STUDY OF FAILURE MODES IN ELECTRON LINAC-BASED X-RAY SOURCES FOR INDUSTRIAL APPLICATIONS

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Abstract

Electron linac-based x-ray sources (XRS) have an increased demand in industrial applications, mainly for their advantages of compactness and ease of use. In order to achieve reliable operation, it is necessary to have rugged components in the linac system. Hence, this study focusses on achieving high reliability design; also, in formulating a preventive maintenance programme to optimise the availability and prognostic methods for performance monitoring of components.

This paper investigates the failure modes in the important sub-systems of a 6 MeV electron linac, including electron gun, RF power source, vacuum system, x-ray target, control system, etc. Electron guns suffer from problems related to the filament heater damage and high voltage insulation failure. In the RF source, major components (line-type pulsed modulators, magnetrons, circulator and RF window) are studied. Fault tree analysis of the individual sub-systems and the effect of individual failures on the linac down-time are studied qualitatively. A few mitigation techniques used in practical systems are also discussed here.

INTRODUCTION

RF Electron Linac-based x-ray sources are used for various industrial applications, including cargo-scanning and NDT radiography. They are more popular than isotope-based gamma ray radiography systems, due to the high beam current, simplicity of operation, relatively low cost and better image quality compared to Co-60 based systems.

SYSTEM DESCRIPTION

The 6 MeV RF linac system [1], shown in Fig. 1 (a) and 1 (b), has an LaB_6 cathode-based indirectly heated electron gun [2], as injector. Electrons at an energy of 50 keV are injected into the S-band bi-periodic standing-wave linac cavity, operating at 2856 MHz, to obtain an output electron beam with 6 MeV energy. The linac operates in the pulsed mode with pulse repetition rate of 250 Hz (max) and pulse width of 3-4 µs. Acceleration gradient in the linac is generated with the help of 3 MW (peak), 3 kW (average) Magnetron based RF source [3] at 2856±5 MHz.

The accelerated 6 MeV beam is focussed with the help of a focussing coil to reduce beam size to < 2 mm. The focussed beam falls on a water-cooled tantalum target to produce x-rays. Collimation of these x-rays is achieved through a trapezoidal collimator, made of mild steel as shown in Fig. 1. Vacuum level of 1×10^{-7} torr is maintained in the system, with the help of turbomolecular and sputter-ion pumping system. Radiation shielding is provided for the linac in order to reduce the radiation levels to permissible limits. Control of the x-ray source is done using a PLC-based system. Remote operation, monitoring of essential parameters and their display as well as data-logging is possible with the C&I system.

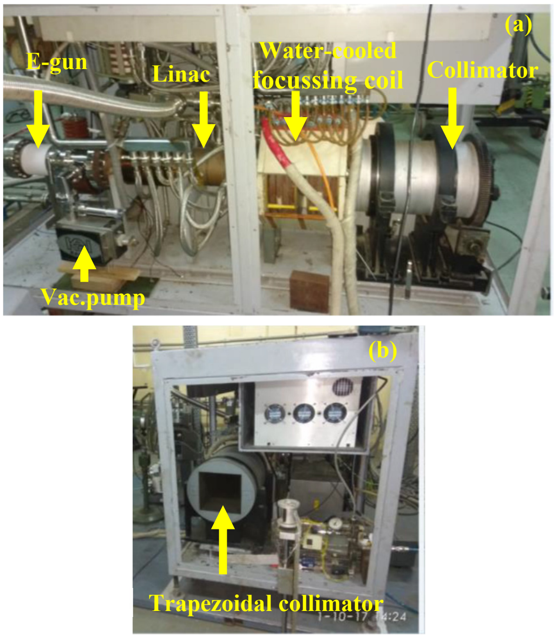

Figure 1: Side view of XRS (a). Front view of XRS (b).

SYSTEM PERFORMANCE

RF conditioning and Beam conditioning was carried out after assembly of the linac-based x-ray source. Qualification of the linac for radiography applications was conducted at dose level of 1-2 Gy/min at various exposure rates. Wire-type (ASTM E 747) and hole type (ASTM E 1025) penetrameters were used. Sensitivity of ~ 1- 2% was achieved. It is observed that linac can be used for industrial radiography of steel of thickness 100 – 200 mm with acceptable density requirement. Focal spot size of ~ 1 mm was estimated using MTF method.

FAILURE ANALYSIS

During the operational phase of the linac, several faults have been observed. Some of the faults have led to major shutdowns, while others are minor trips of the linac. In this context, failure refers to a condition when linac system is not able to deliver the desired output beam, as per the specifications. It is important to note that system is so

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engineered that linac trip occurs in case of any of the failures, in order to ensure both human and machine safety Most common causes of failure that have been recorded during 2 years of operation include vacuum trips, failures of electron gun and RF power source.

In order to assess the performance of the linac-based system qualitatively and for analysis of failures, two of the most commonly used techniques – Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) [4, 5] have been used. The following sections give a brief description of the analysis.

FAILURE MODES AND EFFECTS ANALYSIS

There are several causes of failure in the linac system which occur commonly. Failure Modes and Effects Analysis (FMEA) is used to study failures in various sub-systems and/or components and their effect, both local and global, on linac operation. Table 1 gives the FMEA conducted for electron gun. Similar analyses were carried out for other sub-systems also. A brief description of the analysis of each sub-system is given below:

Electron Gun

Electron gun failure can occur due to several reasons, all of which result in cessation of beam from electron gun. Tungsten filament, which is wound as a helical coil, can break due to mechanical and thermal stresses. Vacuum conditions can also cause deterioration of the filament. Theoretical estimation of filament life, for operation at 2600 K is ~ 760 hrs [6]. Cathode of the electron gun is a mm (dia) LaB_6 pellet. If exposed to atmosphere in the heated condition, pellet gets poisoned and a film is formed on the surface, causing the emission from the cathode to reduce and results in loss of e-gun beam. Ceramic tube used to provide HV insulation can experience HV breakdown or can develop mechanical defects. Sparking can occur and cause leakage currents. Gun modulator is a pulsed HV source producing 50 kV, 4 A, 3-4 μs pulses at 200 Hz (max), used as the extraction voltage in the gun. In case of a failure of any component of modulator, output pulse is not available. Gun filament power supply is a DC source, capable of supplying 15V/20 A to heat the filament for thermionic emission. In case of failure of this power supply, current ceases to flow in the filament, resulting in no electron emission.

RF Power Source

Magnetron-based RF power source provides RF power to linac to establish accelerating gradient. Failures can occur in any of the components or when there is an impedance mismatch between the RF power source and the linac cavity. The 3 MW Magnetron that is used in this system has an estimated life of ~ 2000 hrs filament life. But, when operated at 2.5 MW, filament life extends to over 3000 hrs. Faults may arise due to HV breakdown, filament breakdown and vacuum failure within magnetron. Line-type modulator, has several critical components, including the CCPS, thyratron switch, pulse transformer, etc. Failure in any one of the components, leads to the termination of pulses fed to the cathode of the magnetron. Any waveguide-plumbline component (3-port circulator, bends, dual directional coupler and ceramic window) can fail and lead to increase in reflected power. Also, fall in pressure of SF6 gas in WR284 waveguide plumbline leads to HV breakdown, causing arcing in waveguide and is detected by increase in reflected power signal from the dual directional coupler. (iv) Impedance mismatch between RF power source and linac cavity causes increase in reflected power and causes HV to trip. It is detected by the reflected power signal from the dual directional coupler.

Focussing Magnet and X-Ray Target

Focussing magnet is used to reduce beam size to < 2 mm. Failure in magnetic system leads to defocussed beam which can heat up the beam tube excessively. Most common cause of failure in magnet is absence of cooling water, leading to an increase in the temperature of the magnet coil and insulation failure, causing shorting between coil turns. Uncontrolled increase in temperatures can lead to rupture of the coil. Failure in the constant current power supplies can also lead to deviation of output from its required parameters.

The x-ray target temperature generates a large amount of heat and failure in the cooling system can cause the thin target to rupture, leading to break in vacuum and air inrush into the linac system.

Auxiliary Systems

Auxiliary systems used for linac operation include the vacuum system, the control & interlock (C&I) system and safety systems, such as radiation monitoring system, search & secure system, etc. Vacuum System ensures that the linac system is maintained better than 1x10-6 torr. During operation, any increase in pressure in any section of the linac system leads to a system trip. Increase in pressure can be caused due to malfunctioning/failure of pumps, gate valves and gauges, leakages through gaskets, etc. Failure in the RF window in linac and magnetron can also lead to vacuum failure. C&I systems can fail when any electronic component in the control circuits malfunction/fail. Software failure can also cause C&I system malfunction. EMI issues can give rise to spurious signals, which when coupled to the signal lines, can cause malfunctioning/failure of the C&I Systems. Safety systems, including the radiation monitoring systems are interlocked with linac operation, so that a failure leads to linac system trip.

FAULT TREE ANALYSIS

Fault Tree Analysis is deductive, top-down approach, which is quantitative and considers external events during the failure analysis. Linac Beam failure is the top-most event that will occur in case of any failure in the subsystems, as depicted in the fault tree in Fig.2. It can be seen that the failure of the electron gun, RF power source, focussing magnet & x-ray target or the auxiliary systems causes beam failure and the RF linac stops operation.

Table 1: FMEA for Electron Gun

Module Name	Description	Functional Failure Modes	Detection Mechanism	Local Effect	Global Effect
Electron Gun	Tungsten filament	Filament breakage	DC Current monitor	No e-gun current	No output beam
	Ceramic insulation tube	HV Insulation breakdown	Gun modulator signal on oscilloscope	Sparking & Large leakage current	No output beam
	LaB$_6$ pellet (10 mm dia)	Cathode poisoning	Visual inspection - no increase in e-gun current with increase in filament current	No e-gun current	No output beam
	Gun modulator 50-70 kV, 4 A, 10 µs, 400 Hz	Gun modulator failure	Capacitor probe signal on Oscilloscope	No egun current	No beam output
	Gun filament power supply 15 V/20A DC	Gun filament power supply failure	Current meter signal	No egun current	No beam output
	Filament cooling fan	Filament Fan failure	Visual inspection on camera	Increase in temperature of gun components	System trip

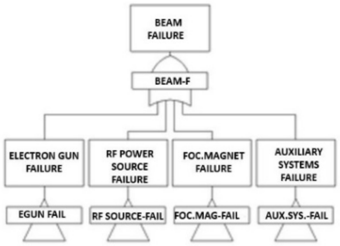

Figure 2: Fault tree for linac-based x-ray system.

Similarly, fault trees for individual sub-systems, viz, electron gun RF power source, etc. have been created to fully understand the effect of the failures.

It has been observed during operation that faults that occur in linac systems have different occurrence frequencies and impact linac operation differently. While some faults occur repeatedly, with low impact on linac operation, other faults may be rare, but can cause catastrophic results.

Mild faults, are those which exist for a short while, and system can be reset and operation resumed in a span of 1-2 minutes, keeping downtime very low. Medium-level faults are those that result in relatively longer downtimes and need personal intervention repair/replacement of faulty component / sub-system. Severe faults, due to excessive damage to components/sub-systems, often result in linac shutdown for long periods, for several hours or days. Any activity which results in admittance of air into linac cavity falls in this category. For example, a sudden crack in the ceramic window or rupture of the target window, due to improper cooling, causes vacuum to fail. Though the system trips, severe damage takes place in various sections of the linac. There is a sudden inrush of air into the system, which while moving at supersonic speeds, travels to the hot cathode of the gun and poisons the LaB$_6$ cathode. At the same time, entry of air into the linac cavity results in the contamination of the RF conducting surfaces. It then becomes necessary to replace and perform HV conditioning of electron gun, as well as cleaning and RF conditioning of linac, which is a long and laborious process. It can be seen here that a fault in one sub-system, cooling system in this case, results in damage to other sub-systems, like electron gun and RF cavity.

MITIGATION TECHNIQUES

Mitigation techniques that have been adopted in this system, to ensure reliable operation with low down-time, are as follows: (i) Derating of components for longer life and reliable operation; (ii) Fail-safe methods incorporated for operation of sub-systems, like introduction of fast acting vacuum valves for protecting the hot cathode; (iii) Stringent quality control during design, fabrication, testing and operation phases; (iv)Maintenance of spares and preventive maintenance for components, such as magnetron, egun filament, PFN capacitors in line-type modulators, etc., (v) EMI mitigation methods adopted, with proper isolation of signals, shielding and grounding in the presence of high level of noise from high frequency, high voltage sources; (vi) Stringent quality control during design, fabrication, testing and operation phases; (vii) Maintenance of spares and preventive maintenance for components such as magnetron, egun filament, PFN capacitors in line-type modulators, etc. (viii) EMI mitigation methods adopted, with proper isolation of signals, shielding and grounding in the presence of high level of noise from high frequency, high voltage sources.

CONCLUSION

Study of failures using FMEA and FTA techniques has been conducted for the 6 MeV RF Linac-based x-ray source. Failure modes have been identified and discussed and mitigation techniques have been suggested for reliable operation. Further work on prognostic health monitoring is in progress.

ACKNOWLEDGEMENT

Acknowledgement is due to Chairman, BARC Safety Council, for permission to carry out this work. The authors sincerely thank all persons who have directly or indirectly contributed to this work.

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