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A Novel Data Fusion Method for Incipient Fault Detection in TRU of Aircraft Electrical System

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Abstract: Incipient fault detection in the Transformer Rectifier Unit (TRU) can prompt early preparedness for replacement of Line Replaceable Units (LRUs) thereby reducing the downtime of the aircraft. This paper describes a novel incipient fault detection and fault localization method of TRU in the context of an aircraft electrical system. Results from Failure Mode and Effects Analysis (FMEA) study identified diode failure as the primary reason for failure of TRU. The incipient fault detection of TRU is done by applying data fusion algorithm. The algorithm uses Hilbert transform as one of the computing tools to derive Health Index Parameter (HIP). Fast Fourier Transforms (FFT) and wavelet transforms were used for fault localization of the component within the TRU. The developed incipient fault detection method is validated on a TRU test rig. Though the test rig is configured on 50Hz supply the results can be read across on 400Hz supply. A scheme of communicating the fault status integrating through 1553B network is also addressed.

Keywords: Incipient fault detection, Hilbert transform, data fusion, TRU,MIL-STD1553B,IVHM,OSA-CBM

1. INTRODUCTION

Commercial and military aviation sectors are making major commitments to the platform of Integrated Vehicle Health Management (IVHM) to acquire real-time data. This helps in developing models, algorithms and software that can effectively and efficiently detect faults and predict the remaining useful life (RUL) of failing components while minimizing false alarm rates [1][2]. Integrated Vehicle Health Management (IVHM) is a concept for complete maintenance cycle of a vehicle. It makes use of embedded sensors along with self-monitoring equipment and diagnostic reasoning.

This paper proposes (i) a new method to develop, analyse and validate fault diagnosis and (ii) methods for incipient fault detection and localization. This framework for fault diagnosis relies on engineering principles and failure models, algorithms and measurements acquired through induced faults on a Transformer Rectifier Unit (TRU) test setup. Fundamental to this approach is the development of models and the optimum selection and extraction of features or health indicators from raw data that form the characteristic signatures of specific fault modes[3] [4].

In this paper, incipient fault detection, fault localization in a TRU in the context of aircraft electrical system (ES) and interface of health status to the Avionics bus (MIL STD 1553B bus) was done[8]. In aircraft of the old era, the bulk of the power requirement was for AC. The prime sources of power for the electrical generating system were therefore alternators driven by the aircraft engines through constant-speed drives. The aircraft used DC power to provide the essential flight services such as communication and navigation, so that, in the event of a complete generating-system failure, standby batteries could be used. The DC power could be obtained conventionally from a DC generator. There are, however, two drawbacks that militate against doing this. Firstly, the power to weight ratio, maximum power rating limit of 9KW, fire hazard due to commutation, complex maintenance requirements and unreliability associated with the commutators pose limitations around the aircraft engine and make it extremely difficult to incorporate both AC and DC generators. Secondly, long, heavy, low-voltage feeder cables are required to connect the DC generator in the engine bay to the bus bars, which are usually situated in the centre of the aircraft[6]. For these reasons, an alternative method of obtaining DC power was considered. On most modern aircraft the source of DC power is a TRU which converts AC power to DC, which is supplied from an AC generator[5].

The study of dynamics of TRU was carried out by simulating it using Orcad Pspice tool. The simulation model behaviour provided the foundation in development of the TRU test-rig, which maintained the output voltage ~28VDC at varying load conditions. This is according to the Aircraft DC power requirement[6]. The TRU test-rig was developed using the three phase transformer with single primary and two secondary windings, two bridge rectifiers and interphase reactor for converting the 115VAC and 50Hz frequency into 28VDC. The developed TRU is matching with MIL STD 704 F [8] output characteristics as it maintains the output voltage very close to the required 28VDC. Incipient fault is introduced in TRU by shorting one of the diodes in either of bridge rectifiers. Incipient fault detection methodology of the TRU is developed by acquiring the current signatures of the TRU using sensors. The current signature is computed by data fusion using Hilbert Transforms as one of the component for building algorithm which runs on National Instrument (NI) Data Acquisition (DAQ) and processing system with a form factor of PCI eXtensions for Instrumentation (PXI). The result is the Health Index Parameter (HIP). Fault localization is carried out using frequency signatures of sensor data of one phase current. This is done using Wavelet Transform and Fast Fourier Transform (FFT). The scheme for TRU health management in Aircraft Electrical System is shown in Figure 1.

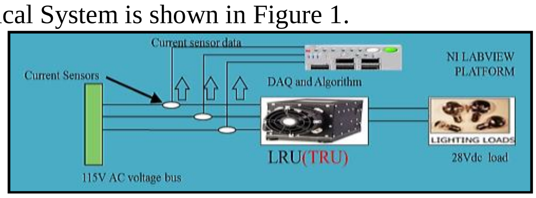

Figure 1. Scheme for Health management of TRU in aircraft Electrical System

2. SYSTEM BACKGROUND

2.1. Transformer Rectifier Unit (TRU)

A transformer rectifier unit (TRU) is a combination of a static three phase transformer of single star primary winding, two secondary star/delta windings and a rectifier for converting an AC input of one voltage into DC output of another voltage. This TRU system takes the mains 115VAC and converts it in to approximately 28V. This is achieved by a transformer, which first steps down the AC voltage to a reasonable level and then converts it via a bridge rectifier assembly into DC. Most of the aircraft AC generator systems have dedicated TRUs which operate on the same principle[5].

A typical unit is illustrated below. The TRU that is fitted to an aircraft is typically supplied with 115 V 400 Hz three-phase AC, which is stepped-down through a three phase transformer of single star primary winding, two secondary star/delta wound windings and changed to 28 VDC by a two-rectifier six diode bridge assembly along with interphase reactor to balance output voltage. The output from the TRU is then fed to the aircraft's DC bus bars. The DC bus bar voltage should match MIL STD 704F aircraft electrical standards. Figure 2 shows the functional block diagram of a TRU.

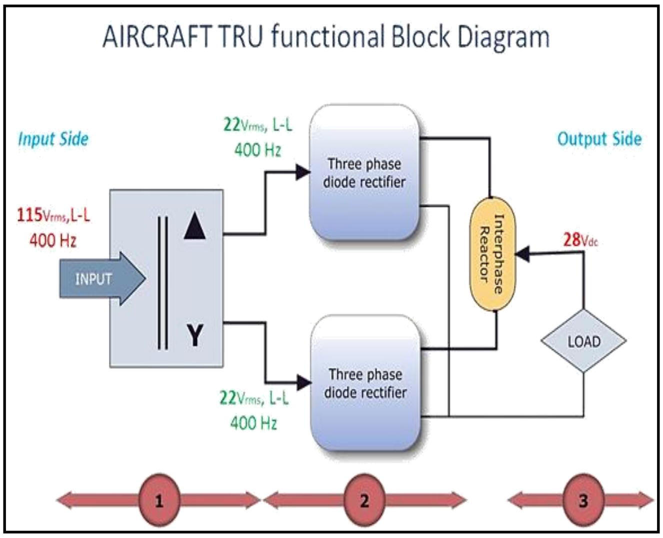

Figure 2. Functional block diagram of a TRU

2.2. Dynamic Simulation of TRU

The simulation is carried out by tuning the internal parameters of the TRU such that the input and output rating matches according to MIL STD- 704F. The simulation diagram using Orcad-Pspice is as shown in Figure 3.

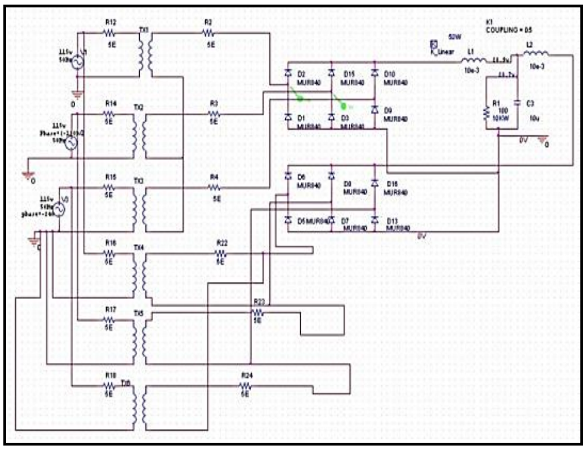

Figure 3. Simulation diagram of TRU using PSpice

The parameters used in simulation are shown in Table 1.

Table 1. Parameters used in simulation of TRU.

Parameters	Value
Input Voltage	115 Vrms,3 ph,50Hz
Output Voltage	28 V DC
Primary Y- Winding parameter L-L resistance L-L inductance	 290 ohm 160 mH
Secondary Delta-winding parameter L-L resistance L-L inductance L-L resistance L-L inductance	25 ohm(Star Side) 22 mH(Star Side) 22 ohm(Delta Side) 13 mH(Delta Side)
Interphase inductor	10 mH each
Diode	MUR840
Load	100 ohm(Rheostat)

Figure 4 shows the DC output voltage and input AC line voltage of the simulation. The output of 28V DC is maintained by the TRU for the input line voltage of 32 V AC peak to peak.

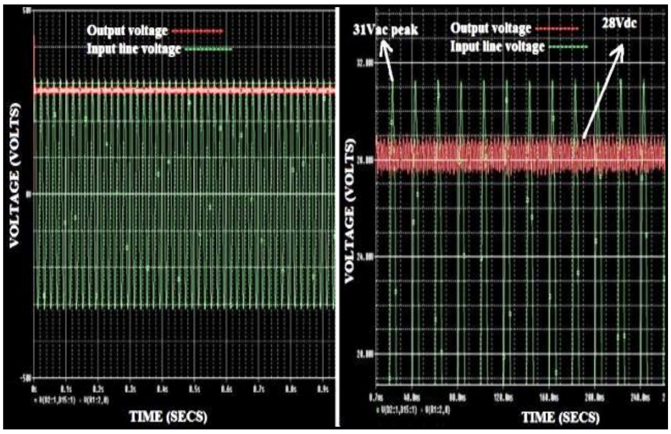

Figure 4.TRU Simulation Output

Figure 5 shows the input phase current and the load current, under healthy condition. The current of 280mA is maintained across the connected load of 100ohm for 28V DC output voltage.

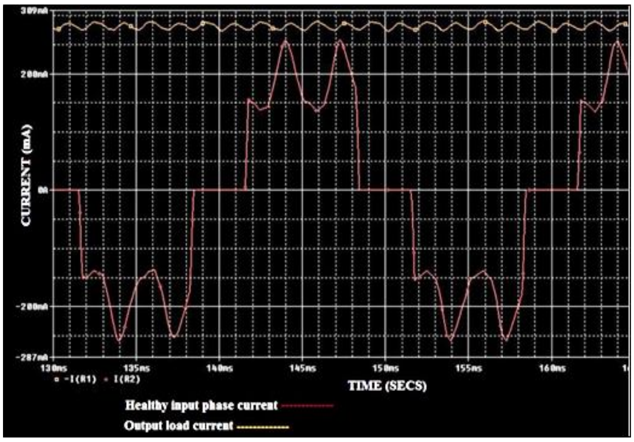

Figure 5. Output Load Current and Input Phase Current under Healthy Condition

The figure 6 shows output voltage waveforms before the output filter for both healthy and faulty condition i.e., short circuit and open circuit in diode. When the fault is inserted, the average DC value of the output voltage remains the same so the fault in the diode cannot be determined easily. The TRU compensates for the fault and maintains the constant voltage across the load.

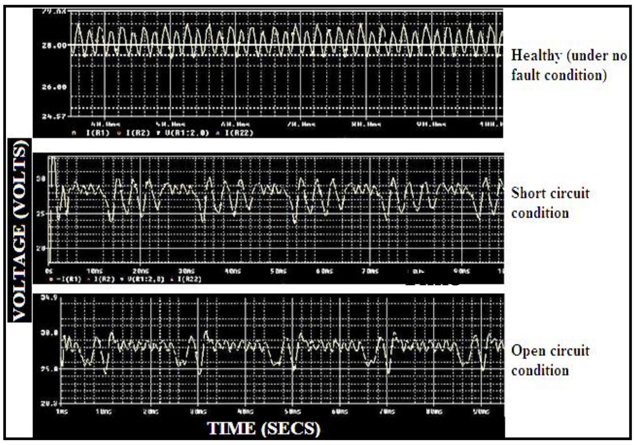

Figure 6. Output Load Voltages under different conditions

Figure 7 shows the faulty input phase current and output load current. It clearly indicates that there is no change in load current but significant change in the input phase current under fault condition. Hence, based on the simulation, it is observed that input phase current has valid information to be tapped under faulty condition. This is the basis for data fusion algorithm development.

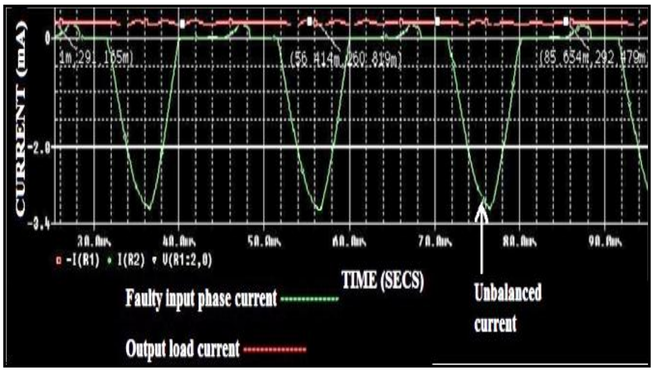

Figure 7. Output Load Current and Input Phase Current under Faulty Condition

3. DATA FUSION ALGORITHM AND EXPERIMENTAL VALIDATION

3.1. Incipient Fault Detection using Data Fusion Algorithms

The incipient fault detection of TRU is developed by using the current signatures of input three phase currents of TRU. The current signature is computed by a data fusion algorithm which runs on LabVIEW software Platform. The concept which is developed for incipient fault detection of TRU is unique. The cost of implementation of the above scheme is very minimal (only three current sensors are required). A flowchart describing the incipient fault detection using Data Fusion Algorithm is shown below in Figure 8. The Hilbert Transform can be described by the following mathematical equation. Health Index Parameter (HIP) selection and extraction constitute the cornerstone for accurate and reliable incipient fault detection. Fault diagnosis depends mainly on extracting a set of features from sensor data that can distinguish between fault classes of interest, detect and isolate a particular fault at its early initiation stages.

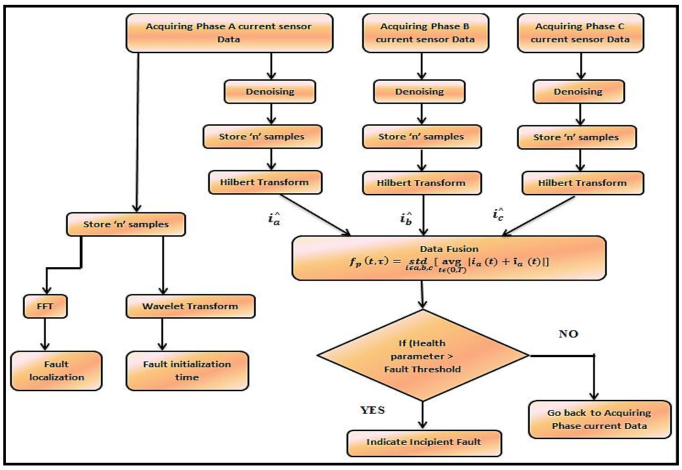

Figure 8. Flowchart describing Incipient Fault Detection using Hilbert Transform

The remainder of this section evaluates a feature derived from simulated phase currents using the Hilbert transform to identify asymmetries as a result of diode faults.

Definition—The Hilbert transform[9] $f(t)$ of a function $f(t)$ is defined as follows

$$\hat{f}(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{f(\tau)}{t-\tau} d\tau \qquad (1)$$

The symbol P denotes the Cauchy principal value. The Hilbert transform can be used to create an analytic signal z (t) from a real signal (t) ,

$$z(t) = f(t) + i\hat{f}(t) \qquad (2)$$

Using this representation it is possible to describe the signal z (t) as a rotating vector with an instantaneous phase φ (t) and an instantaneous amplitude A(t) in the time domain,

$$z(t) = A(t)\exp[i\varphi(t)] \qquad (3)$$

Where A(t) and φ(t) are related to $f(t)$and $\hat{f}(t)$ by the following expressions,

$$A(t) = \sqrt{f^2(t) + \hat{f}^2(t)} \qquad (4)$$

$$\varphi(t) = \arctan[\hat{f}(t)/f(t)] \qquad (5)$$

Now consider the following real signal and its corresponding Hilbert transform (H.T.), provided in Equation 6, where the symbols A_0, ω_0 and φ_0 correspond to arbitrary constants for the amplitude, frequency and phase shift respectively.

$$f = A_\circ \cos(\omega_\circ t + \varphi_\circ) \overset{H.T.}{\longleftrightarrow} \hat{f} = A_\circ \sin(\omega_\circ t + \varphi_\circ) \qquad (6)$$

By applying Equation 4, the functions $f(t)$and $\hat{f}(t)$ form an analytical signal, z (t), where the instantaneous amplitude is shown to be phase invariant in Equation 7,

$$A(t) = A_\circ \qquad (7)$$

Health Indicative parameter—from the Equations 6 and 7 demonstrated $|f(t)$and $\hat{f}(t)|$ is phase invariant provided that f is a sinusoidal signal of constant amplitude and frequency. Extending this to a time-varying vector of three phase current signals $\mathbf{i}_{abcs}$ (t) provides a measure, or CI, of the amplitude of each phase during steady state. Finally, by taking the standard deviation of the average amplitude of each phase current (a, b and c) over a finite time interval T, the following HIP, denoted as f_p *(t, T)* can be used to describe asymmetry as a result of diode failure.

$$f_p\,(t,\tau) = std_{i\epsilon a,b,c}\,[\underset{t\epsilon(0,T)}{avg}\,|i_a\,(t) + \hat{\imath}_a\,(t)|] \quad (8)$$

3.2 Experimental validation on scaled down TRU test rig

A scaled down prototype version of TRU test rig was built for the purpose of validation as shown in Figure 9.

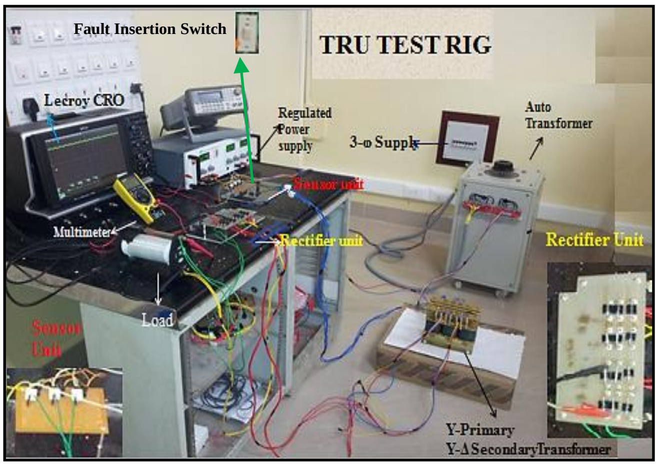

Figure 9. Test rig setup of TRU

Auto transformer is used to power up the TRU test rig. The power rating of the TRU is 28Watts. The components used to develop the TRU test rig are shown in the Table 1.The Hall Effect current sensors considered are capable of measuring the currents up to 2A. Three Hall Effect sensors are used for the three phase currents for instantaneous current measurement. For the fault injection, one of the diodes in the bridge rectifier circuit is shorted using a switch as a shown in Figure 9. The three input phase currents from the three Hall Effect sensors are continuously acquired into data acquisition system for processing of sensor data. Figure 10 shows the output voltage of TRU from the test rig matching MIL STD-704F electrical characteristics.

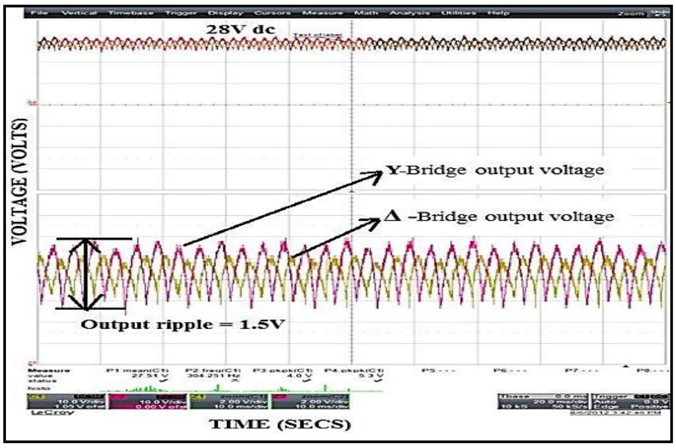

Figure 10.Output voltage of TRU matching MILSTD-704F electrical characteristics

3.3 Real time Implementation of Data fusion Algorithm in NI PXI system

Graphical User Interface (GUI) is developed using LabVIEW software with NI PXI hardware. GUI backend is developed in such a way that sensor data can be acquired and processed with data fusion algorithm to find out the incipient fault detection, fault localization and fault initiation time. Figure 11 shows the LabVIEW GUI indicating the healthy working of the TRU. This clearly indicates HIP or significant feature value will not vary under the healthy condition.

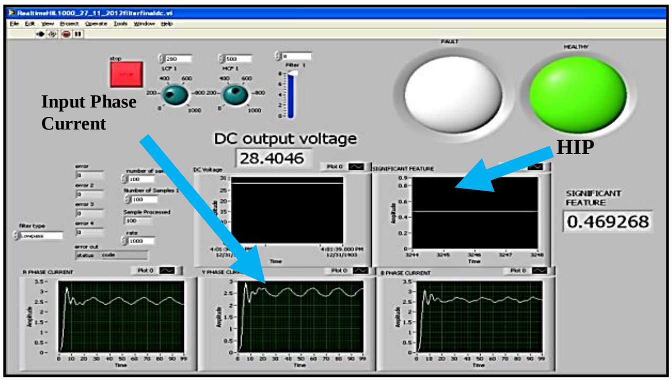

Figure 11. TRU front end GUI in LabVIEW showing healthy condition

Figure 12 indicates the faulty condition. When the fault is injected in the diode, the HIP or significant feature varies indicating the fault in TRU without any noticeable change in the output DC voltage with response time of 10 ms. Figures 11 and 12 clearly indicate that the output voltage of TRU is maintained constant in both the faulty and healthy conditions but a significant change is observed in the input phase current.

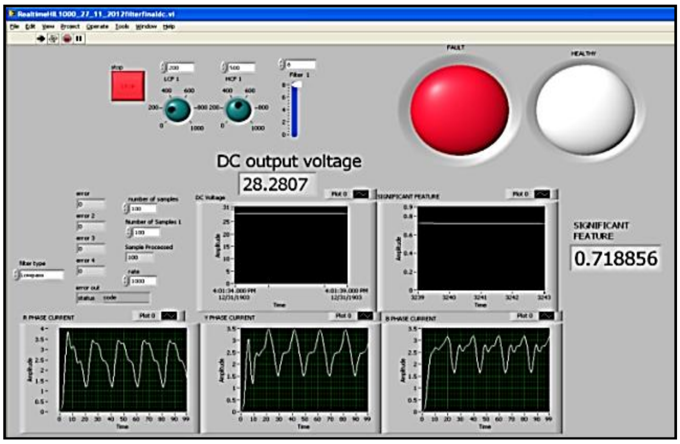

Figure 12. TRU front end GUI in LabVIEW showing faulty status

3.3 Fault Localization in TRU

Fault localization is carried out using frequency signatures of sensor data of individual phase current. It is found that when diode fault occurs, harmonics of double the fundamental frequency exists in the current. Figure 13 shows FFT of the frequency signatures of sensor data of individual phase current.

Wavelet analysis helps to find out the Fault Initiation time to estimate the Remaining Useful Life (RUL) time of the TRU. However, RUL time estimation analysis is not part of this paper. FFT and Wavelet analysis help as redundancy check for incipient fault detection in TRU. Figure 14 shows the sensor data of individual phase currents based on the number of samples with fault and without fault. Figure 15 shows the wavelet analysis of the sensor currents having two frequency components i.e., fundamental (50Hz) and secondary (100Hz) under fault condition. As the time progresses with incipient fault of diode, the TRU starts degrading with thermal runaway condition due to input current harmonics and asymmetry. This condition leads to total failure of the TRU.

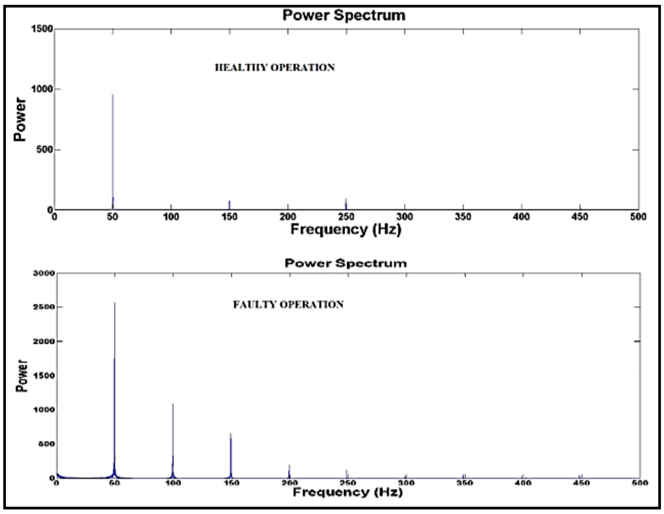

Figure 13. FFT of the frequency signatures of sensor data of individual phase current

Figure 16 shows the variation of HIP or significant feature with time. It increases with the incipient fault. The HIP value increases till the point of complete failure of TRU.

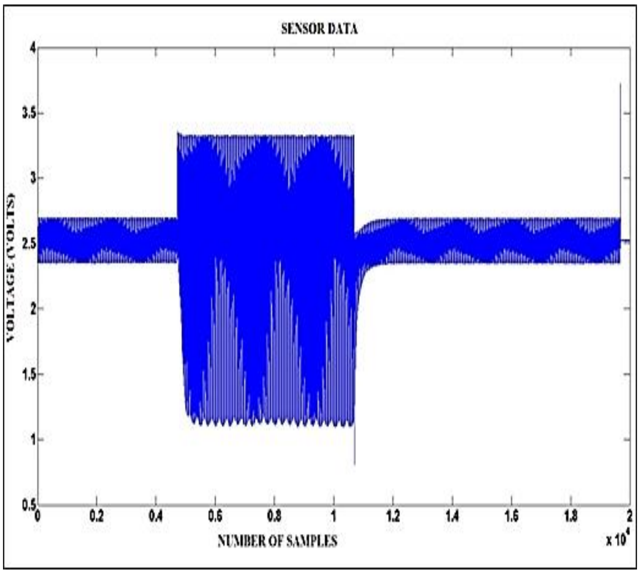

Figure 14. Sensor data of individual phase current

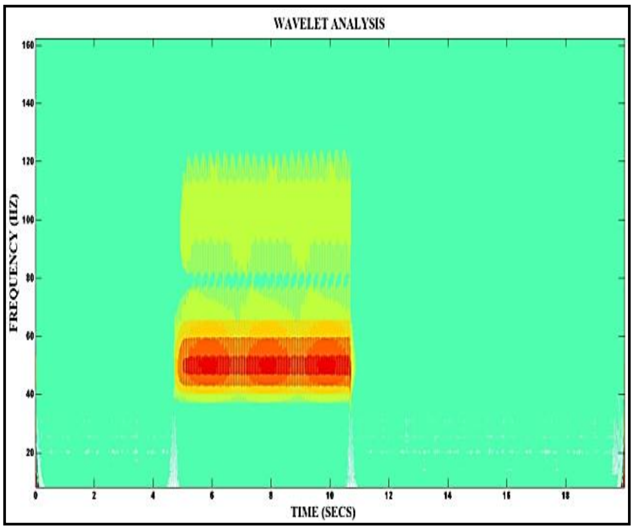

Figure 15. Wavelet Analysis of the sensor currents data

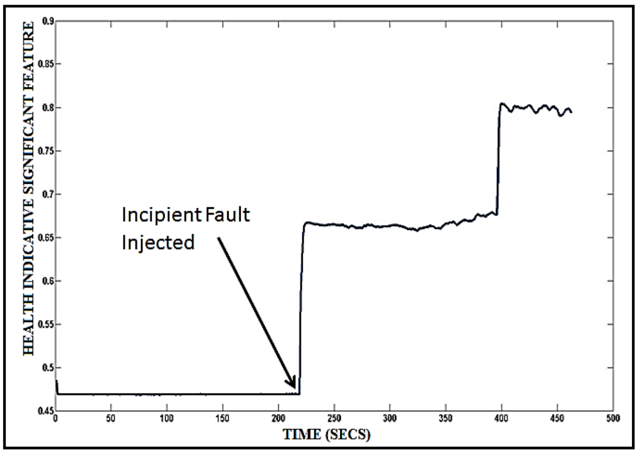

Figure 16. Graph showing the variation of significant feature with time

4. AVIONICS BUS INTERFACE

The detected fault in TRU, as a health monitored event, is registered in an electronic unit where the algorithm is processed. Typically in the aircraft this could be an ES monitoring unit or a Remote Data Concentrator (RDC) depending on the integration philosophy and functional partitioning in the units. The event will have to be logged into a central maintenance computer with the help of aircraft Avionics systems. In modern day aircraft the Avionics system uses digital network in Arinc 429 or 1553B standard to transact data with subsystem electronic units or RDC. Here 1553B standard has been chosen for proving the concept for data transaction due to likely availability of an aircraft test platform. RDC functionality is implemented as it can be an independent entity. This RDC functionality is developed in the NI PXI platform for proof of concept. In such a scenario the following data is to be communicated to the Avionics system:

- Status of Healthy condition
- Status of incipient fault condition
- Status of failure condition

Figure 17 shows the scheme of the interface of Aircraft Electrical system to the Avionics MIL-STD-1553B bus. The vital parameters from the Aircraft ES are measured using sensors. The TRU is one of the subsystems in Aircraft electrical system. The sensor data of the TRU is acquired in to the RDC platform wherein Diagnostic & Prognostic algorithms with complex mathematical computations can be applied in real time to obtain the Health Index Parameter (HIP). For proof of Concept, NI data acquisition system (DAQ) system is configured as RDC.

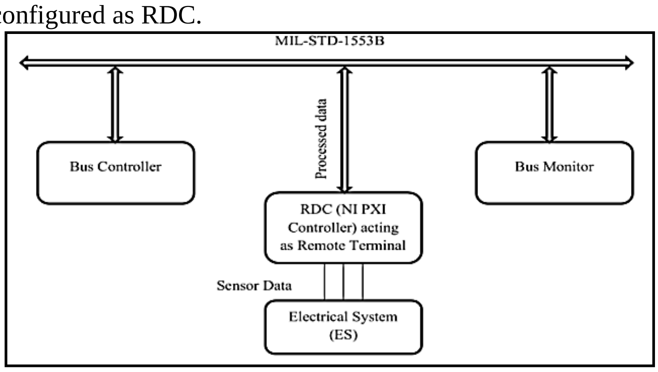

Figure 17.Electrical System (ES) interface to Avionics Bus via RDC (MIL STD 1553B bus)

Figure 18 shows the flowchart for configuring the MIL STD 1553B avionics bus for data communication. The bus card is configured and scheduled for different transfers by using the AIT Flight Simulyzer tool. Bus controller (BC), Remote Terminal(RT)s, remote sub addresses, Bus monitors(BM) are enabled to schedule the transfer of data by flight simulyzer tool. The .xml file is generated based on the data transfers configured from the Flight Simulyzer tool. The HIP or significant feature extracted is stored in one of the RT buffers. For proof of concept RDC is acting as remote terminal in MIL STD 1553B bus network.

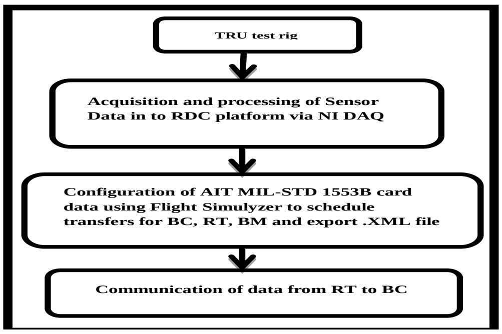

Figure 18. Flowchart of TRU test rig interface to Avionics bus via RDC

RDC application for real time processing of sensor data is created by using LabVIEW environment. The PXI controller configured as a Remote Terminal (RT) of the AIT MIL-STD-1553B card is shown in Figure 19. In this work, sensor data from (TRU) of the ES is acquired into the PXI DAQ platform to proof of concept. The GUI is done in the following steps:

- Sensor data acquisition to PXI Platform
- Data processing (Data fusion algorithm)
- State detection and Health assessment interface to Avionics Bus

Figure 19. NI PXI system with AIT MIL-STD-1553B card

Figure 20 shows the front panel view of the LabVIEW environment showing the Data Acquisition (DA) module, Data Processing (DM) and Data Interfacing (state detection and health assessment) on Avionics Bus following Open Systems Architecture for Condition-Based Maintenance (OSA-CBM) architecture[2].

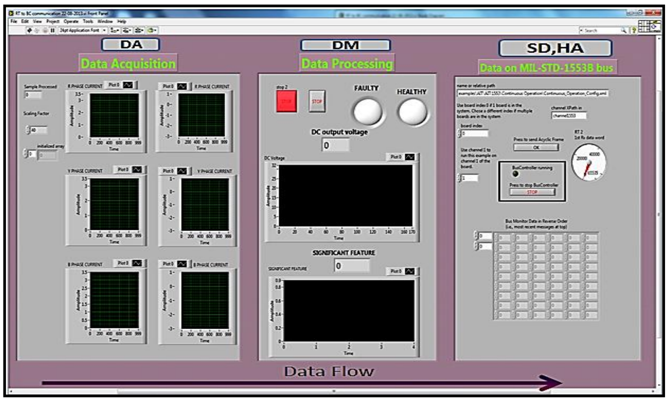

Figure 20. Front panel view showing the Data Acquisition Unit, Data Processing and Data Interfacing on Avionics Bus

Figure 21 shows the front panel view of the TRU system in healthy condition. The HIP or Significant feature value under healthy condition has decimal value of 10. It is communicated to avionics bus MIL STD 1553B in digital Hex format of 0XA.

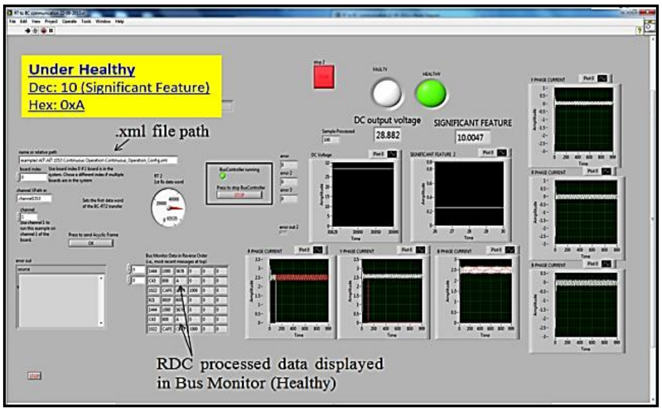

Figure 21. Front panel view of the system in healthy state

Figure 22 shows the front panel view of the TRU system in faulty condition. The HIP or Significant feature value under healthy condition has decimal value of 23. It is communicated to avionics bus MIL STD 1553B in digital Hex format of 0X17.

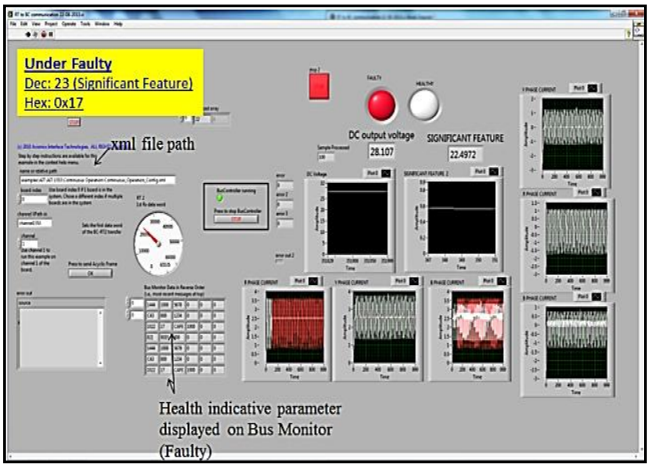

Figure 22. Front panel view of the system in faulty state

5. CONCLUSION

The input supply current signature of TRU is a valuable indication in the detection of the incipient fault. The fault in diode, which is more probable to fail in the life cycle of the product, is clearly detectable in the current signature. This developed concept is validated in the TRU test rig and health information is communicated to the avionics bus (MIL STD 1553B). The proposed scheme of monitoring has minimum cost impact. The sensors configured are non-intrusive and hence easy to integrate the methodology. Though the TRU test rig used is a commonly available 50 Hz AC supply for proof of concept, the results can be read across on a 400 Hz aircraft AC supply.

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