structure of anode and cathode polarities and two-polarities of permanent magnets, generates the resonant frequency to accelerator tube. The resonant frequency of 2.998 GHz and the peak power of 3.1 MW are suitable parameters with influence to the energy of an electron. The analysis of a magnetron is very complex and it usually requires solving transcendental equations. Both Hull-cutoff and Hartree conditions are estimated properly as parameters of the resonant frequency by using the fundamental principle of an electron motion in structured magnetron. This paper demonstrates the design procedures of automatic frequency control of the magnetron system for the MedLINAC using the Fuzzy Logic Control (FLC) and adjusts the parameters of fuzzy identifier model by using recursive least square algorithm. The controller has a recursive form and model uncertainties. The experimental results obtained from adjusting the desirable resonant frequency, which excites the electrons charge and makes High-power energy for performance of X-RAY radiation.

1 Introduction

The MedLINAC has been developed the capability to accelerate an energy of an electron and to generate radiation of X-RAY by SLRI for medical use in hospitals. It is a necessary equipment for the radiotherapy treatment implies a cancer. Two modes Operations of the radiotherapy treatment can be used. They are the treatment by the X-RAY and electron beam. The MedLINAC consists of 3 main parts: Linear Accelerator (LINAC), LINAC treatment head and the treatment couch system. The prototype of the MedLINAC at SLRI has used LINAC of S-band type

and the resonant frequency of 2.998 GHz. The generation of an electron is emitted by the electron-gun type of hot-cathode, which sets to be negative voltage of -30 kV. In the process for producing of frequency or the resonant frequency of 3 GHz approximately, the Magnetron system is operated the power rating of 3.1 MW and generated the frequency range between of 2,993 to 3,002 MHz by applying high-voltage from a modulator and the voltage must set at 1,043 V.
The Magnetron system has generated high-power frequency which requires to match properly the accelerator tube at resonant frequency of 2.998 GHz. Two techniques for the control of the magnetron system were currently used. They were using to tune the technique of the frequency with applied voltage for experimenting the magnetron by [11, 15] and using to tune the technique of the multiple-cavity magnetron with consideration of the internal structures such as amount, dimension, space and gap of cavities, which depends on the actuator with rod of a motor by [10, 13, 14]. A stepping-motor is manually controlled by Users via a program on computer. Result of the manual control can control constantly the resonant frequency. If the magnetron system is disturbed by the ambient temperature, it takes effect on the resonant frequency as change and canвЃЄt adjust the frequency back to the reference point rapidly. The energy of an electron and the radiation are fast decreasing. Therefore, it is the unstable system. [5, 6, 7, 8, 9] The control system with the FLC Algorithm is a simple, reliable and accurate system. It usually uses in the feedback control loop and improves capable of the performance under external disturbance, which is using to control a linear or non-linear system.
In this paper, The FLC designs and applies the Automatic Frequency Control of the magnetron system for the MedLINAC and it controls to generate constantly the resonant frequency of 2.998 GHz. The FLC of the resonant frequency can control back to the reference point as automatically, although the external disturbance is occurred. The FLC is designed by LabVIEW programming. The objective of the FLC controls the position of stepping motor by keeping the voltage from modulator and shows the dynamic response of X-RAY radiation on the screen. The performance of the FLC was found better than the control of manual user.

2 Magnetron System Analysis

2.1 An electron motion in an electromagnetic field

Both electric and magnetic field influence significantly the motion of an electron, that depends on the orientation of the two fields. If the electric and magnetic field are at the right angle (90°) to each other, this type of field is called a crossed field. The electrons were emitted by the cathode polarity, which are accelerated by the electric field and the more their path is bent by the magnetic field. Since electric and magnetic field or called an electromagnetic field directly influence acting on an electron, it can be explained by Lorentz force law. [1, 2] For rectangular coordinates were written to replace by cylindrical coordinates, which are analyzed data from structure of the magnetron. Hence, the equation of motion for electrons in cylindrical coordinates is written to rearrange the equations as.

$$\frac{d^2r}{dt^2} - r(\frac{d\phi}{dt})^2 = \frac{e}{m}E_r - \frac{e}{m}r\frac{d\phi}{dt}B_z \tag{1}$$

$$\frac{1}{r}\frac{d}{dt}(r^2\frac{d\phi}{dt}) = \frac{e}{m}B_z\frac{dr}{dt} \tag{2}$$

2.2 Hull cut-off and Hartree conditions

General operation of a cylindrical magnetron is controlled by applying the voltage (V_{OC}) at the anode and cathode polarities from a modulator, generates the characteristic dc-voltage of 980 to 1,043 V and the pulse width of 5 μS. The magnetron system connects with perpendicular fields of between the magnetic field (B_{OC}) and the electric field. The electrons are emitted by cathode. They move to the anode and be grazed by the influence of magnetic field. The electron leaves from the cathode with initial velocity of zero and the behavior of the electron grazes the anode block. It can be called the cut-off condition. From equation (2), rearrangement of the equation result in the condition of both the Hull cut-off magnetic field and dc-voltage to the equations as [3, 4, 12].

$$B_{OC} = \frac{\sqrt{\frac{8mV}{e}}}{r_a(1 - \frac{r_c^2}{r_a^2})} \tag{3}$$

$$V_{OC} = \frac{e}{8m}(B_{OC})^2(r_c)^2(1 - \frac{r_c^2}{r_a^2})^2 \tag{4}$$

where r_a, r_c are the radius of anode and cathode, respectively.

The Radio Frequency (RF) Field occurs, this voltage is the condition at which oscillations should start. From an equation (1) and (2), applying this synchronous condition govern an electron movement in a cylindrical coordinate system. It provides at the same time that the magnetic is sufficiently large, so the undistorted space charge does not extend to the anode. The general working operation of cylindrical magnetron is operated by applying the anode-voltage that is slightly above the Hartree-voltage curve and the magnetron system starts to oscillate. [3, 4] However, the anode-voltage of a magnetron is always set below the $\pi - 1$ mode line to avoid mode competition. The Hartree voltage V_H for RF oscillation to start in a magnetron can be obtained.

$$V_H = \frac{\omega_o B}{2}(r_a^2 - r_c^2)^2 - \frac{m}{2e}(r_a\omega_o)^2 \tag{5}$$

where $\omega_o = \frac{\omega}{n}$, ω_o is the angular frequency of the electron, ω is the angular frequency of RF field and n is the modes of oscillation.

3 Automatic Frequency Control (AFC) System

The control of the RF signal is generated by the coupling from the cavity of the magnetron. It depends on the adjustable position of the structured magnetron with the tuning on the rod of a stepping motor. The result of the tuning indicates a changing frequency. The appropriate RF signal for the LINAC of s-band type (2 to 4 GHz) requires the frequency of 2.998 GHz approximately. It is called *the resonant frequency*. An electron was emitted by the electron gun. If when it hits the resonant frequency, the electron increases more energy. After the electron with high-energy moves towards and hits the x-ray target, it causes to affect the radiation of X-Ray. In part of the resonant frequency, the disturbance of the temperature is one main factor of working operation on the magnetron system to effect of the frequency inconsistently. Therefore, the resonant frequency must be measured by using the sensors (AFC circuit). They are the Forward (FWD) power and Reflect (REFL) power. The adjustment of the resonant frequency depends on the design via the linguistic development of program and operates the frequency automatically. The algorithmic FLC is part of the key component for controlling the output signal and compensating the frequency.

The experimentation of the AFC system, the start writes the code to form based GUI on Main Computer (Main PC). The developmental code of based language uses Graphical programming language. It is called *LabVIEW*, which can write the code on the Embedded system under the real-time system (Fuzzy Controller). The Fuzzy Controller is controlled by the Ethernet network communication. It controls and monitors the positional movement of the stepping motor with the hardware and software of the National Instruments products or be called *SoftMotion Module*. This is the central communication of devices between the name of NI-9512 and Motor driver. Both the NI-9512 and Motor driver generate the pulse signal and convert the pulse signal to the position of a stepping motor, respectively. The radiation of X-Ray is caused by hitting the X-Ray target. It can use the sensor (Radiation Monitor) on the measurement of the radiation and displays on Main PC. Finally, the procedures of the AFC system are shown in Fig. 1.

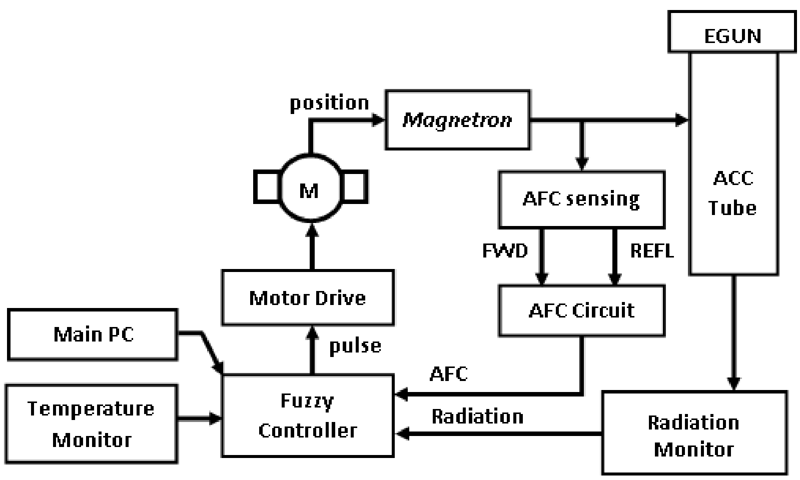

Figure 1: Block diagram of automatic frequency control

In section of tuning for the resonant frequency, the AFC sensing is the measurement device of the feedback signal system. Main components consist of Directional coupler and Circulator. Which are the monitor of the FWD and REFL signal, respectively. Both FWD and REFL signal are compared by AFC circuit module, which uses a particular frequency of 2.998 GHz. The results of the comparison signal can use in the process of the FLC towards the future. All components for the experimentation of the AFC system are shown in Fig. 2.

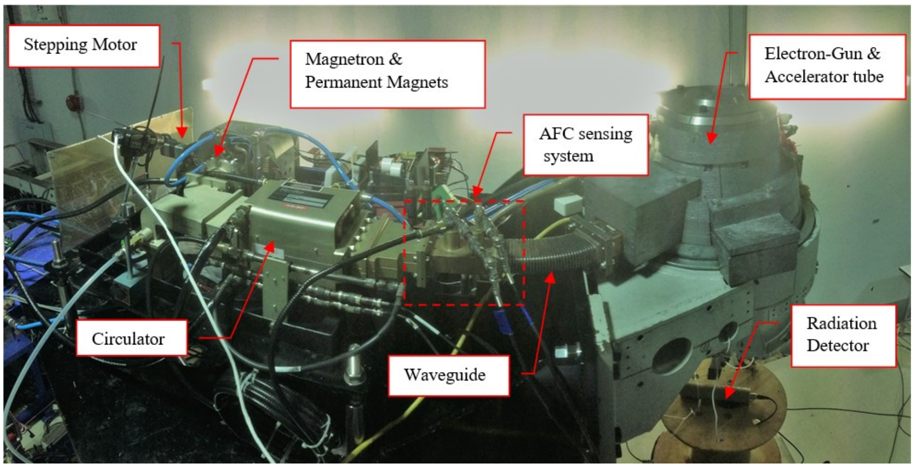

Figure 2: The AFC system of Medical Linear Accelerator

In Fig. 2, the component of the generational resonant frequency is a magnetron. It is a structured form in the shape of a cylindrical tube and that was produced by e2v technologies. The Oscillation of the magnetron (MG7095) depends on working operation by applying the anode-voltage supply between region of Hull cut-off curve and the straight Hartree line. It is always set the mode oscillation of the magnetron as $\pi - 1$ mode. [3] The anode structure of the hole-and-slot-Magnetron (MG5193) with twelve-cavity forms the same as the Magnetron (MG7095) such as the dimension shape and structured form but the output rating differs. Therefore, the MG7095 type of the magnetron can use the same specification of the dimension as the MG5193. It is presented in the Table 14 and can be calculated by using the equation (5) and illustrates results of calculation in Fig. 3.

Table 14: Hull cut-off/Hartree conditions of the cylindrical magnetron (MG7095)

No.	Magnetrons parameters	Results
1	Radius of anode (mm)	17
2	Radius of cathode (mm)	9.25
3	Permanent magnet (Tesla)	0.152
4	Hull cut-off curve (kV)	72.6378
5	Hartree line π mode (kV)	40.4312
6	Hartree line $\pi - 1$ mode (kV)	46.5712
7	Frequency (GHZ)	2.998

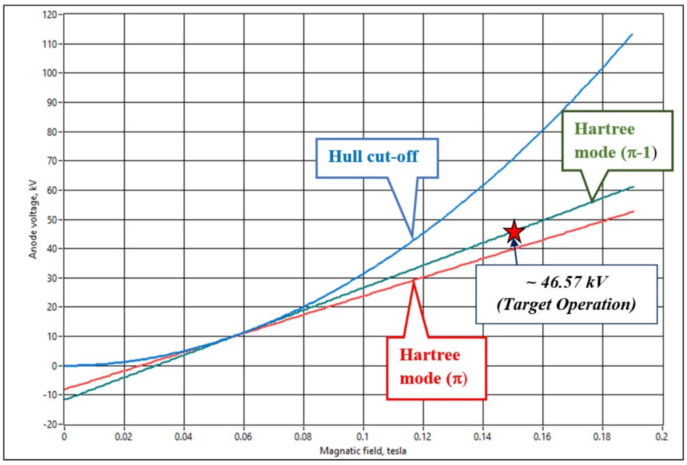

Figure 3: Operating anode-voltage of mode oscillations

4 Implementation of Fuzzy Controller

The design of Fuzzy controller is the key component of the controller for engineering design. The preprocessing and postprocessing steps depend on the determinant laws of the control such as the adjustment of the input and output membership. They must be converted by using the rules-based or the inference engine of the FLC and results in the degree of membership. The characteristic membership indicates the upper-lower and maximum-minimum value and can assign the value of membership function such as triangular shape and straight-line membership function, which uses for input and output variables, respectively. The Input and Output membership function is shown in Fig. 5, 6 . The rules-based FLC determines the human linguistic expression in the series of IF-THEN rules and is illustrated in Table 15. Hence, both the memberships and rules-based FLC should be interpreted by an expert.

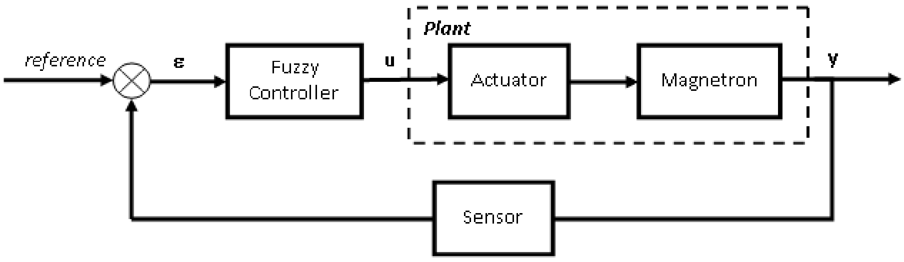

Figure 4: Block diagram of the Fuzzy controller

Block diagram of Fuzzy controller is shown in Fig. 4. An error (ϵ) of the system is the feedback signal (y) of the AFC system. The feedback signal includes of the AFC-A and AFC-B and they are compared by the AFC circuit module, which is a key component within a control loop for the frequency tuning of the operation of LINAC. After that the feedback signal compares again with the reference input. Hence an error value uses in the rules-based FLC. For Block of Fuzzy controller, the preprocessing and postprocessing data always convert the data such as a real signal to the Fuzzy sets and the Fuzzy sets to a real signal, respectively. The example of the output data (u) should convert type of data from digital signal to analog signal and determines properly the value for moving position of the actuator. So, it can set the value in percentage unit (0-100%). Next, Block of the actuator is the stepping motor. It can control to desire the position consistently by applying the pulse signal from the motor driver. The position of the stepping motor is changed by a mechanism of the structured magnetron or space of cavity, which it changes. This directly affects the frequency output or AFC signal. The AFC system is controlled by the linguistic rules and uses in the Fuzzy Controller Block. It is used by Takagi-Sugeno or center of sum (COS) method. [5] A. Basci proposes the inference of Fuzzy, which uses an on-line method or adjusts the parameters of a Takagi-Sugeno identifier model to matching behavior of the control system. From Fig. 5, 6, it is straight line group that can be calculated as follow.

$$COS = \sum_{m=1}^{L} \frac{\mu_{(k_m)} k_m}{\mu_{(k_m)}} \tag{6}$$

where $\mu_{(k_m)}$ is the degree of membership of the input variable and k_m is the output variable range.

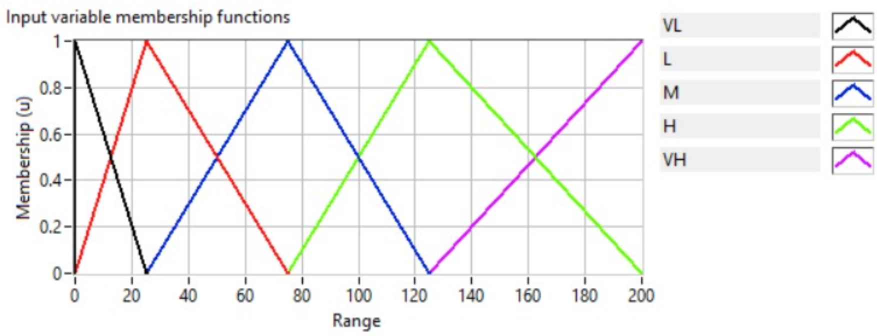

Figure 5: Membership function: Input variables

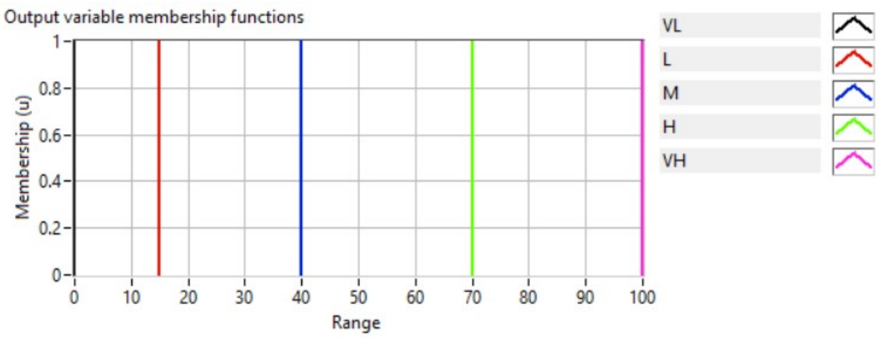

Figure 6: Membership function: Output variables

The output variable of the AFC system is chosen. It should convert to the position control of 0 to 100 %. The membership function of the rules-based FLC includes the input and output logics. They consist of very Low (VL), Low (L), Medium (M), High (H) and very High (VH). The linguistic values of Fuzzy Controller and the

Table 15: Fuzzy Rules Bases

No.	If Input is	Then Output is
1	VL	VL
2	L	L
3	M	M
4	H	H
5	VH	VH

inference system are evaluated by Takagi-Sugeno method. Therefore, the rules of the FLC are mentioned and can be edited by the Fuzzy system designer, which adds the add-on LabVIEW. The system of the fuzzy controller is a single input and single output (SISO) system. It determines the input of position error and the output of position movement. The design of the LabVIEW program writes the code with two sections such as the front panel and the block diagram, which are together called VI (Virtual Instrument).

5 Experimental Results

The magnetron system is controlled by using Algorithm of the FLC for the MedLINAC via LabVIEW program. The determined reference of the temperatures at important components consist of the magnetron system and accelerated tube. The tuning of device requires to set the constant temperature by heating of the inlet water manifolds of 40°C. Next, the input-voltage and the output-voltage is applied by a modulator, which is capability of device generates a pulse width of 5 μS and the input and output voltage with rating of 1,043 V and 45 kV, respectively. The Magnetron system works in the region between range of the Hull cut-off and Hartree line refer to Fig. 3. The experimentations of AFC system for the MedLINAC and results are shown in Fig. 7–9.

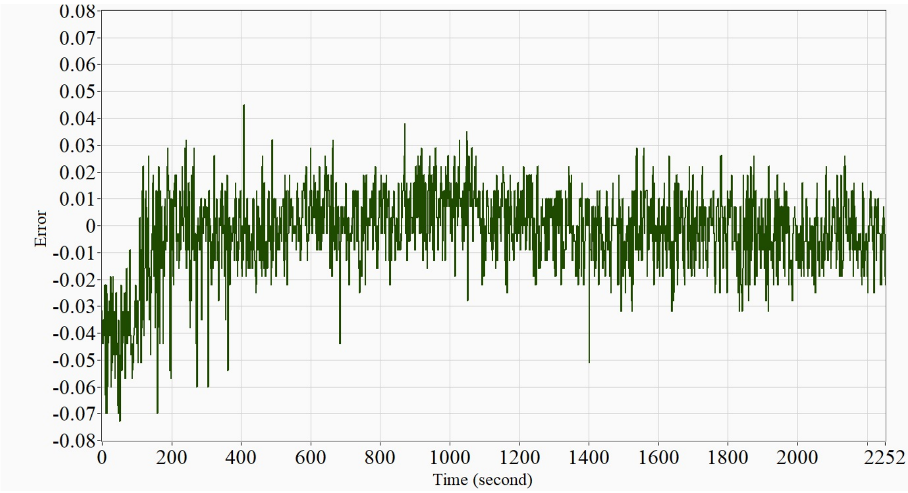

Figure 7: Fuzzy system response: Error response

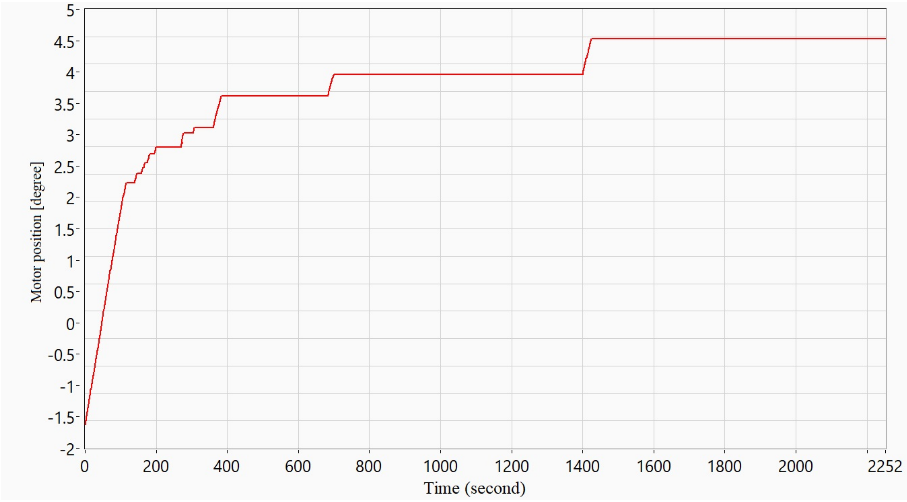

Figure 8: Fuzzy system response: Position response

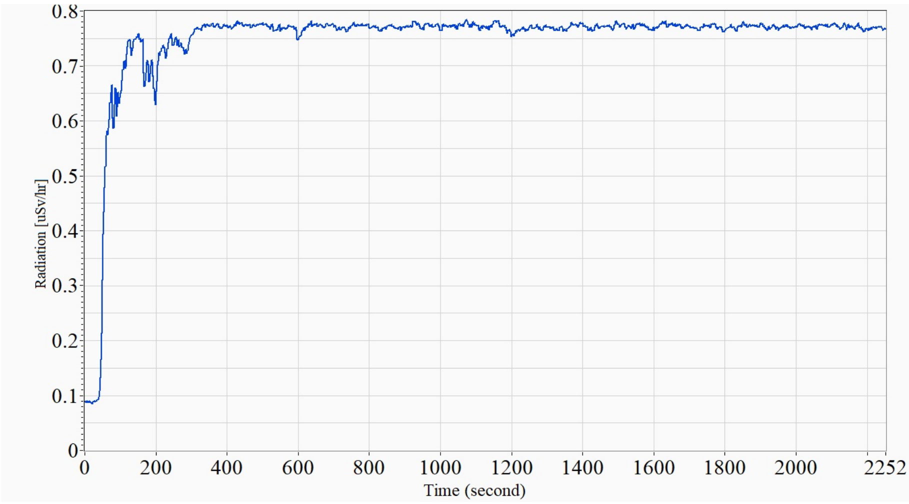

Figure 9: Fuzzy system response: Radiation response

Fig. 7–9 show all experimental results of 2,252 seconds or 38 minutes approximately. An error response (ϵ) or AFC comparative signal in Fig. 7 response compares between the frequency output and the input reference (Required 2.998 GHz). It controls the feedback frequency (Resonant frequency) of 2.998 GHz constantly. The boundary of control sets at the range of between -0.04 to +0.04 V. Results of the signal are out of range, which consist of 0 to 400 second, 700 and 1400 second approximately. In Fig. 8, the effect of the moving Stepping Motor with out of range tunes automatically the position. This moves from 1.6 to 4.6 degree approximately and the signal of the motor position response is zero overshoot, rise time of 100 second and the system of positional Motor in time of 1,430 second constantly. And finally, the results of X-RAY radiation (Fig. 9) from the MedLINAC of 0.775 μSv/hr approximately, the signal of the radiation likely follows direction of an error and the positional Motor response. It observes that the radiation signal of the AFC system. The Fuzzy logic control can control the X-RAY radiation response constantly. However, if the disturbance caused, The Stepping Motor properly moves to tune the position by the Fuzzy logic rules and the magnetron system can adjust itself so the output converges to its desired boundary.

6 Conclusions

The experimental result presents the effective performance control system for frequency control of the magnetron system using the FLC design with LabVIEW program. The dynamic response of the frequency shows no overshoot, rise time of 100 seconds and settling time of 320 seconds. The disturbance caused in system such as the changing ambient temperature in the system. The FLC can adjust itself and output signal is in range of the desired input. This control system is an engineering research and development study for sustainable technology of the MedLINAC at SLRI, Thailand.

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