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Development of FPGA Based System for Failed Fuel Subassembly Localization Using Cover Gas in Fast Reactors

M.Sivaramakrishna, Dr. Chellapandi, IGCAR, Dr.S.V.G.Ravindranath (BARC) IGCAR, Kalpakkam, India

Abstract: The work mentioned in the paper involves analyzing the spectrum obtained from the mixture of cover gas and fission gases released on fuel subassembly failure, using the technique of Fourier transform. The aim is to detect the location of failed subassembly by estimating the amount of burn up in the subassembly.

Index Terms -- **Cover Gas, Area, Pulses, Spectrum.**

I. INTRODUCTION

The aim of the work is to design and synthesize a FPGA based system to identify the amount of fuel burnup in a failed subassembly. The mixture of fission gases and cover gases released during a fuel subassembly failure is sent to a spectrometer system to develop a voltage signal corresponding to the energy of the constituent atoms and the percentage yield of the various gases in the mixture. The frequency domain technique of Fourier Transform is applied through a hardwired logic system to separate out the Kr^{85} pulses from the signal. Kr^{85} has been selected due to its half-life period being suitably long i.e 10 years which ensures that the computational and signal transfer delays do not result in significant changes in concentration. The frequency of the KR^{85} pulses in the input signal is the key factor which is to be determined by the FPGA based device. The burnup of the fuel subassembly is related to the frequency. Knowing the burnup, the location of the subassembly can be estimated. The monitoring and identification of failed fuel sub-assemblies is essential in the PFBR. This ensures that the coolant remains pure and there is no increase in radiation levels. An online monitoring and identification system significantly reduces reactor downtime and also the time involved in detection of fuel burnup in subassembly. Previous studies conducted at IGCAR have revealed that some techniques and properties in the frequency domain like power spectral density, fast Fourier transform, cross correlation, and principle component which can help estimate the frequency of the pulses due to Kr^{85} which is proportional to the concentration of the required isotope Kr85. The processing time for computing the values of these properties is short enough to enable their inclusion in any online monitoring system. Also the accuracy of 2% is good enough for an initial estimate given the time required for conversion of failure to a wet rupture.

II. NECESSITIY FOR THE SYSTEM

Present systems necessitate SCRAM (Safety and Control Rod Accelerated Mechanism) on failed fuel detection on delayed neutron detection, followed by reduced power operation for identification. This reduces the reactor availability and requirement of complex engineered systems. Online analysis of cover gas constituents to identify the failed fuel subassembly substantially reduces the identification time from weeks to hours and hence reduces the reactor downtime. Cladding tube failures are unavoidable despite careful fabrication and testing. In case of fuel clad failure, the fuel might be lost into the coolant, with the following potential consequences. There is contamination and unsafe release of fuel in the reactor vessel, resulting in difficult conditions for maintenance and repair. Also it leads to reduced safety of the core. There are certain cooling disturbances in the bundle due to deposited fuel particles, which may result in failure propagation to other subassembly and fuel melting Due to the above mentioned safety issues, it is imperative that there should be systems designed for Detection of Failed Fuel Subassembly in the core, and Location of Failed Fuel Subassembly in the core at the earliest possible juncture. Being Field Programmable, it is future-proof in the sense that updates or changes can be made to the hardware later with minimum hassles. An FPGA based system can be deployed close to the reactor itself, thereby reducing the distance the analog signals from the spectrometer have to travel, and hence reducing the noise in the signal. Once the signal has been processed, the digital output can be easily sent to the control room without being corrupted by noise.

III. VARIOUS MODULES

The work is split into various modules as given below.

- **Sampling** – The input to the FPGA is a complex waveform composed of contributions from many sources, as well as noise. Using an Analog to Digital Convertor, the input signal is sampled and then stored in a digital format for further analysis.

- **Conversion of input time-domain signal to frequency-domain signal** – The pulse arising because of the Kr^{85} activity need to be isolated from the rest of the signal. This can be achieved in the frequency domain. The frequency of the Kr^{85} pulses is 700 times smaller than that of the other fission gases. The conversion from time-domain to frequency domain is done using Fast Fourier Transform Algorithm.

- **Generating a Lookup table for estimating fuel burn up**- Input waveforms are simulated, within the given constraints. After performing FFT on the generated signals, it is tried to find linear relations between the fuel burnup and the frequency domain plots. The data accumulated is stored for one particular graph parameter from these simulations in a lookup table for comparison with input signal. .

- **Development of VHDL code to accomplish the above** –VHDL code is selected for accomplishing each of the various objectives enlisted above. Also prior to synthesis of the design onto an FPGA, the correctness of developed code needs to be proven by simulation. A test bench file also needs to be written towards this end. A test bench file, as mentioned previously, is an VHDL file which simulates the input signals of the circuit and hence checks the output to test the proper working of the code.

IV. SAMPLE SIGNAL GENERATION AND ANALYSIS

There are a lot of possible techniques for generating the sample signals in accordance with the observed parameters. The algorithm has been reached its final form after many changes to improve the efficiency and optimize the use of system memory resources. In order to develop a relationship between the frequency and FFT graph characteristics, sample signals for a large number of frequencies over a wide range need to be generated and analyzed. Hence this makes it imperative for the signal generation code to be highly efficient in terms of speed and memory. Also the entire process can be made faster and autonomous by importing the sample frequencies from a text file and also writing the relevant data to a text file. The method of storing data into a text file also keeps freeing up the system RAM and hence reduces the memory requirements of the code. Initially, the frequency of the noise pulses and the Kr^{85} pulses is set. The amplitude of each of the pulses is fairly constant. Then an array initialized to 0 is used to represent the signal with the index of an element representing the time and the value representing the magnitude of the signal. There are two values computed- the time till the next noise pulse and the time till the next relevant pulse. The smaller of the two times are considered and the array values around the time are suitably changed to represent the rise time, the fall time and the amplitude of the pulse. Then the time which was larger presently is decreased by an amount equal to the smaller time. Also a new value of the smaller time is computed. In case of the two times being equal, the pulse has amplitude equal to the sum of the two amplitudes. Also both the times are recomputed in this case. This goes on till the signal is generated for the required duration. Then sampling of the signal is done to get the 1024 samples required for the FFT. The sampling rate should be higher than the Nyquist rate i.e more than twice the highest frequency present in the signal. For finding a relationship between frequency and the FFT, frequencies throughout the expected range need to be analyzed. Also for a particular frequency, the signal generation and analysis needs to be repeated at least 5 times. Also Microsoft Excel has been found to be excellent software for the purpose of obtaining a relationship from large amounts of data points. It has been used in the course of the work is to derive the 2nd order polynomial expression which has been utilized to estimate the frequency.

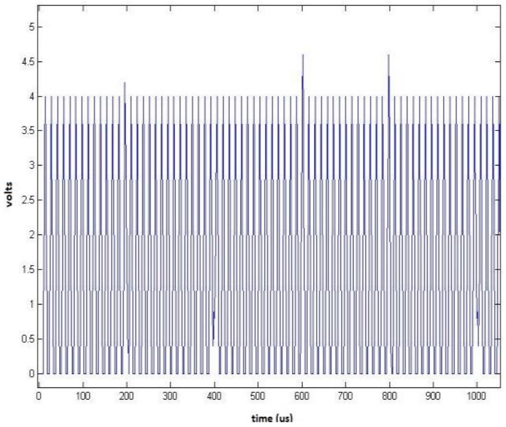

Fig 1 Sample Signal (Kr85 pulse frequency 5000 Hz, Noise frequency 70000 Hz)

V. RELATIONSHIP BETWEEN FREQUENCY AND FFT

The fundamental problem was to estimate the frequency of the Kr^{85} pulse in the input signal. The frequency once found, could be linked to the burn up of the failed subassembly. The burn up would provide a rough location of the subassembly. A method to be found for determining the frequency of the required pulse using the frequency domain technique of Fast Fourier Transform. The first step has been the development of code to simulate the input signal according to the frequency specified. The signal generated is in accordance with the observed signal values. 1024-point FFT of the signal is also done after sampling it at a rate of 146.285 kHz. The pulses in the input signals are not uniformly spaced in accordance with their frequency but in fact are poisson distributed. This gives rise to a lot of components in the frequency domain. A lot of parameters in the frequency domain plots were analyzed to try and identify that key parameter which would be constant for a particular frequency but would vary linearly with change in the frequency. The parameters computed included weighted mean of the peaks, location and height of various peaks. This analysis was carried out by suitably modifying the code. Peaks are those FFT coefficients in the FFT power spectra whose absolute value falls within 90% of the maximum coefficient. Also the poisson random distribution of the pulses made it necessary that the analysis be done for different sample signals of the same frequency. This was imperative to find out a pattern in the FFT graph that repeated itself for every signal and rule out stray observations. Hence, about the entire analysis was repeated 20 times for a particular frequency. The frequencies were varied from 100 Hz to 10 kHz. The pattern which finally emerged and has been used is as follows. The magnitude of the 0th coefficient is decreases almost linearly with increase in frequency. Also the location of the peaks, as defined above, is highly constant for a particular frequency of the noise. However there is no perceptible pattern in their values. Hence to find the frequency of the Kr^{85} pulse in the input signal, the FFT of the signal is done. The peaks in the FFT power spectra are located. The positions of the peaks are compared to certain reference positions, which are found by analyzing signals of known frequency. The peaks should be in the same locations because the frequency of noise is mostly constant. This is done to verify that the signal is valid. Once the validity of signal is ensured, the height of the 0th coefficient is observed. The relation between frequency and height is determined by running tests on sample signals of known frequency. For the signal parameters, a 2nd degree polynomial equation approximates the relationship to a highly accurate level. This gives a certain range for the frequency, which is then used to find the burn up and subsequently the location of the failed fuel subassembly.

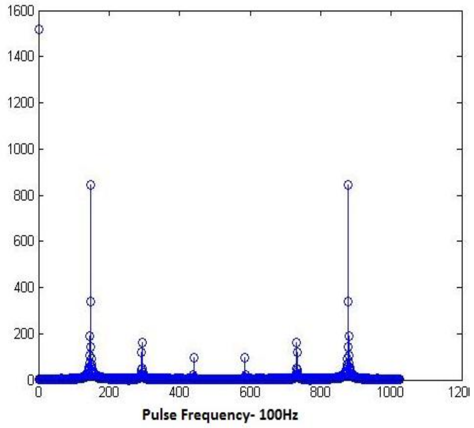

Fig 2 FFT Graph of Sample Signal (Pulse Frequency 100 Hz, Noise Frequency 70000 Hz)

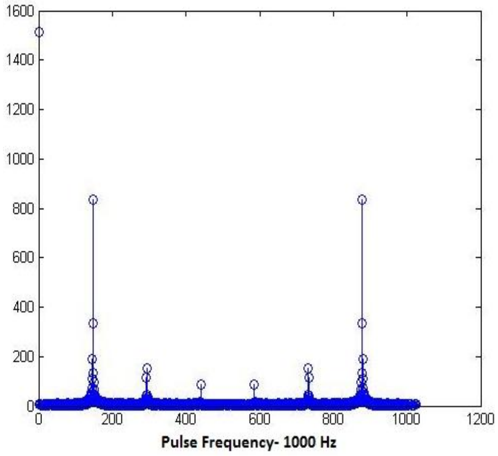

Fig 3 FFT Graph of Sample Signal (Pulse Frequency 1000 Hz, Noise Frequency 70000 Hz)

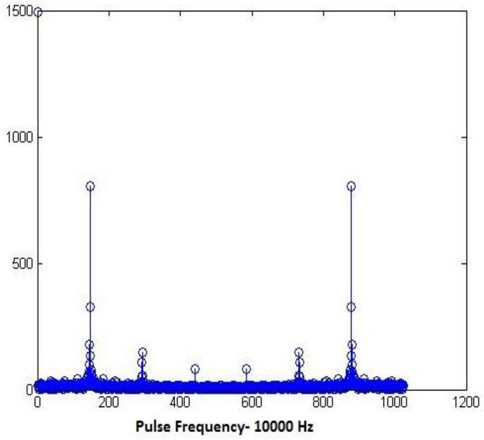

Fig 4 FFT Graph of Sample Signal (Pulse Frequency 10000 Hz, Noise Frequency 70000 Hz)

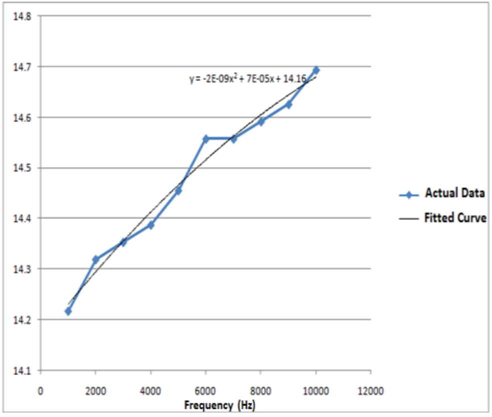

Fig 5 Graph Showing Relationship between Frequency and the Height of the 0th FFT Coefficient

VI. SIMULATION

The simulation consists of two different modules which are executed sequentially. The two modules are based on different software packages.

Input Signal Generation – The input data signal which is to be given to the FPGA device is generated. There are two parameters required as input from the user – the desired frequency of the Kr^{85} pulse as well as the expected frequency of noise i.e the other gases in the fission mixture. Using the given parameters, the code simulates the signal amplitude for a duration of 0.1s with the steps being in microseconds. The signal generated is in accordance with observed signal parameters of rise time, fall time and pulse distribution. The pulses are poisson distributed with their mean as the frequencies provided by the user. The random number generated is using the Merseynne Twister stream. The problem of repetition of random numbers on startup by setting intial seed to system clock. After this, the signal is sampled at regular intervals to generate a total of 1024 samples i.e 10.240 kHz These samples are then written to an unformatted text file as required for reading in through VHDL. The entire code takes around 10s on 4GB RAM machine. Also this method is computationally efficient and faster.

Simulation of the VHDL code- Simulation of VHDL code requires creation of a test bench in order to provide stimulus i.e input signals to the top level entity-architecture pair and verify the output signals. The required input signals are start, reset, the clock and the data signal. The output signals are outdataen, input busy and the FFT result data streams. The test bench developed manipulates the start and reset signals as required by the underlying code. The text file generated by the MATLAB code is read and this drives the input data signal. The clock pulse is also provided by the test bench. The start signal is set to high momentarily to begin the data read process. The input busy signal correspondingly goes high. Once the input data stream is read and the values stored, the FFT computation begins. The outdataen signal goes high after about 50 us (assuming a clock period of 10 ns) to signify the end of the FFT computation. The FFT coefficients appear on the output data streams in a bit-reversed order. These are analyzed to find the various peaks and their magnitudes. These peaks are compared to a reference lookup table to obtain a value for the input frequency.

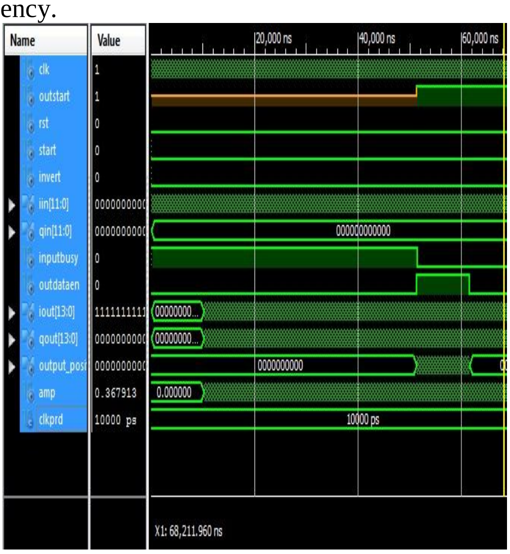

Fig 6 Screenshot Showing the Simulation of VHDL Code

VII. IMPLEMENTATION

The VHDL code is implemented on an FPGA based device. This FPGA along with required spectrometers and preamplifiers is deployed in the field close to the reactor. The device receives a voltage signal. The device has 4 inputs as can be seen in the schematic. An external clock pulse is needed to drive the system clock. The reset signal stops all processes on the FPGA and restores it to its default startup condition. The start signal is to be asserted to HIGH for a clock cycle in order to begin the entire process. Once start goes low, the device starts to read in the voltage signal. It finishes reading in the signal and computing the FFT in about 5000 clock cycles. It takes 1024 clock cycles to store the FFT coefficients after which it computes a value for the frequency using a previously determined 2nd order polynomial relationship.

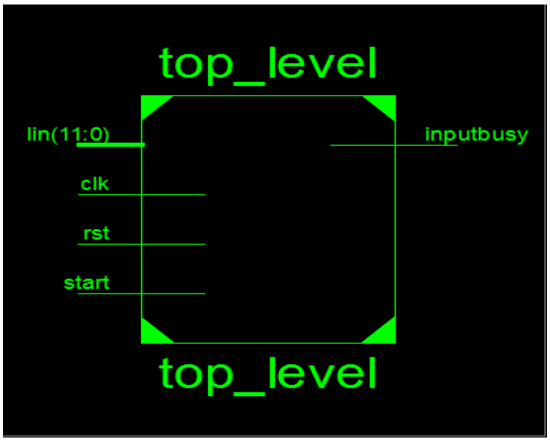

Fig 7 Schematic of the Final VHDL Implementation for an FPGA Device Showing Input/Output Ports

VIII. ADDITIONAL INFORMATION

This section is meant to provide a detailed explanation about fuel subassembly failures. These descriptions have been essential to the development of the algorithm and subsequent code of the system. There are two types of cladding tube failures possible-

1. The Leaker- This involves the release of only fission gases and volatile fission products, without direct contact between fuel and the coolant. This may take months to develop into a wet rupture.
2. Wet rupture- This failure is characterized by an indication of direct contact between fuel and coolant, thus possibly resulting in release of both gaseous and solid fission products into the coolant thus contaminating the fuel and the coolant. The lengthy delay for a micro fissure on the subassembly to develop into a wet rupture is the reason for the absence of an online failed fuel subassembly system in the FBTR. The various fission gases i.e isotopes of Krypton and Xenon are present in the leaked mixture such that the ratio of concentration of Kr^{85} to that of other fission gas isotopes is proportional to the burnup of failed fuel subassembly. The voltage pulses on spectroscopy of the gas sample are such that the frequency of pulses due to a particular gas is directly proportional to its yield percent and the height of the pulses is directly proportional to its energy. The yield %, half life and energy of the various gases are given in table1.

Table 1

Isotope	Half life	Yield %	Energy (Kev)
Kr83m	1.83 h	1.017	41.55
Kr85m	4.36 h	1.013	304.87
Kr85	10.76 yrs.	0.031	84.91
Kr87	1.27 h	3.455	86.91
Kr88	2.86 h	4.198	87.91

Kr89	3.07 min.	5.246	88.91
Kr90	3.3 s	--	89.91
Xe133m	2.19 d	0.525	233.22
Xe133	5.29 d	21.214	132.90
Xe135m	15.7 min.	4.506	526.55
Xe135	9.08 h	22.373	134.90
Xe137	3.83 min	19.059	136.91
Xe138	14.13 min	16.076	137.91
Xe139	41 s	--	138.91

There are many techniques used to analyze samples of the cover gas. Two of them are described below-

Analysis of the actual cover gas sample to find out the burnup of the fuel assembly- In the cover gas monitoring system in Prototype Fast Breeder Reactor, a sample gas is taken and passed through a delay tank of 5 minutes. This ensures that the isotopes with the shorter half-lives in the mixture do not reach the detector. Some may partially decay. After passing through charcoal beds, Spectroscopy electronics (comprising High voltage power supply, pre-amplifier, amplifier and MCA, all integrated into a single unit) is used to obtain the spectrum. The output spectrum is analyzed using reference data to find out required ratio of isotopes.

Simulation technique to analyze the cover gas sample- When there is an alarm on the cover gas, a sample is taken offline. The cover gas sample under spectroscopy using hp Ge sensor+PMT gives voltage pulses which seem random, following a poisson distribution. However the pulses have some distinct properties. The frequency of the pulses can vary from 1 hz to 100 k hz and height varies from 1 V to 10 V. The pulse duration of the pulses is less than 50 µs. The rise and fall profiles of the signal are exponential and of the order of 5 µs and 5 µs width typically. Hence there are more noise pulses whose frequency is 700 times more than the signal pulses to be counted. In addition to this, The height of the pulse required is 1 V compared to the noise pulses whose height can go upto even 10 V. The original signal is generated using known signal parameters and follows pseudorandom poisson distribution. 16384 point radix-4 FFT has been done to obtain the frequency domain graph on the top. Simulation time is 0.1 seconds and scale is in the order of microseconds.

IX. RESULTS

The simulation results are shown in table 2 given below. The error is higher for the smaller frequencies on account of the high sampling rate of 146.825 kHz, which is only slightly greater than the required Nyquist rate of 140 kHz. However the error is acceptable because as per known statistics, there is only about a 1% chance that a gas leak leads to a fuel subassembly failure. Also there is a minimum time lapse of months before the possibility of a failure from a gas leak.

Table 2

Frequency Range (Hz)	Average Error
1000-2000	17.11%
2000-3000	17%
3000-4000	7.22%
4000-5000	7.04%
5000-6000	4.68%
6000-7000	7.59%
7000-8000	4.17%
8000-9000	1.74%
9000-10000	8.84%

X. FUTURE WORK

The Cooley-Tukey algorithm for FFT has been used in the work. Although this is one of the most efficient methods available, the computation required is still immense. The toughest part of the work, is the synthesis of the code onto the FPGA. This involves not exceeding the number of logic blocks or the RAM(Random Access Memory) available on a FPGA. The number of logic blocks used is directly proportional to the complexity of the code. As a result, every part of the code has been optimized so that the logic resources used can fit on a single FPGA. Another roadblock is the lack of available sample signals for analysis. Although the sample signals used have been generated following observed signal characteristics, there are changes in the relationship developed between the FFT graph and the frequency. The simulations reruns using actual data as generated at the Fast Breeder Test Reactor. The spectrometer signal has been analyzed by using Fast Fourier Transform. Other frequency domain techniques like Peripheral Component Analysis, Cross- Correlation amongst others can be also be applied. The best technique is the one which is the most efficient in terms of time as well as logic resources and at the same time is highly accurate. A Prototype is being made to evaluate the feasibility of the simulation studies. Better methods of identification and localization of failed subassemblies need to be developed perhaps with an ASIC based system. Current methods are not highly accurate but are time consuming. Accuracy and time required can be improved by reducing the number of fuel subassemblies monitored by one instance of the system. Also having cover gas with unique tags can also be researched upon.

REFERENCES

VHDL Library packages used-

IEEE.STD_LOGIC_1164,

IEEE.STD_LOGIC_ARITH,

std.textio,

IEEE.std_logic_textio,

IEEE.math_real,

IEEE.std_logic_signed,