Multiprocessor Architecture for Monitoring and Control of Power Transformer

A Dissertation

Submitted in partial fulfillment of the requirement for the award of Degree of

Master of Engineering

In

Electronics Instrumentation and Control

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Declaration

I hereby declare that the work which is being presented in this dissertation entitles as, '**Multiprocessor Architecture for Monitoring and Control of Power Transformer**' in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics Instrumentation and Control Engineering at Thapar University, Patiala is an authentic record of my own work carried out under the supervision and guidance of Dr. Suraj Kumar Pardeshi and Mr. M.D. Singh and refer to the other researcher's work which are duly listed in the reference section.

The matter emboided in this thesis has not been submitted to any other University/Institute for the award of any Degree or Discipline.

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(Rohit Kumar Arora)

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Abstract

The failure of a power transformer is an area of significant concern since it can result in large capital loss as well as possible interruption of power. Therefore, it is desirable to detect the existence of abnormal or anomalous changes in the transformer's internal condition which could indicate an incipient failure. This thesis proposes and tests an anomaly detection scheme that is based on both spatial and temporal information and ultimately integrates intelligence into the detection process. It was developed from experience gained from the field-deployed system. Results indicate that nuisance or false alarms are virtually eliminated while the sensitivity to anomalous changes is preserved.

The interest in transformer monitoring has accelerated over the last few years due to structural changes in the electricity industry. This thesis examines the existing and potential incentives for the acquisition, utilization, and commercial development of transformer monitoring systems. Potential benefits are calculated based on capital cost avoidance, environmental cost avoidance, and operational benefits. The cost of a monitoring system is estimated using three scenarios. From a commercial standpoint , both transformer monitoring system as a product and a fee-based transformer monitoring service appear to be viable business opportunities.

Chapter 1

1 INTRODUCTION

The electricity supply industry is usually divided into three functional sections, including generation, transmission and distribution. Power transformers, on-load tap changers, circuit breakers, current transformers, station batteries and switch gears are the main devices of a transmission and distribution infrastructure that act together to transfer power from power stations to homes and business customers. These devices are critical assets, and if they were to fail that could cause power outages, personal and environmental hazards and expensive rerouting or purchase of power from other power suppliers. Therefore, these critical assets should be monitored closely and continuously in order to assess their operating conditions and ensure their maximum uptime. Consequently, power transformers enable us to transmit electrical energy over great distance and to distribute it safely to factories and homes. A transformer can fail due to any combination of electrical, mechanical or thermal stresses. Such failures are sometimes catastrophic and almost always include irreversible internal damage. Part of failures may lead to high cost for replacement or repair and an unplanned outage of a power transformer is highly uneconomical. As a result, as major equipment in power systems, its correct functioning is vital to enable efficient and reliable operations of power systems.

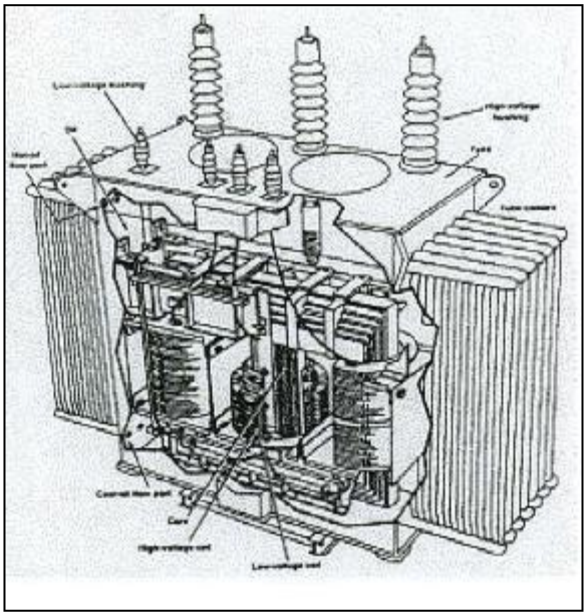

Figure 1: Power Transformer

There are various causes of transformer failures during operations, such as electrical disturbances, deterioration of insulation, lightning, inadequate maintenance, loose connections, moisture and overloading. Many of these failure effects, however, will increase in probability due to the passage of time with age. It is inevitable that some faults will occur, so it is very necessary to monitor closely online and off-line behaviors of transformers.

A transformer is essentially a static electromagnetic device consisting of two or more windings which link with a common magnetic field. The main purpose of power or distribution transformer is to transfer electric power from one voltage level to another. It works on the principal of electromagnetic induction. The main components of the transformer are core, winding, insulation (solid or liquid) and tank.

Power transformers are among the most expensive and critical units in a power system. The normal life expectance of a power transformer is around 40 years, and in many power systems the percentage of transformers operated more than 30 years is increasing due to the investment boom after the 1970s. As a result, the failure rate of transformers is expected to rise sharply in the coming years. Transformer failures are sometimes catastrophic and almost always include irreversible internal damage. Therefore, all key power transformers equipped in a power system should be monitored closely and continuously in order to ensure their maximum uptime. Generally, there are four main aspects of transformer condition monitoring and assessment, including thermal dynamics, dissolved gas, partial discharge and winding deformation, which should be monitored closely in order to determine power transformer conditions.

In recent years, rapid changes and developments have been witnessed in the field of transformer condition monitoring and assessment. Many research institutions and utility companies have their own condition monitoring and assessment guidelines for large power transformers. Most of such efforts are dedicated to developing accurate transformer models and reliable transformer fault diagnosis systems. These approaches are usually based upon empirical models, which are sometimes inaccurate and incomplete concerning abnormal operation scenarios. The major drawbacks are rooted in the inaccuracy of empirical thermal models, the lack of knowledge and evidence in dissolved gas analysis and intricate issues in winding deformation diagnosis. Nowadays, owing to the advance in computational hardware facilities and software data analysis techniques, the in-depth understanding of various phenomena affecting transformer operations has become feasible. With the use of advanced computational intelligence techniques, system operators are able to interpret correctly various fault phenomena and successfully detect incipient faults.

1.1 On-line Sensors and Recent Developments

Transformer monitoring equipment today is on-line and permanently attached to the transformer. The equipment generally consists of sensors that supply a warning signal based on a yes/no type of determination and without any real on-line analysis or diagnosis. This allows maintenance to be condition-based rather than time or periodic-based. The most common types of on-line sensors are described below.

1.1.1 Gas Sensors

Analysis of gases dissolved in oil is the most established diagnostic method for transformers For a number of years, on-line sensors for detecting hydrogen, mainly indicative of partial discharge, have been available commercially. These types of sensors are described below.

1.1.2 Hydrant 201R

One particular sensor that gives a continuous indication of the level of hydrogen dissolved in the oil is the Hydran® 201R sensor from Syprotec, Inc. in Pointe-Claire, Quebec, Canada. The Hydran® 201R is a transformer fault prevention device that provides a direct and continuous combustible gas-in-oil digital reading. It is sensitive to hydrogen, carbon monoxide, acetylene, and ethylene. The reading, R, reflects 100% of the hydrogen concentration, 15% of the carbon monoxide, 1% of the ethylene, and 8% of the acetylene. This can be represented as $R = k (H_2 + 0.15CO + 0.01C_2H_4 + 0.08C_2H_2)$ where k is a scaling factor. It contains two adjustable gas alarm set points and operates over a wide temperature range for all-weather outdoor operation. The alarms are regarded as warning signals and it is recommended by Syprotec, Inc. that a conventional gas-in-oil analysis be performed after an alarm. However, the risk of missing an incipient fault due to long sampling intervals is considerably reduced.

1.1.3 AMS 500

Another device is the AMS 500 by Morgan Schaffer Systems in Montreal, Quebec, which monitors only hydrogen. In this device, dissolved gas is extracted from a continuously circulating oil sample through permeable teflon tubes and hydrogen is detected by a thermal conductivity probe that changes resistance in the presence of hydrogen. It is reportedly capable of responding to a step change in 20 minutes and warning signals can be transmitted by an existing SCADA system.[1],[2]

1.1.4 Hydran® 201i

In 1995, Syprotec introduced the Hydran® 201i monitoring system that is an intelligent dissolved gas monitor that contains the same essential characteristics as the Hydran® 201R with additional features. These features include adjustable hourly and daily gas trend computation with alarming, history logging of data and events with date and time stamping, serial communications with a host computer, networking capabilities and modem control, etc. This system now allows an operator to perform historical data analysis and an on-line survey of the alarm status.[3]

1.1.5 Multi-Gas Sensors

Recent efforts have aimed at the development of on-line sensors that measure individual concentrations of several gases. These sensors are early warning systems, but they will give a better indication of the type of fault, and will give warning for heating of the cellulose that the present sensors do not. Examples are developments made by ABB (metal oxide technology) and by Micro monitors (metal insulator semiconductor technology)[4].

1.1.6 Partial Discharge Detectors

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Other recent work has been directed toward partial discharge (PD) monitoring. A PD is a transient electric discharge which only partially bridges the insulation gap between two conductors. This is opposed to a breakdown which completely bridges the gap. Detection of PDs is important since they indicate a loss of dielectric strength of the insulation or an increase in electric stress, such as might occur if two conductors move closer together by through-fault forces. Many arrangements of acoustic and electromagnetic sensors have been under development but have various problems associated with them[5].

1.1.7 Temperature Sensors

The load capability of the transformer is limited by the "hot spot" of the winding. Conventional temperature measurements are not direct since temperature sensors are attached to the outside of the transformer tank. The "hot spot" temperature is calculated indirectly from measurements of oil temperatures and of load current. Direct temperature measurements may be obtained from expensive fiber optic temperature sensors installed in the winding when the transformer is manufactured. These sensors consist of fibers which measure the temperature in one point or consist of distributed fibers which measure the temperature along the length of the fiber[6].

1.1.8 Other Types of Sensors

Other types of on-line sensors have been developed and investigated. These include moisture content of the oil[7], static charge in oil[8], pump monitoring[9], etc. Oftentimes, status indicators such as oil level or vibration are monitored. Efforts must be made to make these types of sensors more reliable, less expensive, and directly linked to important and frequent failure modes. New sensor developments must be accompanied by better and more advanced models and both the sensors and models must be extensively tested before they will add value as on-line monitoring tools.

1.2 System Architecture

Transformer parameters are collected from various sensors and devices (e.g. Temperature Sensor) through the RTU. The RTU transfers data to the central server via the Local server in case of wired connection or directly through the wireless network. The data can be viewed using an interactive HMI or analyzed using customizable tools. Automatic evaluation of these data allows the early detection of oncoming failures and performing condition based maintenance.

1.3 Why we need monitoring?

Excessive heat and mechanical stress are major reasons for transformer damage. These factors can cause hot spots, breakdown of winding insulation, short circuits, and catastrophic failures. The good news, however, is that transformer failures are attributable to manageable problems and new technology in transformer protective relays enable Engineers to implement a diagnostic approach to assess the health of power transformers.

1.4 Power transformer Failures and problems

Transformer failure can occur as a result of different causes and conditions. Generally, transformer failures can be defined as follows:

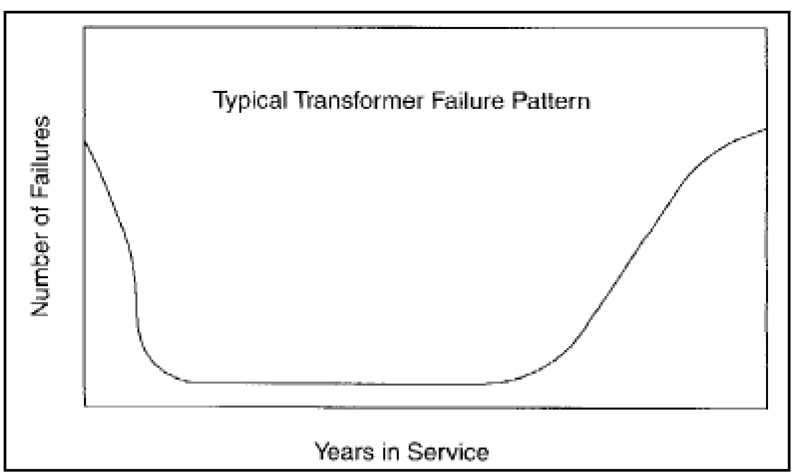
Table 1: Typical Causes Of Transformer Failure

Typical causes of transformer failure	
Internal	**External**
Insulation deterioration	Lightning strikes

Loss of winding clamping	System switching operations
Overheating	System overload
Oxygen	System faults(short circuit)
Moisture	
Solid contamination in the insulating oil	
Partial discharge	
Design and manufacture defects	
Winding resonance	

Transformer failures can be broadly categorized as electrical, mechanical, or thermal. The cause of a failure can be internal or external. Table 1 lists typical causes of failures. In addition to failures in the main tank, failures can also occur in the bushings, in the tap changers, or in the transformer accessories.

The failure pattern of transformer follows a “bath-tub” curve, as shown in Fig. 2. the first part of the curve is due to infant mortality; the second part of the curve is the constant failure rate; and the last part of the curve is failure due to old age.In addition to normal aging a transformer may develop a fault that results in faster than normal aging, resulting in a higher probability of failure.



[10]

Figure 2: Bath-Tub Failure Curve

1.5 Objective

To Develop a Transformer Monitoring Operation and Control System (TMOC) for “Online Condition Monitoring, Cooling control and Tap changer monitoring of transformers”. To provide all the required protocols in single unit only.

Since transformers are vital elements of the electric power transmission and distribution infrastructure, they need to be monitored to prevent any potential faults. Failures in a transformer can easily costs several million dollars to either repair or replace, and will also cause a loss of service to customers and revenue until the symptom is found and repaired.

Currently, there are several monitoring systems available, including Dissolved Gas Analysis (DGA) and Particle Discharge. However these monitors are very expensive. The objective of this research is to develop an online, inexpensive monitoring system for the health assessment of high voltage transformers, using the multiprocessor architecture. A new monitoring system, based on multiprocessor architecture, has the potential to be an online diagnostic tool that can provide early detection of potential abnormalities. This new monitor has the potential for detection of multiple failure modes simultaneously. Finally, given its operational principles and the required hardware and software, this monitoring system will provide an inexpensive approach to transformer diagnostics.

1.6 Features

- Remotely monitor, control, automate and track your products during operation or in the Logistics chain.
- Alerting & notifications via local indication in case asset parameters are beyond acceptable limits.
- Customizable reporting and analysis tools.
- Graphically rich HMI for plotting of monitored parameters for better visual display and layout of asset condition.
- Data security provided at each layer of product architecture
- Support for your existing hardware like ODGA, Shock Recorder etc.
- Supports both wired and wireless networks like LAN etc.
- Supports standard protocols like RS485, Serial, Ethernet, IEC 60850 etc.

- Continuous automatic monitoring to ensure that the solution is constantly reliable and secure.
- Allows remote trouble shooting in case of faults.

1.7 Benefits

- Helps you in gathering data from various sensors and devices for your predictive maintenance, this helps protect against equipment failures and avoidable downtime.
- Risk estimation of asset condition enables failure prediction and provides time to rectify problems before they escalate and result in significant downtime and loss in revenue.
- The powerful alarm rules engine generates real-time event alerts which provide your organization the agility to respond.
- Provides data and control to remotely troubleshoot problems, reducing field visits.
- Provide access to asset information to anyone anywhere as per their technical or commercial requirement.
- Demonstrate superior technological leadership of your products to competitors.
- Allows monitoring of multiple assets with one application, no need of various applications to support different hardware's.
- Real time location monitoring provides information on location of assets.

2 Literature Review

In the last four decades, three monitoring strategies have been developed for transformer fault detection and diagnosis:

A variety of relays have been developed to respond to a severe power failure requiring immediate removal of a faulty transformer from service, in which case, outages are inevitable. This is the so called reliability-centered monitoring, which cannot detect incipient faults.

Various off-line tests can be applied to detect possible incipient faults, and these tests are usually undertaken with respect to a regular time interval. However, such a time-based monitoring strategy is labour intensive and not cost effective, which is also ineffective in identifying problems that develop between scheduled inspections.

There is a trend in the power industry to move from time-based monitoring to condition-based monitoring, which employs advanced fault diagnosis techniques for detecting on-line and off-line incipient faults. A condition-based monitoring program can supply information about unit conditions in real-time, process these information and then determine when maintenance should be performed.

All the three strategies have been investigated for many years. The condition based monitoring strategy is related to a wide range of on-line condition monitoring applications, which include the detection of partial discharges and insulation degradation, winding deformation diagnosis, monitoring of dissolved gas evolution, classification of hazards and assessing thermal conditions. On the other hand, off-line tests can only be employed to identify faults after a transformer outage or after a scheduled time interval. It can be seen that, condition-based monitoring of power transformers can open the possibility of obtaining the maximum practicable operating efficiency and optimum life of power transformers, minimizing risks of premature failures and providing the potential to optimal system maintenance strategies.

In recent years, rapid changes and developments have been witnessed in the field of transformer condition monitoring and assessment. The performance and reliability of transformers can be improved greatly by employing advanced online and off-line fault diagnosis systems. Many research institutions and utility companies have developed their own condition monitoring and assessment systems for key power transformers.

2.1 Previous Products Developed

2.1.1 DRMCC-Dynamic Ratings Monitoring Control and Communications System

The Wilson Transformer DRMCC[**11**] (Dynamic Rating, Monitoring, Control and Communications) system is an integrated microprocessor-based monitoring and control system for power transformers by **DYNAMIC RATINGS**.

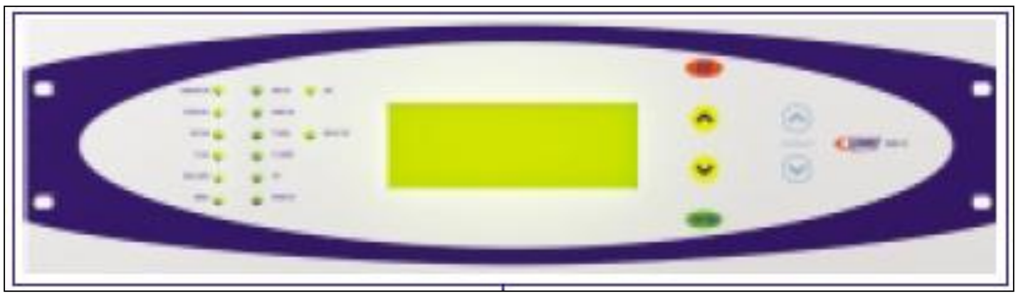


Figure 3: Dynamic Ratings Monitoring Control and Communications System

The DRMCC offers the following features and benefits:-

- **Dynamic Rating** – The Dynamic Rating feature provides load dispatch operators with the real time loading (and overloading) capability of the transformer based on the current operating conditions. Predictive “Smart Cooling” functions are of great benefit in reducing the aging of the transformer while providing increased dynamic loading capacity. Information can be presented in two ways; how long can a transformer carry the present load or what is the maximum load that can be carried for a specified time without exceeding the pre-set loss-of life limits.
- **Cooling System Monitoring & Control** – Basic thermal monitoring is via top oil and ambient probes using rugged solid-state RTDs. Control is provided for one or two pumps and up to two banks of fans. Cycling and forced running can be programmed to maximize reliability. Status of selector switches, contactors, etc. and motor current can be monitored to detect problems.

- **On-Load Tap changer Monitoring & Control** – OLTCs are one of the most common sources of transformer failure. Monitoring parameters such as drive motor current, number of operations and contact wear levels at each tap can assist in determining appropriate maintenance strategies. Automatic Voltage Control (AVC) and Line Drop Compensation (LDC) the DRMCC provides a range of paralleling capability including independent, master/follower, circulating current, VAR control and reverse reactance.
- **HV Bushing Health Monitor** – HV bushings are another major source of failure in high voltage transformers. With the addition of bushing sensors at each capacitor tap the optional module detects changes in Power Factor and/ Capacitance to provide alarm and tripping functions for bushings to give warning and protection well in advance of potential failure. Online Partial Discharge monitoring can also be integrated with the DRMCC.
- **Direct Winding Temperature Measurement** – Dynamic Ratings can supply an optional module for processing the signals from Lumasense Fiber-Optic sensors embedded in the transformer windings. This provides a more accurate measurement of hot-spot temperature for comparison with the calculated values. Other makes of F/O WTI can also be integrated with the DRMCC.
- **Data Concentration** – Data can be marshaled from a range of inputs including third-party systems for on-line DGA such as Serveron, Calisto or Hydran; Vaisala moisture-in-oil, etc. The data is presented as salient information including various stages of alarm. Data is time and date stamped and stored for 52 weeks as well as being relayed to the SCADA system via a single connection.
- **Multi-mode Communications** – Interface with other transformer and substation monitoring devices, local consoles and SCADA systems can be made via RS232 or fiber-optic cables for point-to-point connections and/or RS485 for multi-drop communications links. A range of protocols is supported. An Ethernet port is available for connection to LAN/WAN from which remote monitoring and control may be obtained using an Internet browser.
- **Fail-safe System** – In the event of a sensor failure required for the thermal model, the DRMCC deems the model to be unreliable and all the available cooling is turned on

and an alarm is generated. If the entire DRMCC fails as detected by the system watchdog, the cooling is turned on and a hardwired alarm is activated.

- **Control Cubicle** – The DRMCC Control Unit (CU) and associated cooler controls are usually located in a weatherproof control cubicle attached to the transformer. The Interface Unit (IU) with display and user input buttons can either be located in this cubicle or remotely at the substation control room.
- **Engineering Support** – The DRMCC is offered as an engineered system and we have allowed for the work required to support the end user in defining the communication points for the SCADA interface. We have also allowed for the checking, confirmation and further tuning of the thermal models of the transformer after sufficient operating data has been gathered, should this be necessary
- **Training** - We can offer an optional training program for end users, project and operational staff to ensure a smooth entry and use of the DRMCC system. or

2.1.2 GE Intellix* MO150

The Intellix MO150[12] transformer monitoring system, from GE Energy, is an intelligent, cost-effective solution which provides comprehensive monitoring and interactive transformer condition diagnostics, to provide early warning of incipient failure conditions.

Figure 4: GE Intellix* MO150

2.1.2.1 System Features

MVA model which computes the apparent power on primary, secondary or tertiary winding

Winding hot-spot temperature model which computes the hot-spot temperature of each winding where load current is measured

Moisture model which computes the moisture content in the thin conductor insulation and in the barrier insulation

Insulation aging model which computes the aging acceleration factor from IEEE or IEC guidelines

Cooling control model for management and operation of the transformer cooling system

Cooling efficiency model which monitors the actual efficiency of the cooling system

Tap changer thermal model which computes the temperature difference between the LTC tank and main transformer oil tank

Tap changer position tracking model as the tap position transitions are recorded and tracked

2.1.3 ABB TEC (Transformer Electronic Control) System

TEC[13] integrates ABB’s transformer knowledge. A model of the transformer and its working conditions is generated, and then by comparing the measured values with the parameters calculated by the model, the system is able to early detect malfunctions and discrepancies. The model can also simulate load conditions and predict the hot-spot temperature.

Figure 5: ABB TEC (Transformer Electronic Control) System

TEC is modular and expandable for additional requirements that may be needed in the future, its functionality may include any of the following parameters:

- Top oil and bottom oil temperature
- Hot-spot temperature on HV, LV and TV
- Load
- Current on HV, LV and TV
- Transformer aging
- Hot-spot forecast
- Overload capability
- Transformer temperature balance
- Gas and moisture in transformer oil
- Bubbling temperature in transformer
- OLTC position

2.1.4 Areva- MS 3000

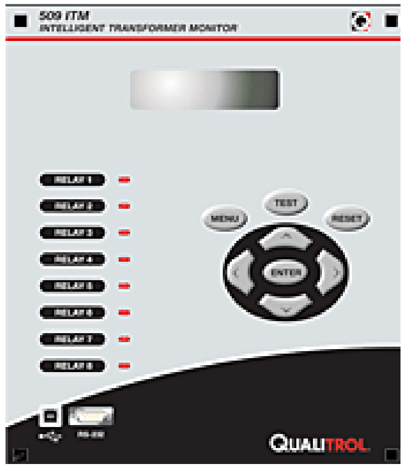
The MS3000[14] is Alstom Grid's next generation of online condition monitoring systems. As the successor of the globally recognized MS2000 system, it combines practical experience with innovative features and high technological standards.

Figure 6: Areva- MS 3000

- Additional features and measurements
- Fibre optic hot-spot measurements
- Partial discharge
- Bushing power factor (tan delta)
- Transformer power factor (cos phi)
- Transformer efficiency
- Bottom oil temperature
- Monitoring module temperature
- Moisture of OLTC oil
- Gas quantity and rate in Buchholz relay
- Oil pressure and oil pressure differences
- Acceleration (tank wall, OLTC)
- Oil level
- Humidity of air inside conservator
- Air pressure
- Cooling power
- Intake and outlet cooling equipment temperatures
- Differences of intake and outlet temperatures
- AVR
- Controlling of cooling equipment
- Digital status information, etc.
- Others on request

2.1.5 QualiTROL 509 ITM Intelligent Transformer Monitors

The QualiTROL Electronic Cooling Monitor (ETM)[15] for Liquid-Filled Transformers (Model #509-200 Series) is an Intelligent Electronic Device (IED). Combining microprocessor technology and advanced digital signal processing, to accurately assess the health, and performance of three phase or autotransformers.[16]



[17]

Figure 7: Qualitrol 509 ITM Intelligent Transformer Monitors

The 509 Transformer Monitor offers:

- Advanced thermal modeling of winding temperatures
- Superior temperature control for higher loads
- Integrated Load Tap Changer temperature monitoring
- Stand alone or networked substation monitoring
- Diagnostic tool for condition based maintenance
- Eight (8) form C adjustable relays to operate cooling equipment, signal alarms, and provide trip functions, depending on transformer conditions
- Up to four (4) 0-1 or 4-20 ma DC loops for use with SCADA systems
- Digital communication ports RS-232, RS-485

2.2 Competitors Comparison

Table 2 : Comparision With Other Products

Features	**SPECIFICATIONS**	**GE INTELLIX**	**ABB TEC**	**AREVA MS 3000**	**Qualitrol-509**	**DRM CC-SIC M2B**	**A-EBERLE-REG**	**G-TMOC**
Price of Competito	In USD	41666 USD	37500US	50000 USD	20833	27083 USD	10416 USD	50% of competitor

rs unit approx			D		USD			
Load Monitoring	HV current	√	√	√	√	√	X	√
	LV Current	√	√	√	√	√	X	√
	TV Current	√	√	√	√	√	X	√
	HV Voltage	X	X	X	√	√	X	√
	LV Voltage	X	X	X	√	√	X	√
	TV Voltage	X	X	X	√	√	X	√
	active power	X	X	X	√	√	X	√
	reactive power	X	X	X	√	√	X	√
	apparent power	√	X	X	√	√	X	√
	Load	√	√	√	√	√	X	√
Thermal	Top Oil temperature	√	√	√	√	√	√	√
	Top Oil Temperature Balance	√	√	√	√	√	√	√
	Bottom Oil temperature	X	√	√	√	√	√	√
	Bottom Oil Temperature Balance	X	√	√	√	√	√	√
	Ambient temperature	√	√	√	√	√	√	√
	HV Hot Spot temperature	√	√	√	√	√	√	√
	LV Hot Spot temperature	√	√	√	√	√	√	√
	TV Hot Spot	√	√	√	√	√	√	√

	temperature							
	Hot Spot Forecast	X	√	√	√	√	√	√
	Loss of life	√	√	√	√	√	√	√
	Over Load Capability	√	√	√	√	√	√	√
GAS/ Moisture	Gas in oil	√	√	√	√	√	√	√
	Trends	√	√	√	√	√	√	√
	Moisture in oil	√	√	√	√	√	√	√
OLTC	position	√	√	√	√	√	√	√
	Contact Wear	X	√	√	√	√	√	√
	time in position	√	√	√	√	√	√	√
	position count	√	√	√	√	√	√	√
	Temperature	√	√	√	√	√	√	√
	Temperature Balance	√	√	√	√	√	√	√
	Moisture OLTC	√	√	√	√	√	√	√
	Automatic Voltage regulator	X	X	√	X	√	√	√
Cooling	advanced cooling control	√	√	√	√	√	√	√
	monitoring of coolers	√	√	√	√	√	√	√
	Cooling Control	√	√	√	√	√	√	√
	power consumption of coolers	√	√	√	√	√	√	√
	warning and	√	√	√	√	√	√	√

	alarms							
	event recording	√	√	√	√	√	√	√
	service logs	√	√	√	√	√	√	√
	PC based software interface	√	√	√	√	√	√	√
Special features	Tan-delta measurement	X	X	√	X	√	X	X
	PD Monitoring	X	X	√	X	√	X	X
Hardware								
Power Supply		100-230vAC,5060 hZ	85-265 Vac, 85-265vdc	48-125Vdc 150-250vdc/ac supply	90-264Vac;47-63Hz ,40-290V DC	48-264 Vdc 60-264V dc	85V-264V AC OR DC	85V-264VAC OR DC
Digital Inputs		2	12	16	8	48	16	16
DO-Outputs		5	3	13	8	32	13	16
4-20mA sensor inputs		3	8	14	4	8	14	8
4-20mA analog outputs			4	2	8	8	2	8
RTD Inputs		8	4	1	8	8	1	8
AI-Inputs		3	3	6	8	7	6	6

Communication	RS485	√	√	√	√	√	√	√
	RS232	√	√	√	√	√	√	√
	Ethernet	√	√	√	√	√	√	√
	fiber optic ST				√	√	√	√
	USB				√	√	√	√
Protocols	DNP 3.0	√	√	√	√	√	√	√
	Modbus RTU	√	√	√	√	√	√	√
	IEC 61850	√	√	√	√	√	√	√
	IEC 60870	X	X	√	√	√	√	√
Remote HMI		X	X	√	X	√	X	√
HMI LCD		128 x 64 graphical lcd	2X 16 Alpha numeric	128 x 64 graphical lcd	2x16 Alpha numeric	128 x 64 graphical lcd	240X 320 graphical LCD	128X 128 Graphical LCD

2.3 Future Trends

Transformer monitoring is now moving toward on-line systems in contrast to offline techniques and stand alone on-line sensors that were primarily used for years. The rapid development of new technologies and cheaper and reliable computers has facilitated this shift. The system aspect has become much more important as multiple sensors are being combined to provide better on-line monitoring and diagnostic information. The transformer is now being thought of as a system, rather than a series of individual components.

In general, on-line sensors and monitoring systems by themselves have limited value. Much research is needed to interpret and understand the output from the sensors and monitoring systems used in real time. On-line experience with theses sensors and systems is critical for developing new types of knowledge that consist of interpretation skills and diagnostics that emerged as G-TMOC personnel monitoring transformers on a 24 hour a day basis.

Other trends are geared towards diagnostics. Here the shift is from off-line, human-intensive diagnostic to on-line, machine-intensive analysis and diagnostics. While off-line diagnostics will remain important, it will be used to provide additional information when the on-line systems make this type of recommendation. Diagnostic methods must be developed that must be used without taking the transformer out of service.

3 Multiprocessor Architecture

3.1 Embedded System

An embedded system is a special-purpose system in which the computer is completely encapsulated by or dedicated to the device or system it controls. Unlike a general-purpose computer, such as a personal computer, an embedded system performs one or a few predefined tasks, usually with very specific requirements. Since the system is dedicated to specific tasks, design engineers can optimize it, reducing the size and cost of the product. Embedded systems are often mass produced, benefiting from economies of scale. An embedded system is usually classified as a system that has a set of predefined, specific functions to be performed and in which the resources are constrained.

3.2 Real-Time Operating Systems

Real-Time Operating Systems (RTOS) are commonly used in the development, productizing, and deployment of embedded systems. Unlike the world of general purpose computing, real-time systems are usually developed for a limited number of tasks and have different requirements of their operating systems.

A RTOS is responsible for offering the following facilities to the user programs that will run on top of it. The first responsibility is that of scheduling: a RTOS needs to offer the user a method to schedule his tasks. The second responsibility is that of timing maintenance: the RTOS needs to be responsible in both providing and maintaining an accurate timing method. The third responsibility is to offer user tasks the ability to perform system calls: the RTOS offers facilities to perform certain tasks that the user would normally have to program him, but the RTOS has them included in its library, and these system calls have been optimized for the hardware system that the RTOS is running on. The last thing that the RTOS needs to provide is a method of dealing with interrupts: the RTOS needs to offer a mechanism for handling interrupts efficiently, in a timely manner, and with an upper bound on the time it takes to service those interrupts.

3.3 Description in Project

There are two basic techniques that have been used to increase computer performance — 1) implement the machines in faster technology, or 2) perform more operations in parallel. These techniques are not mutually exclusive, but as semiconductor technology has matured it has become apparent that more parallelism must be exploited in order to keep increasing system performance. A wide variety of architectures have been proposed that attempt to exploit the parallelism available in application programs at different granularities. For example, pipelined processors and multiple instruction issuing processors, such as the superscalar and VLIW machines, exploit the fine-grained parallelism[18] available at the machine instruction level. In contrast, shared memory multiprocessors typically exploit coarse-grained parallelism by distributing entire loop iterations to different processors. Each of these parallel architectures have significant differences in synchronization overhead, instruction scheduling constraints, memory latencies, and implementation details, making it difficult to determine which architecture is best able to exploit the parallelism available in an application program. In addition, several high-performance microprocessors have recently been announced that are capable of simultaneously executing two to four independent operations. These microprocessors may provide excellent building blocks for constructing a large-scale multiprocessor that can exploit parallelism at several different granularities simultaneously. To maximize the performance of this type of ‘‘multigrained’’ architecture, however, the best mix of fine-grained and coarse-grained parallelism must determined. That is, the degree of fine-grained parallelism needed within each of the individual processors must be determined in conjunction with the total number of processors to be used in the system. In our project we have used the multiprocessor architecture. Each card contains its individual 16-bit dsPIC33F processor. Main card has 2 processors one is 16-bit dsPIC33F and other is 32-bit AM1808. Multiprocessing sometimes refers to the execution of multiple concurrent software processes in a system as opposed to a single process at any one instant. However, the terms multitasking or multiprogramming are more appropriate to describe this concept, which is implemented mostly in software, whereas multiprocessing is more appropriate to describe the use of multiple hardware CPUs. In a multiprocessing system, all CPUs may be equal, or some may be reserved for special purposes. A combination of hardware and operating-system software design considerations determine the symmetry (or lack thereof) in a given system. For example, hardware or software considerations may require that only one CPU respond to all hardware interrupts, whereas all other work in the system may be distributed equally among CPUs; or execution of kernel-mode code may be restricted to only one processor (either a specific processor, or only one processor at a time), whereas user-mode code may be executed in any combination of processors.

In our project every card has its own controller for processing its parameters. As every card has to do its predefined task so all the data generated by the cards is processed by its own 16-bit dsPIC33F microcontroller and then converted into the appropriate frames before putting it on the bus. Like wise all the processors will process and put their data on the bus. Now the main CPC will take the data from required card and do the appropriate task according to the algorithms. As all the data from different cards will be received as a frame to CPC therefore the main card controller will not be overloaded and don’t need to first process the individual card data before applying the algorithm. As all the cards individually and parallel process their data, speed of process will increase. We can see in the figure that main processor has to run the algorithm only not process the incoming data.

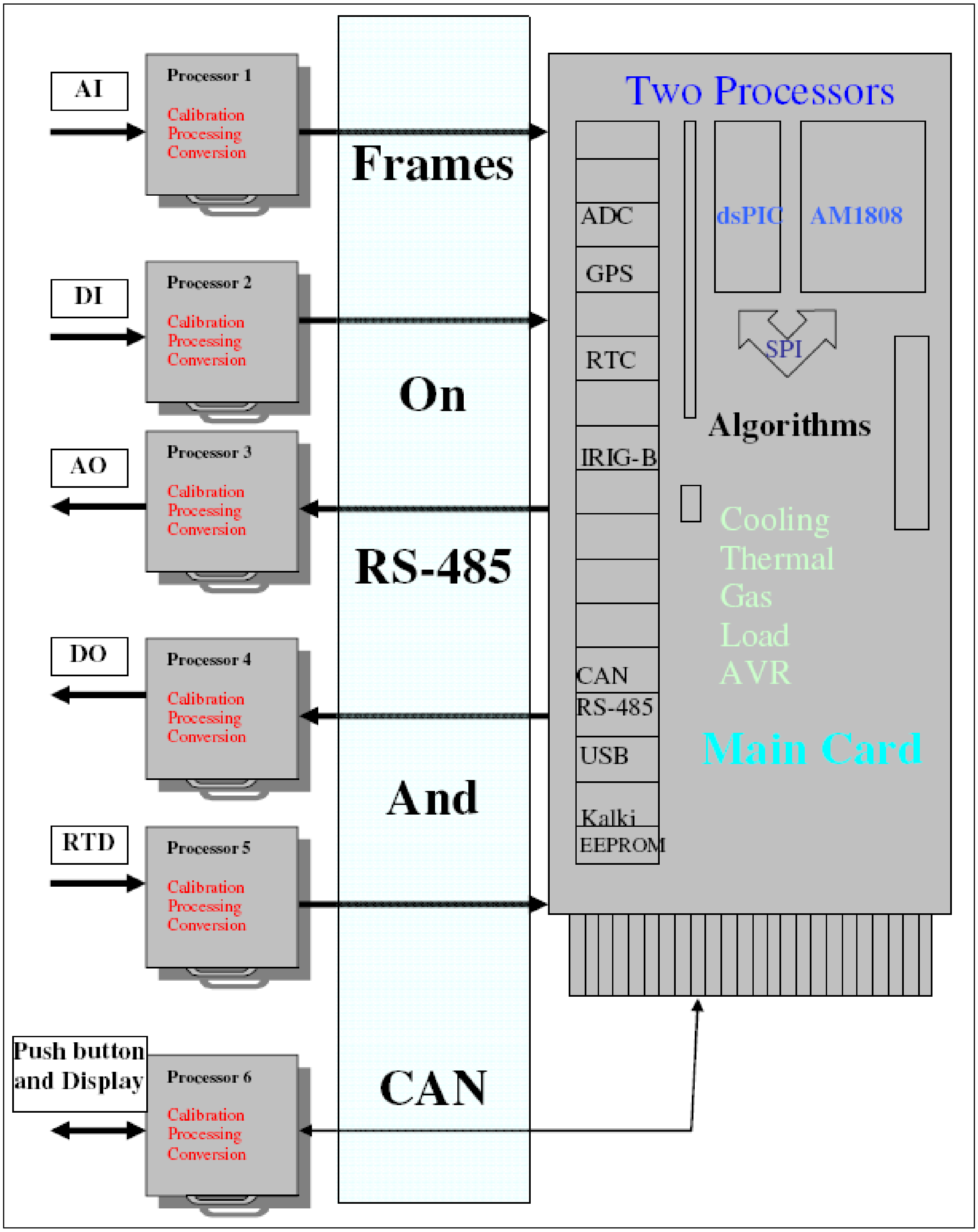


Figure 8: Multiprocessor Architecture

4 Hardware

The product is DIN- Rail type. Product contains eight cards; each card is enclosed in a separate box. All the boxes together create the product. All the cards are communicate with each other through three buses- RS485-1, RS485-2 and CAN. Backplane card is used to interface the one card from other which is detachable type and any card can be removed from the bus at any time just by removing that small backplane card. In this product we can add or remove cards at any time according to requirement.

Figure 9: Prototype of G-TMOC

As shown in the figure the cards are wired from the bottom side and all the cards are communicating from top side using a back plane card.

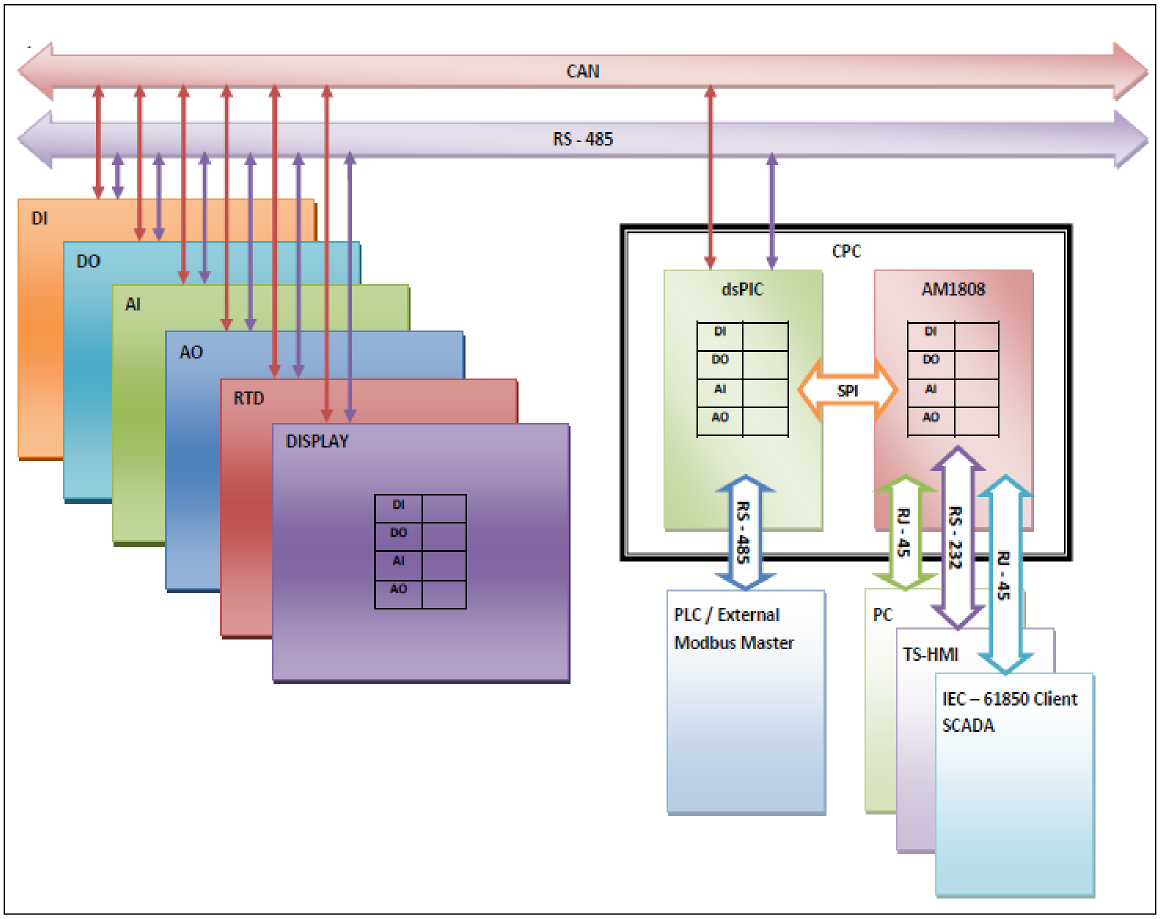


Figure 10: Architecture of G-TMOC

Every card has its own microcontroller for processing. So every card can process its signal alone and then send the frames to the main card. As the individual card processes its signal, so the main card will not be loaded. All the cards work on the 12V power supply which is provided by the power supply card.

4.1 Digital Input Card

For acquiring digital inputs we have digital input card. Digital inputs are measured as high or low. Each channel bank can be fixed with different voltages with a continues maximum overload of 400 DC (280V AC). Card observes high input above 52Vdc and below as low. Channel isolation to Earth 5KV DC. Capacitors and Tranzorbs will provide the EMC protection for the input circuit. Single card has 16 channels so it can attain input from 16 devices at one time. All the inputs are processed by the microcontroller embedded in the card. The controller used for the card is dsPIC33F which is 16-bit microcontroller. It is a

100pin controller. Also EEPROM from Atmel is used for storage purpose. EEPROM is interfaced with the microcontroller using I2C interface. This (i^2c) EEPROM will store the cards set-up (calibration) information along with any manufacturing and production data that may be felt to be useful for future testing, repair or traceability etc. Microcontroller put the frames on the bus after processing the data. The card is provided with 3 different buses- RS485-1, RS485-2 and CAN. If any of the bus is stop communicating then it will move t the other bus to avoid the loss of communication. The card has its own power supply section where it produces the 3.3V and 5V. Card is hot swappable and can be removed during power on condition. Each of the 16 input channels has a single bank common i.e. there is only one common signal returning to the system. The cards inputs are scaled down using a resistor network and are isolated using optocoupler. All the 16 channels inputs are isolated using optocoupler thus providing isolation between the input channel and the dsPIC33F micro-controller.

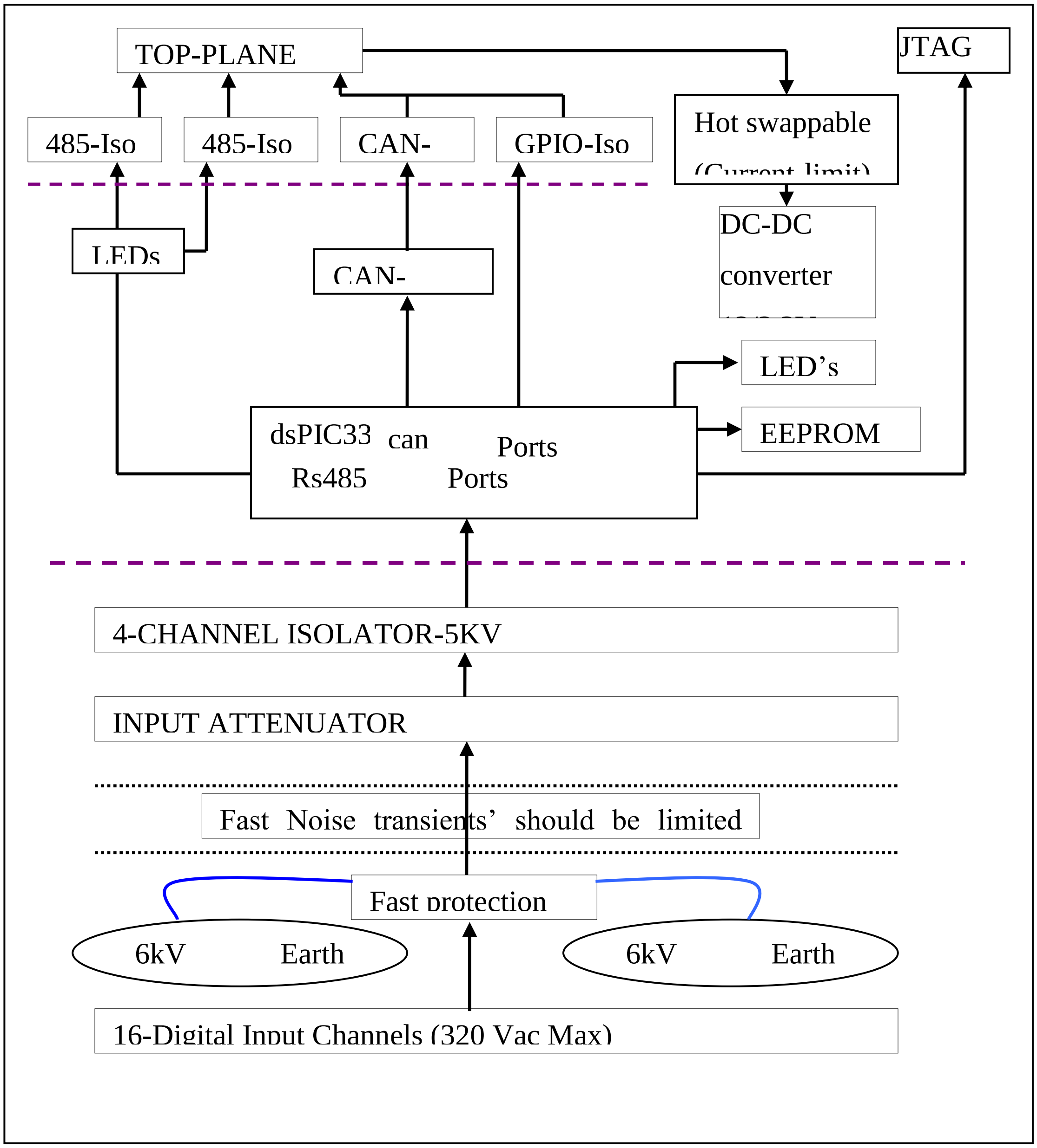


Figure 11: Block Diagram of Digital Input Card

4.2 Digital Output Card

Digital output card is used to produce the digital output. Digital output provides high and low signals. Digital output card is used to provide signal for switching control of transformer like turning On/Off the fans and tap position. The controller used for the card is dsPIC33F which is 16-bit microcontroller. It is a 100pin controller. Also EEPROM from Atmel is used for storage purpose. EEPROM is interfaced with the microcontroller using I2C interface. This (i^2c) EEPROM will store the cards set-up (calibration) information along with any manufacturing and production data that may be felt to be useful for future testing, repair or traceability etc. Microcontroller put the frames on the bus after processing the data. The card is provided with 3 different buses- RS485-1, RS485-2 and CAN. If any of the bus is stop communicating then it will move t the other bus to avoid the loss of communication. All the inputs are processed by the microcontroller embedded in the card. Digital output is derived by using relay. It is also hot-swappable therefore can be removed any time during power on condition. It has 8 output channels. Each of the 8 output channels has a separate return path. Each channel bank can be rated for a maximum voltage of 250Vac @ 6A and 250Vdc @0.25A. Channel isolation to Earth 6KVdc. Capacitors and Tranzorbs will provide the EMC protection for the output circuit. The DOC is powered by top-plane 12-volt card which will be regulated down to 3.3 volts and 5 volts on the card, and used for all the control logic, buffers and dsPIC33 micro-controller. 5 volts is required by the CAN isolator. RS485, CAN and GPIO interface used on the back plane will be having maximum 2kV Isolation.

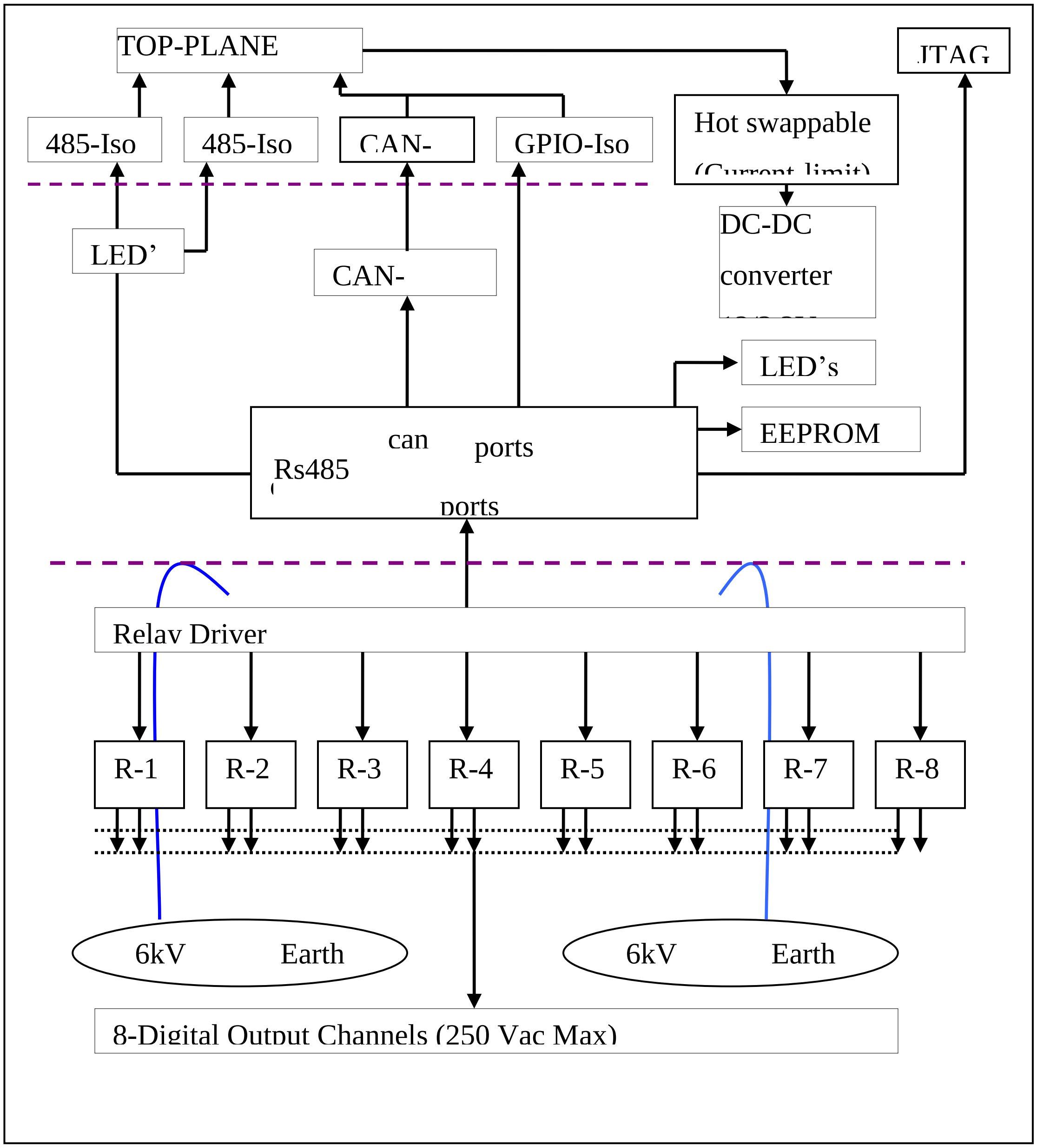


Figure 12: Block Diagram of Digital Output Card

4.3 Analog Input Card

Analog In put Card is designed to acquire the analog signal from sensors. It is designed to process 4mA to 20mA current signal. The controller used for the card is dsPIC33F which is 16-bit microcontroller. It is a 100pin controller. Also EEPROM from Atmel is used for storage purpose. EEPROM is interfaced with the microcontroller using I2C interface. This (i^2c) EEPROM will store the cards set-up (calibration) information along with any manufacturing and production data that may be felt to be useful for future testing, repair or traceability etc. Microcontroller put the frames on the bus after processing the data. The card is provided with 3 different buses- RS485-1, RS485-2 and CAN. If any of the bus is stop communicating then it will move t the other bus to avoid the loss of communication. All the inputs are processed by the microcontroller embedded in the card. AIC is hot swappable and can be removed during power on condition. Each of the 8 input channels has a separate ground. Channel isolation to Earth 6KV DC. Capacitors and Tranzorbs will provide the EMC protection for the input circuit. The card inputs are scaled down using a resistor divider and are isolated with respect to each other. The AIC is powered by top-plane 12-volt power will be regulated down to 3.3 volts and 5 volts on the card, and used for all the control logic, buffers and PIC32 micro-controller. 5 volts is required by the CAN isolator. RS485, CAN and GPIO interface used on the back plane will be having maximum 2kV Isolation.

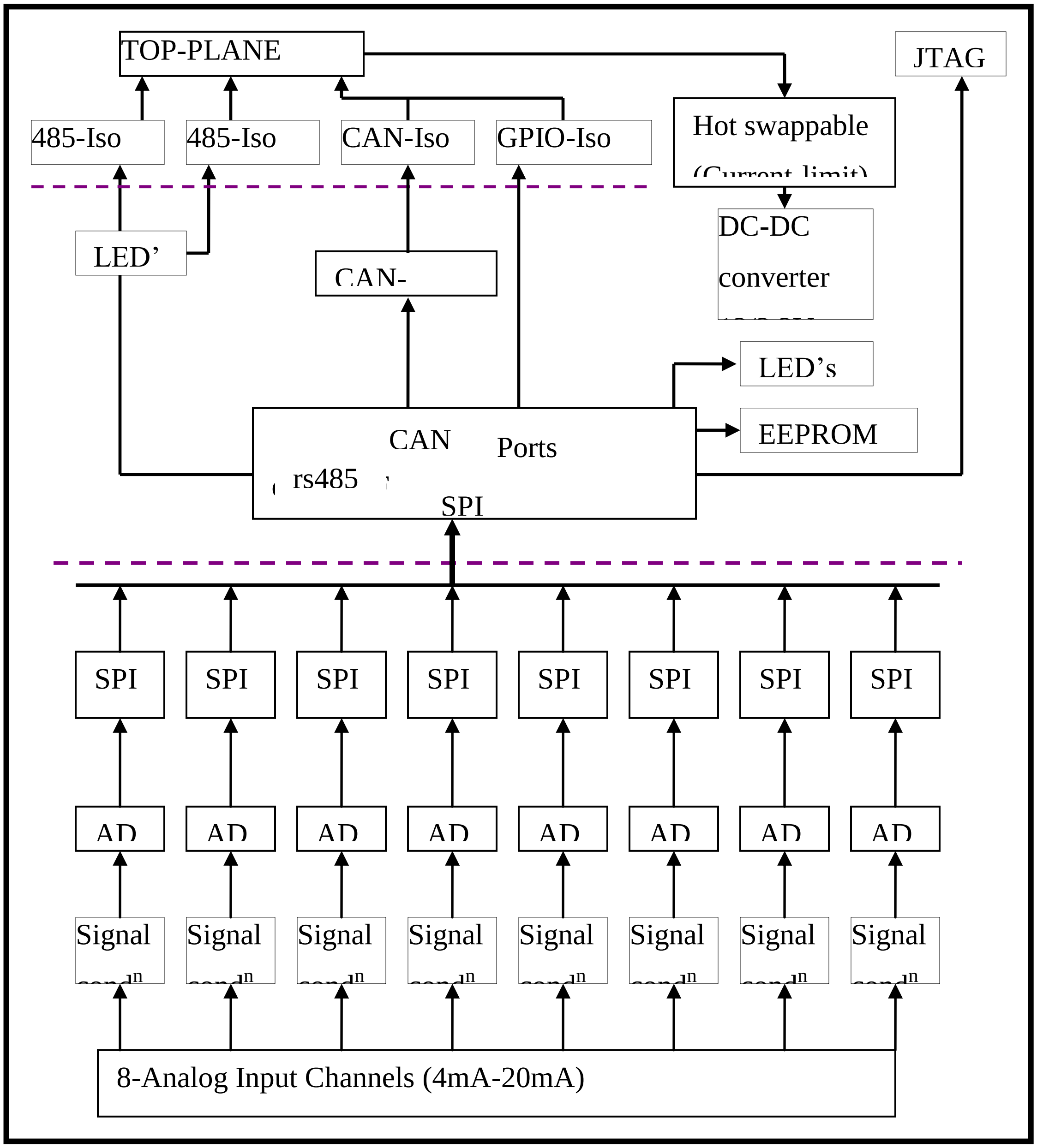


Figure 13: Block Diagram of Analog Output Card

4.4 Temperature Measurement Card

Temperature measurement Card is designed to acquire the analog signal from PT100. It is designed to process RTD output. TMC is hot swappable and can be removed during power on condition. Each of the 8 input channels has a 3 individual signals. The controller used for the card is dsPIC33F which is 16-bit microcontroller. It is a 100pin controller. Also EEPROM from Atmel is used for storage purpose. EEPROM is interfaced with the microcontroller using I2C interface. This (i^2c) EEPROM will store the cards set-up (calibration) information along with any manufacturing and production data that may be felt to be useful for future testing, repair or traceability etc. Microcontroller put the frames on the bus after processing the data. The card is provided with 3 different buses- RS485-1, RS485-2 and CAN. If any of the bus is stop communicating then it will move t the other bus to avoid the loss of communication. All the inputs are processed by the microcontroller embedded in the card. Channel isolation to Earth 6KV DC. Capacitors and Tranzorbs will provide the EMC protection for the input circuit. The card inputs are scaled down using a resistor divider and are isolated with respect to each other. The TMC is powered by top-plane 12-volt power will be regulated down to 3.3 volts and 5 volts on the card, and used for all the control logic, buffers and PIC32 micro-controller. 5 volts is required by the CAN isolator. RS485, CAN and GPIO interface used on the back plane will be having maximum 2kV Isolation.

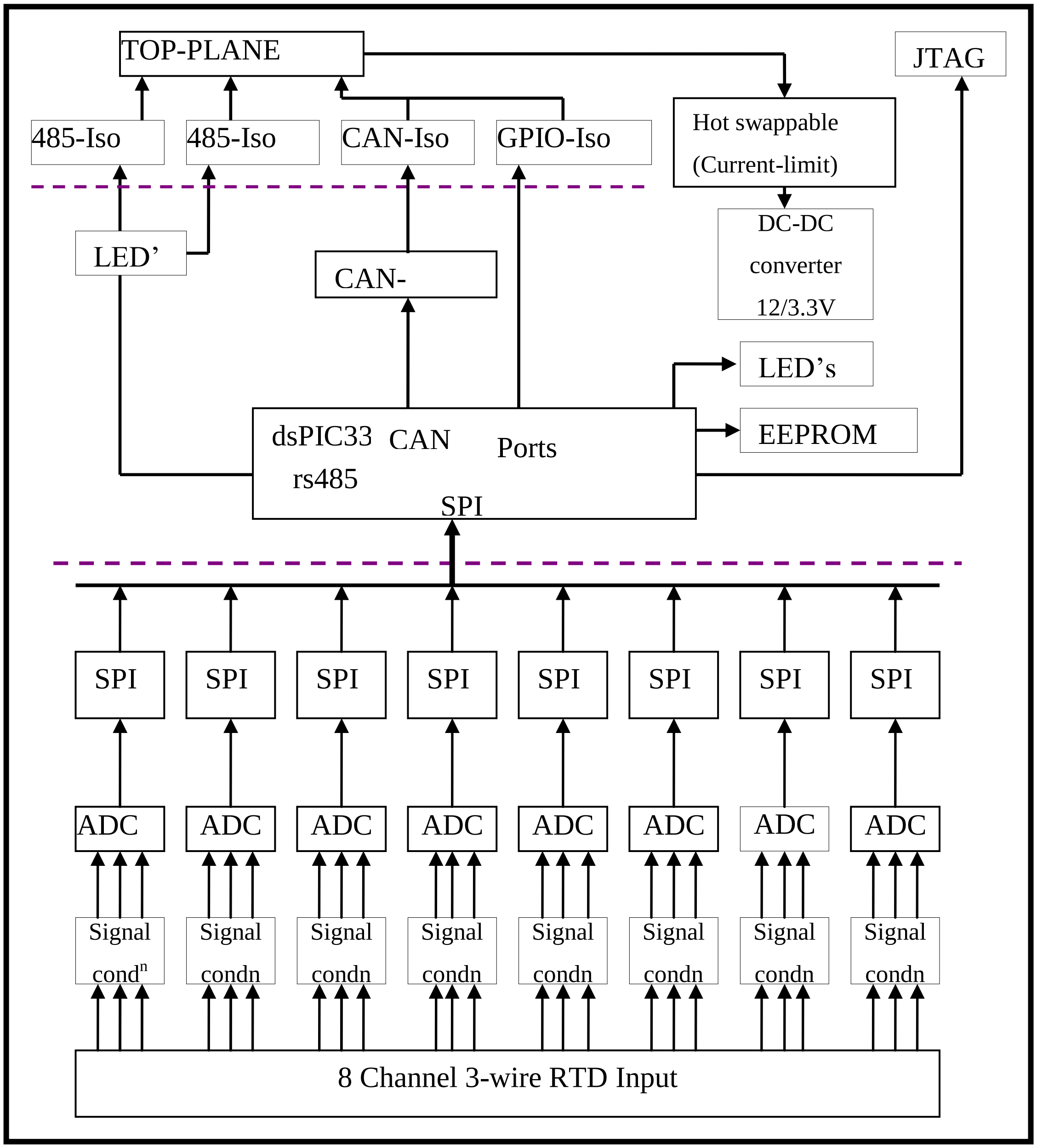


Figure 14: Block Diagram of Temperature Measurement Card

4.5 Display Card

Display card is used to show the all the monitoring data in graphical and text form. Display card consist of 128*128 Graphical LCD. Display Card is hot swappable and can be removed during power on condition. All the data to be displayed on LCD is acquired by the Central Processing Card. Display Card also contains its own PIC controller. For storing the data display card has five FRAM, all the FRAMs are put on the SPI interface.. The controller used for the card is dsPIC33F which is 16-bit microcontroller. It is a 100pin controller. EEPROM from Atmel is used for storage purpose. EEPROM is interfaced with the microcontroller using I2C interface. This (i^2c) EEPROM will store the cards set-up (calibration) information along with any manufacturing and production data that may be felt to be useful for future testing, repair or traceability etc. Microcontroller put the frames on the bus after processing the data. The card is provided with 3 different buses- RS485-1, RS485-2 and CAN. If any of the bus is stop communicating then it will move t the other bus to avoid the loss of communication. All the inputs are processed by the microcontroller embedded in the card. Channel isolation to Earth 6KV DC. Capacitors and Tranzorbs will provide the EMC protection for the input circuit. The card inputs are scaled down using a resistor divider and are isolated with respect to each other. The Display Card is powered by top-plane 12-volt power will be regulated down to 3.3 volts and 5 volts on the card, and used for all the control logic, buffers and PIC32 micro-controller. 5 volts is required by the CAN isolator. RS485, CAN and GPIO interface used on the back plane will be having maximum 2kV Isolation.

The LCD used for graphical display is WGA128*128.

The LCD Module has built in a T6963C LSI controller, It has an 8-bit parallel data bus and control lines for writing or reading through an MPU interface, it has a 128-word character generator ROM (refer to Table 1.), which can control an external display RAM of up to 8K bytes. Allocation of text, graphics and external character generator RAM can be made easily and the display window can be moved freely within the allocated memory range.

4.5.1 RAM Interface

The external RAM is used to store display data (text, graphic and external CG data). It can be freely allocated to the memory area (8 Kbytes max).

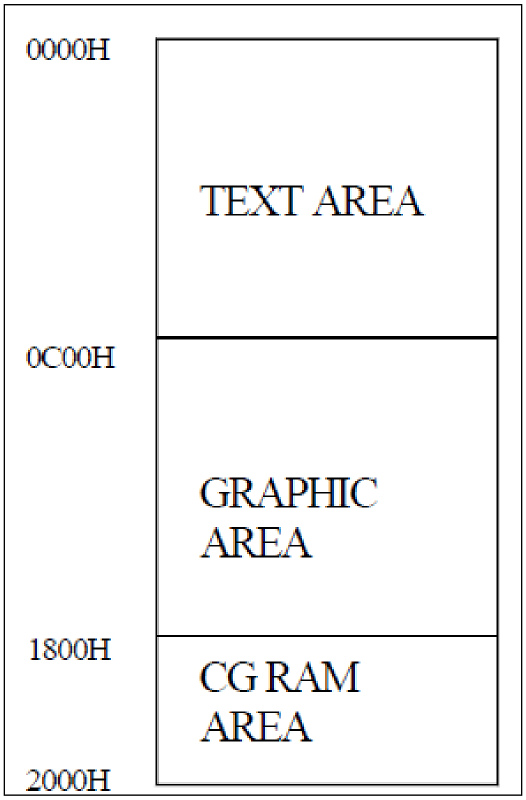


Figure 15: Ram Allocation Of LCD

4.5.2 Interface Pin Function

Table 2: LCD Pin Details

Pin no.	Symbol	Level	Description
1	FG		Frame Ground
2	GND	0V	Ground
3	Vdd	5.0V	Power supply for logic
4	Vo		Power supply for LCD driver
5	/WR	L	Data write
6	/RD	L	Data read
7	/CE	L	Chip enable
8	C/D	H/L	Command/data
9	NC		
10	/RESET	L	Reset signal

11	DB0	H/L	Data bus line
12	DB1	H/L	Data bus line
13	DB2	H/L	Data bus line
14	DB3	H/L	Data bus line
15	DB4	H/L	Data bus line
16	DB5	H/L	Data bus line
17	DB6	H/L	Data bus line
18	DB7	H/L	Data bus line
19	FS		Font select
20	NC		No connection
21	A		Power supply for B/L(+)
22	K		Power supply for B/L(-)

4.6 Central Processing Card

Central processing Card is the main card of the unit which will perform the tasks intelligent tasks according to the algorithms. The card contains two controllers one is 16-bit dsPIC33F and other is 32-bit AM1808. Both controllers have to perform the predefined tasks. Both the controller communicates with each other using the SPI interface. CPC has to acquire data from all the input cards and process to give instructions through output cards. CPC also attain the input from display card push button data enter and from the HMI data entered by user and also sends the data to be displayed on the HMI and Graphical LCD. CPC card communicate with all the I/O cards using MODBUS and CAN protocols. Main will synchronize the time by using three time synchronization inputs from GPS, IRIG-B and RTC. CPC card have 6KV isolation to earth and the card is hot swappable. CPC card need 12V power supply for its working. CPC card works on three supplies 1.8V, 3.3V and 5V. CPC card contains all the protocols at the front side like RS485, RS232, USB, Ethernet etc. USB is used for the fast data transfer purposes.

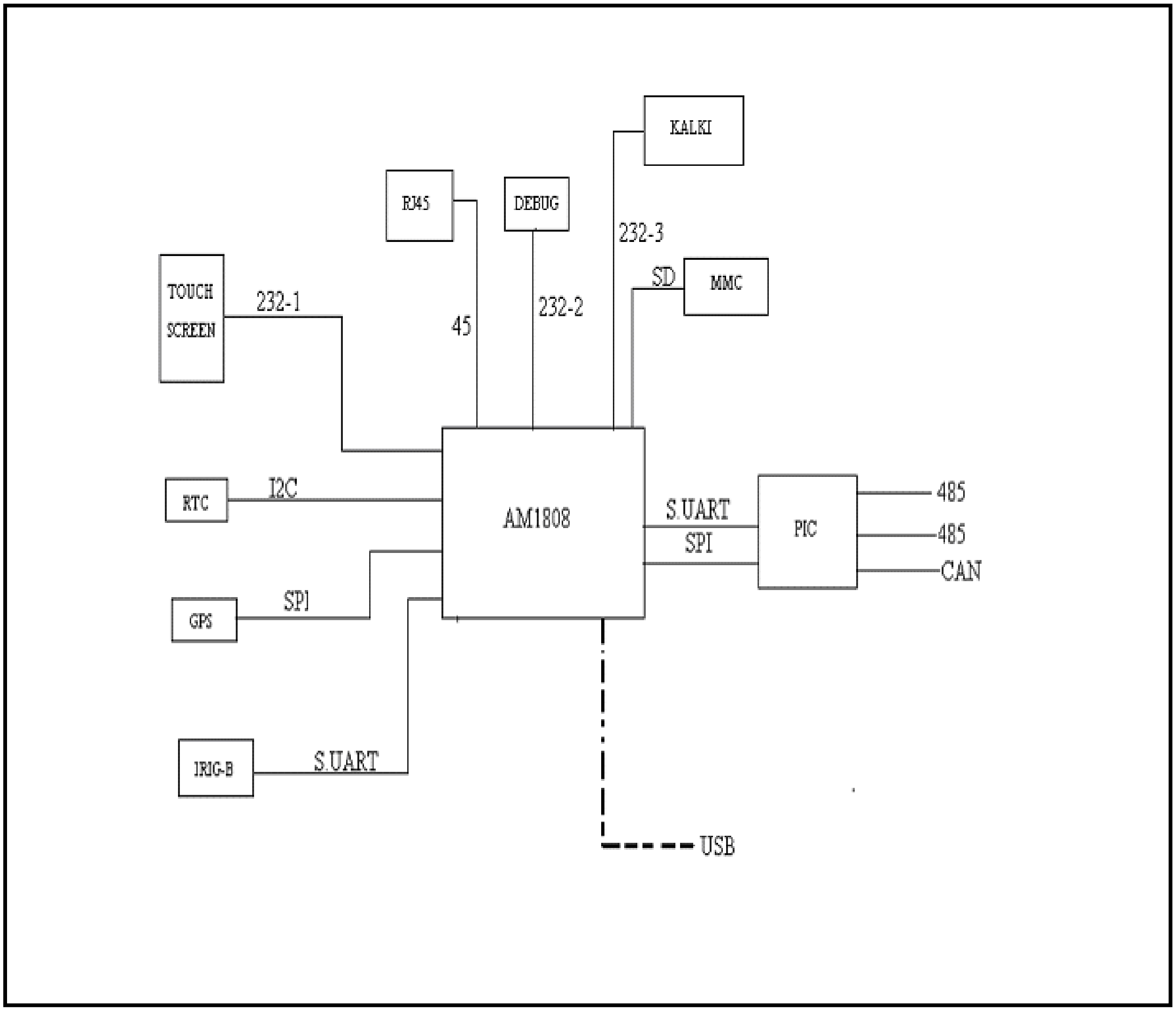


Figure 16: Block Diagram of Central Processing Card

4.7 GPS (Global Positioning System)

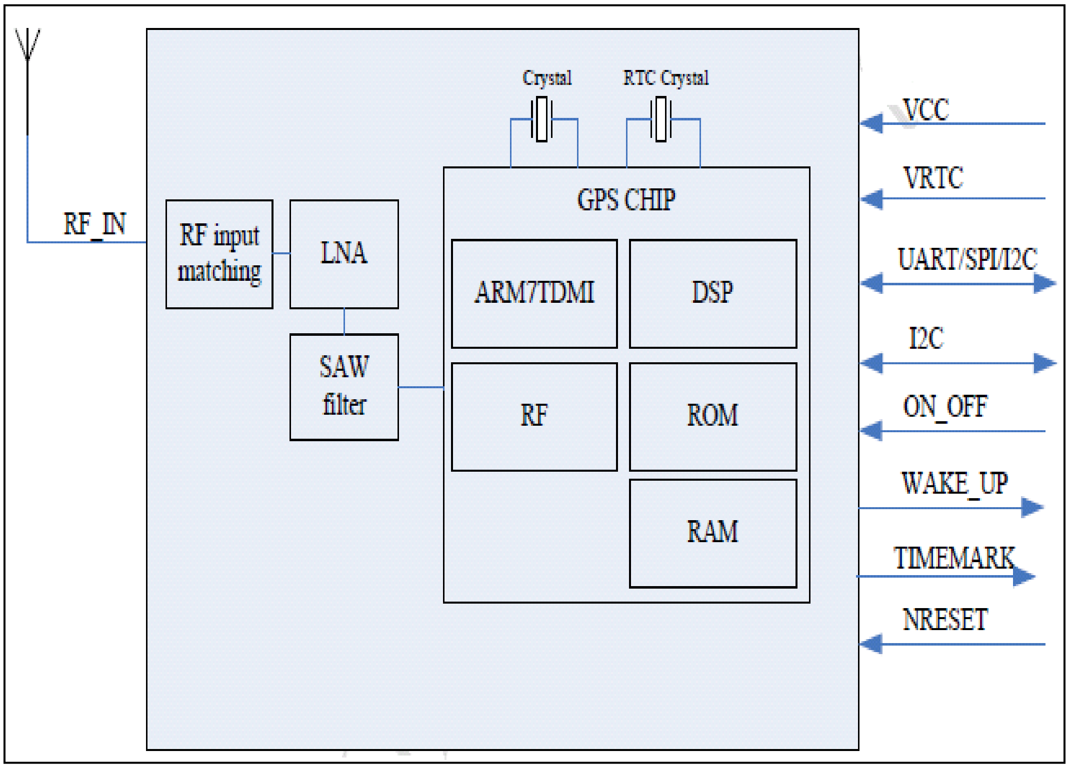


Figure 17: Block Diagram Of SIM18 GPS

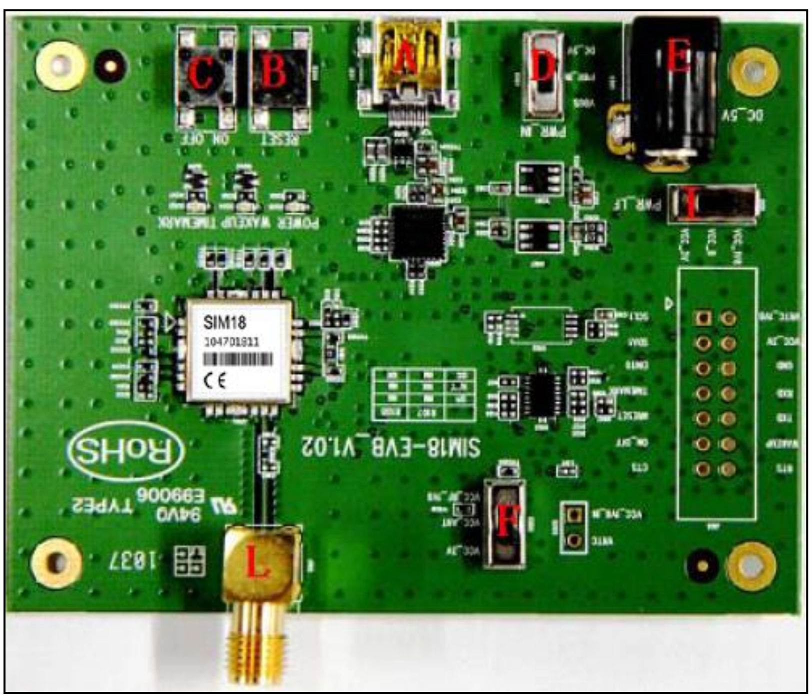


Figure 18: PCB Layout Of SIM18 GPS

SIM18 is a ROM-based stand-alone or Aided GPS receiver. Designed with the new generation of SiRFstarIVTM navigation processor, SIM18 can track as low as -163dBm signal even without network assistance and can cost as low as 36uW @1.8V power consumption in sleep mode. Because of its ROM-based structure, SIM18 requires no host integration and is easy to use.

The module requires 1.8V power supply. The host port is configurable to UART, SPI or I2C during power up. Host data and I/O signal levels are 1.8V CMOS compatible, inputs are 3.6V tolerable.

The following figure shows a functional diagram of the SIM18 and illustrates the mainly functional parts:

- The GPS chip
- LNA
- SAW filter
- The antenna interface
- The communication interface
- The control signals

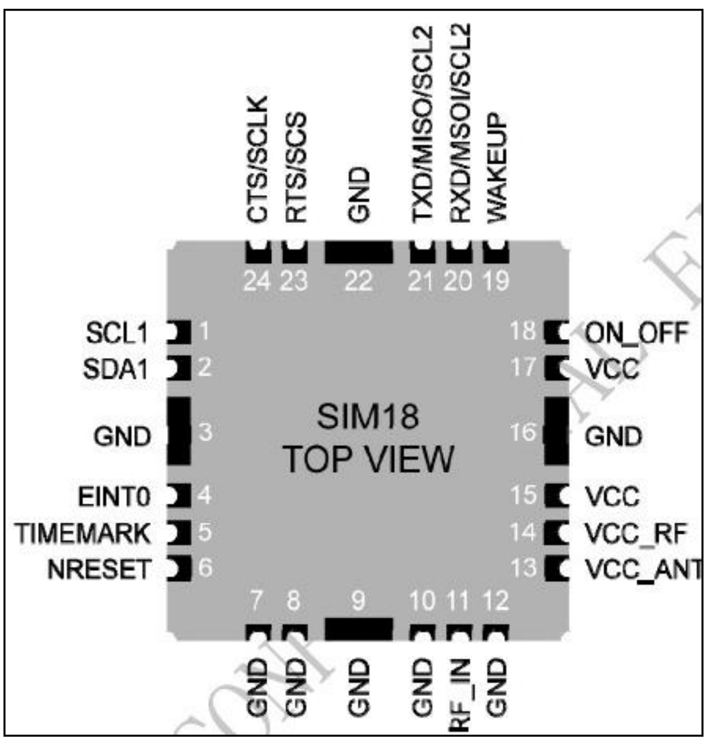


Figure 19: SIM18 Pin Diagram

Table 3: Pin Description Of SIM18

Pin name	Pin number	I/O	Description
Power supply			
VCC	15,17	I	Main power input, which will be used to power the base band and RF section internally.
VCC_RF	14	O	1.8V output power supply for active antenna
VCC_ANT	13	I	Power input for active antenna
GND	3,7,8,9,10,12, 16,22		Ground
Power control			
ON_OFF	18	I	Power control input to control the module going into or wakeup from sleep mode
WAKEUP	19	O	Indicate the module's state, when it is

			running, it is high; when in sleep or off state, it is low
nRESET	6	I	External reset input, active low
Host port interface			
TXD/MISO/SCL2	21	O	Function overlay: slave SPI data output(MISO) UART data transmit(TXD) I²C bus clock (SCL2
RXD/MOSI/SDA2	20	I	Function overlay: slave SPI data input(MOSI) UART data receive(RXD) I²C bus data (SDA2)
CTS/CLK	24	O	slave SPI clock input(CLK) UART clear to send(CTS) active low
RTS/CS	23	I	slave SPI chip select (CS) active low UART ready to send (RTS) active low
GPIOs			
SCL1	1	IO	dead reckoning I²C bus data (SCL)

SDA1	2	IO	dead reckoning I²C bus data (SDA)
EINT0	4	IO	Provide an interrupt on either high or low logic level or edge-sensitive interrupt
TIMEMARK	5	IO	Time Mark outputs timing pulse related to receiver time, GPS time or UTC time
RF interface			
RF_IN	11	I/O	Radio antenna connection

4.7.1 Starting SIM18

- For initial power up, the RTC must start oscillating to sequence the Finite State Machine. RTC startup time may vary.
- When power is first applied, SIM18 goes into a low-power mode while RTC starts and FSM sequences though to “ready-to-start” state.
- The host is not required to control nRESET pin since SIM18 internal reset circuitry handles detection of application of power.
- While in “ready-to-start” state, SIM18 awaits a pulse to the ON_OFF input pin to start.
- Since RTC startup time varies, detection of the time when SIM18 is ready to accept an ON_OFF pulse requires the host to either wait for a fixed interval, to monitor a

pulse on SIM18 WAKEUP output that indicates FSM “ready-to-start”, or simply to assert a pulse on the ON_OFF input every second until SIM18 starts by indicating a high on WAKEUP or generation of host port messages.

4.7.2 Operating Mode

Table 4: Power Supply And Clock State According To Operation Mode

Mode	VCC	Main clock	RTC clock
Full on	on	on	on
Sleep	on	off	on

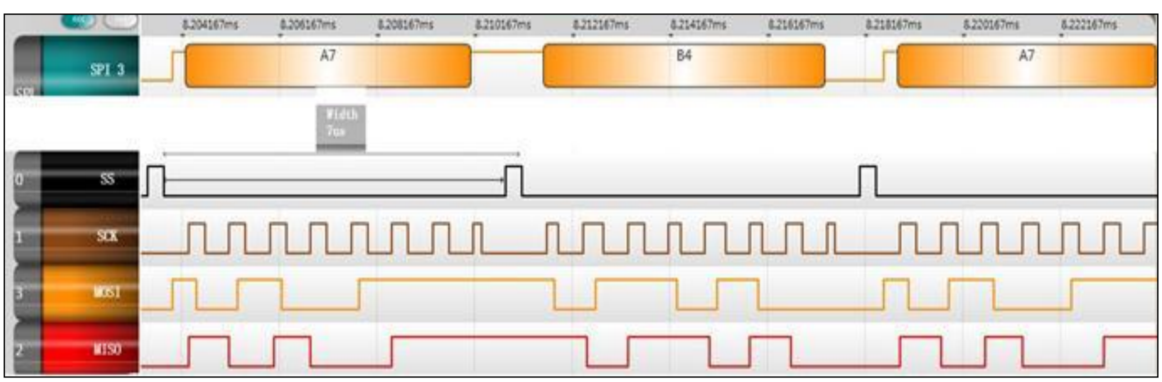
4.7.3 Host Interface

User can select the host port configuration between UART, SPI (slave) and I2C (master/slave) during power up boot.

Table 5: Host Port Type Selection

Port type	CTS/CLK	RTS/CS
SPI(default)	0	1
UART	1 (Add a pull-up 10kΩ resistor.)	1
I^{2}C	0	0 (Add a pull-down)

Figure 20 shows the signals of SPI interface for fetching the GPS information.



[19]

Figure 20:SIM18 GPS SPI Communication Waveforms

4.8 IRIG-B (Inter-Range Instrumentation Group)

Modern day electronic systems such as communication systems, data handling systems, missile and spacecraft tracking, and telemetry systems require time-of-day information for data correlation with time. Parallel and serial formatted time codes are used to efficiently interface the timing system (time-of-day source) to the user system. Parallel time codes are defined in IRIG Standard 205-87. Standardization of time codes is necessary to ensure system compatibility among the various ranges, ground tracking networks, spacecraft and missile projects, data reduction and processing facilities, and international cooperative projects.

4.8.1 General Description Of Standard

This standard consists of a family of rate-scaled serial time codes with formats containing up to three-coded expressions or words. The first word of the time-code frame is time-of-year in binary coded decimal (BCD) notation in days, hours, minutes, seconds, and fractions of seconds depending on the code-frame rate. The second word is a set of bits reserved for encoding of various control, identification, and other special purpose functions. The third word is seconds-of-day weighted in straight binary seconds (SBS) notation.

4.8.2 General Description Of Formats

4.8.2.1 Pulse Rise Time

The specified pulse (dc level shift bit) rise time shall be obtained between the 10 and 90 percent amplitude points.

4.8.2.2 Jitter

The modulated code is defined as < 1 percent at the carrier frequency. The dc level shift code is defined as the pulse-to-pulse variation at the 50 percent amplitude points on the leading edges of successive pulses or bits.

4.8.2.3 Bit Rates and Index Count

Each pulse in a time code word/sub-word is called a bit. The "on-time" reference point for all bits is the leading edge of the bit. The repetition rate at which the bits occur is called the bit rate. Each bit has associated numerical index count identification. The time interval between the leading edge of two consecutive bits is the index count interval. The index count begins at the frame reference point with index count 0 and increases one count each index count until the time frame is complete.

Table 6: The Bit Rates And Index Count Intervals

Format	Bit Rate	Index Count Interval
A	1 kpps	1 millisecond
B	100 pps	10 milliseconds
D	1 ppm	1 minute
E	10 pps	0.1 second
G	10 kpps	0.1 millisecond
H	1 pps	1 second

4.8.2.4 Time Frame, Time Frame Reference, and Time Frame Rates

A time code frame begins with a frame reference marker P_0 (position identifier) followed by a reference bit P_r with each having a duration equal to 0.8 of the index count interval of the respective code. The on-time reference point of a time frame is the leading edge of the reference bit P_r. The repetition rate at which the time frames occur is called the time frame rate.

Table 7: The time frame rates and time frame intervals

Format	Time Frame Rate	Time Frame Interval
A	10 fps	0.1 second
B	1 fps	1 second
D	1 fph	1 hour
E	6 fpm	10 seconds
G	100 fps	10 ms
H	1 fpm	1 minute

4.8.2.5 Position Identifiers

Position identifiers have duration equal to 0.8 of the index count interval of the respective code. The leading edge of the position identifier P_0 occur one index count interval before the frame reference point P_r and the succeeding position identifiers (P_2, P_2...P_0) occur every succeeding tenth bit. The repetition rate at which the position identifiers occur is always 0.1 of the time format bit rate.

4.8.2.6 Time Code Words

The two time code words employed in this standard are

- BCD time-of-year
- SBS time-of-day (seconds-of-day)

All time code formats are pulse-width coded. A binary (1) bit has duration equal to 0.5 of the index count interval, and a binary (0) bit has duration equal to 0.2 of the index count interval. The BCD time-of-year code reads 0 hours, minutes, seconds, and fraction of seconds at 2400 each day and reads day 001 at 2400 of day 365 or day 366 (leap year). The SBS time-of-day code reads 0 seconds at 2400 each day excluding leap second days when a second may be added or subtracted. Coordinated Universal Time (UTC) is generated for all inter-range applications.

4.8.2.7 BCD Time-of-Year Code Word

The BCD time-of-year code word consists of sub-words in days, hours, minutes, seconds, and

fractions of a second encoded in a binary representation (1n 2n 4n 8n) where n=1, 10, 100, 1k...N. Time code digit values less than N are considered zero and are encoded as a binary 0.

The position identifiers preceding the decimal digits and the index count locations of the decimal digits (if present) are:

Table 8: Position Identifiers

BCD Code Decimal Digits	Decimal Digits Follow Position Identifier	Digits Occupy Index Count Positions
Units of Seconds Tens of Seconds	P_0	1-4 6-8
Units of Minutes Tens of Minutes	P_1	10-13 15-17
Units of Hours Tens of Hours	P_2	20-23 25-26
Units of Days Tens of Days	P_2	30-33 35-38
Hundreds of Days Tenths of Seconds	P_4	40-41 45-48
Hundredths of Seconds	P_5	50-53

Format A and B include an optional straight binary seconds-of-day (SBS) time code word in addition to the BCD time-of-year time code word. The SBS word follows position identifier P_8 beginning with the least significant binary bit (2_0) at index count 80 and progressing to the most significant binary bit (2_{16}) at index count 97 with a position identifier P_9 occurring between the ninth (2_8) and tenth (2_9) binary bits.

4.8.2.8 Control Functions

All time code formats reserve a set of bits known as control functions (CF) for the encoding of various control, identification, or other special purpose functions. The control bits may be programmed in any predetermined coding system. A binary 1 bit has a duration equal to 0.5 of the index count interval, and a binary (0) has a duration equal to 0.2 of the index count interval. Control function bits follow position identifier P_5 or P_6 beginning at index count 50 or 60 with one control function bit per index count, excepting each tenth bit which is a position identifier.

Table 9: The number of available control bits in each time code format

Format	Control Functions
A	27
B	27
D	9
E	45
G	36
H	9

Control functions are presently intended for intra-range use but not for inter-range applications; therefore, no standard coding system exists. The inclusion of control functions into a time code format as well as the coding system employed is an individual user defined option.

4.8.2.9 Index Markers

Index markers occur at all index count positions which are not assigned as a reference marker, position identifier, code, or control function bit. Index marker bits have duration equal to 0.2 of the index count interval of the respective time code format.

4.8.2.10 Amplitude Modulated Carrier

A standard sine wave carrier frequency to be amplitude modulated by a time code is synchronized to have positive-going, zero-axis crossings coincident with the leading edges of the modulating code bits. A mark-to-space ratio of 10:3 is standard with a range of 3:1 to 6:1

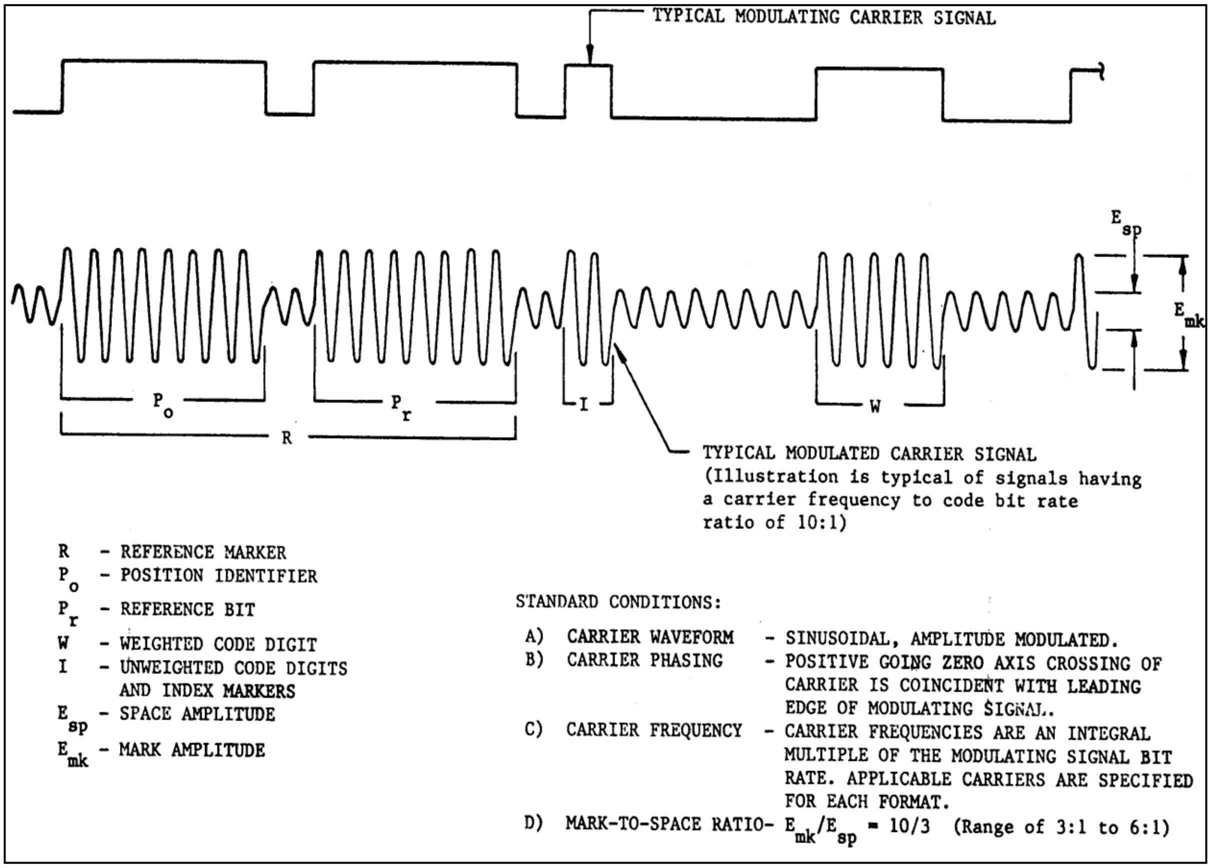


Figure 21: IRIG-B Signal Format

4.8.3 Detailed Description Of Formats

The family of rate scaled serial time code formats is alphabetically designated A, B, D, E, G, and H. various combinations of sub-words and signal forms make up a time code word. All formats do not contain each standard coded expression, and various signal forms are possible. To differentiate between these forms, signal identification numbers are assigned to each permissible combination according to the following procedure.

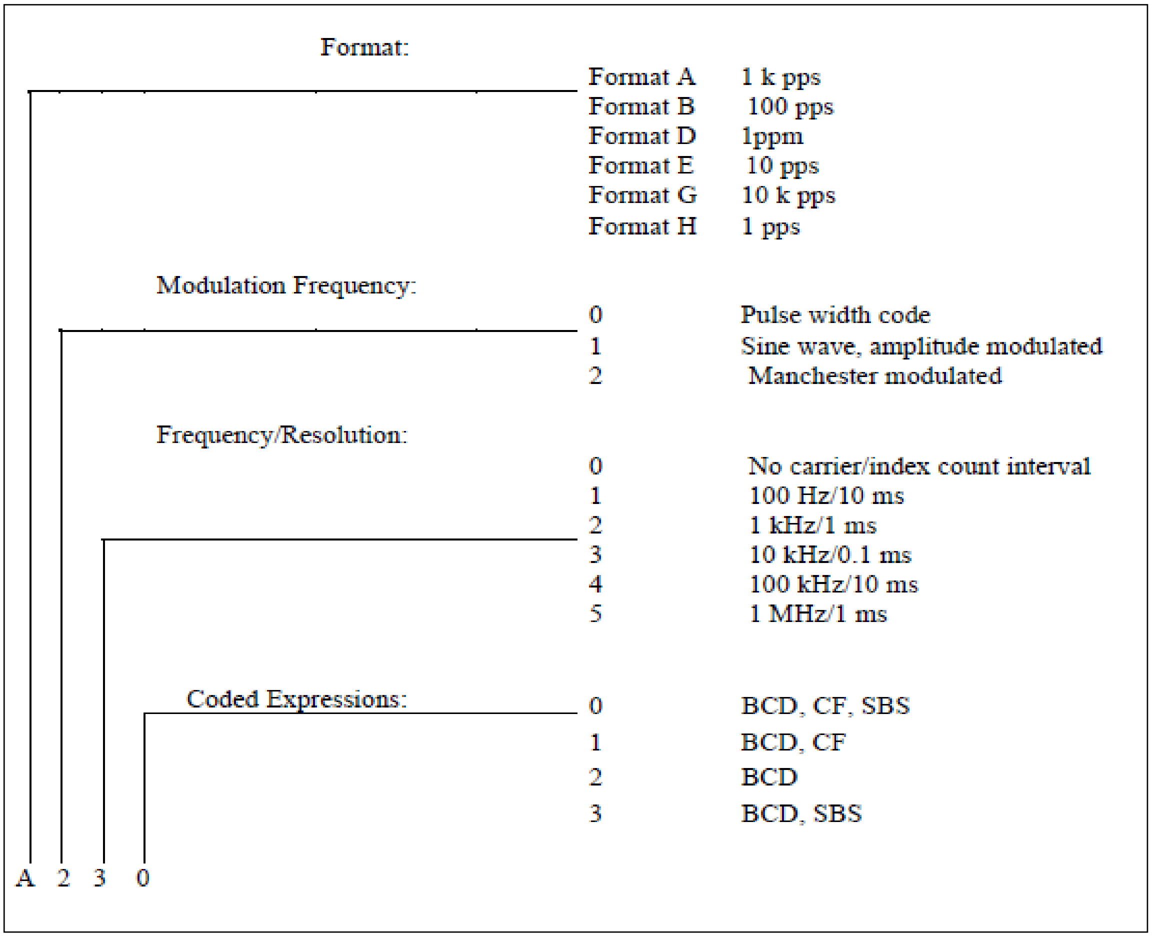


Figure 22: IRIG Format Description

The resolution of a time code is that of the smallest increment of time or the least significant bit which can be defined by a time code word or sub-word. The accuracy of a modified, Manchester time code can be determined by the rise time of the on-time pulse in the Manchester code which marks the beginning of the on-time one-pulse-per-second as shown in Figure 1. The accuracy can be milliseconds to nanoseconds or better depending on equipment and measurement technique. For the case of the unmodulated Manchester codes, the Position Marker, PO, which marks the beginning of the second can be used.

The following chart shows the permissible code formats. Codes D, E and H remain unchanged. Codes A, B and G have changed to permit 1MHz and Manchester modulation as indicated in the chart shown below. No other combinations are standard.

Table 10: Permissible Code Formats

FORMAT	MODULATION FREQUENCY	FREQUENCY/ RESOLUTION	CODED EXPRESSIONS
A	0,1,2	0,3,4,5	0,1,2,3
B	0,1,2	0,2,3,4,5	0,1,2,3
D	0,1	0,1,2	1,2
E	0,1	0,1,2	1,2
G	0,1,2	0,4,5	1,2
H	0,1	0,1,2	1,2

4.8.4 Time Code Format B

The 74-bit time code contains 30 bits of BCD time-of-year information in days, hours, minutes, and seconds; 17 bits of SB seconds-of-day; and 27 bits for control functions.

The BCD code (seconds sub-word) begins at index count 1 (LSB first) with binary coded bits occurring between position identifier bits P_0 and P_5: 7 for seconds, 7 for minutes, 6 for hours, and 10 for days, to complete the BCD word. An index marker occurs between the decimal digits in each sub-word to provide separation for visual resolution. The BCD time code recycles yearly.

The SBS word begins at index count 80 and is between position identifiers P_8 and P_0 with a position identifier bit (P_9) between the 9th and 10th binary SBS coded bits. The SBS time code recycles each 24 hour period.

The control bits occur between position identifiers P_5 and P_8, with a position identifier every 10 bits.The frame rate is 1.0 second with resolutions of 10 ms (dc level shift) and 1 ms (modulated 1 kHz carrier).

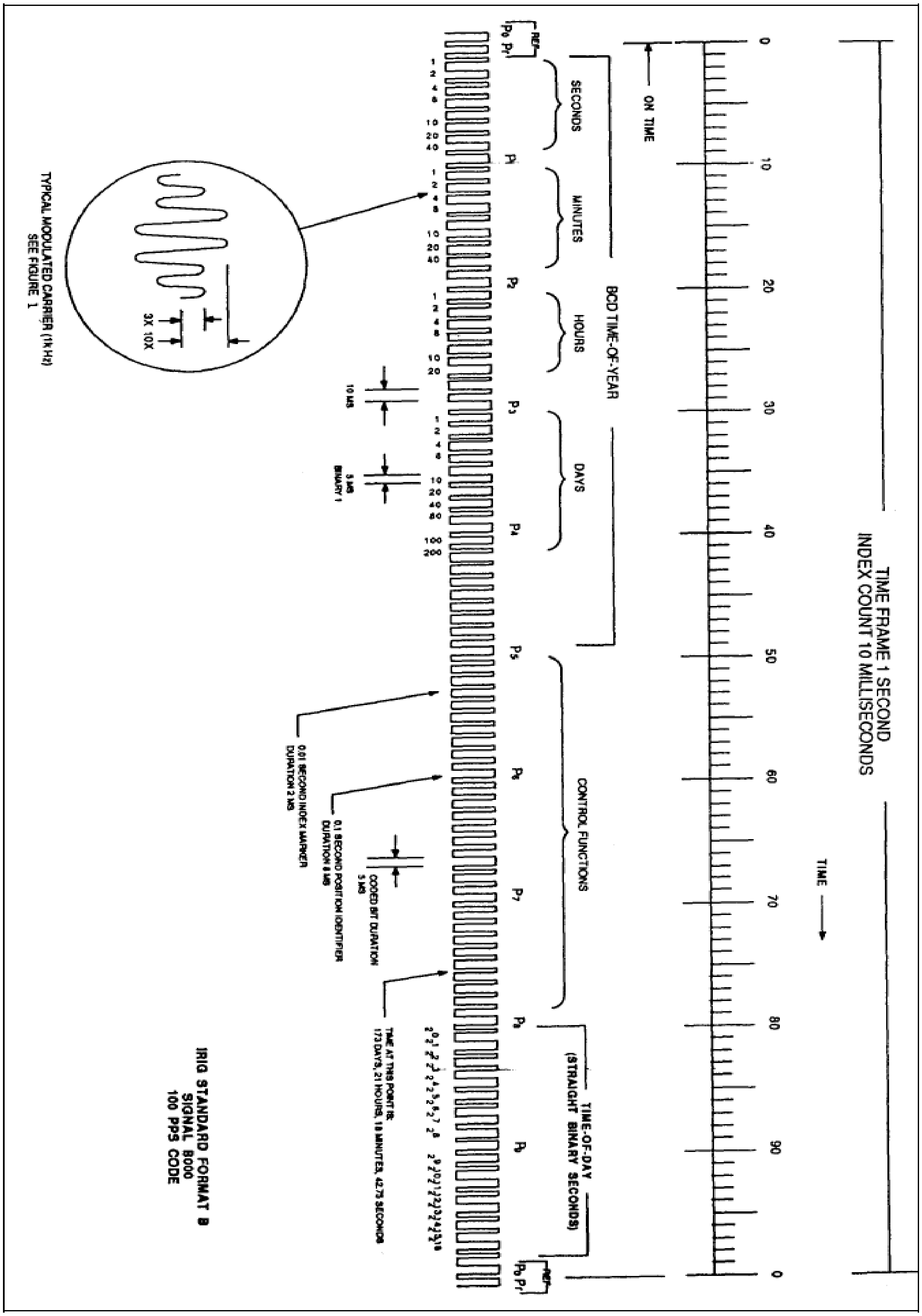


Figure 23: IRIG-B Signal Waveform

4.8.5 Leap Year/Leap Second Convention

LEAP YEAR:

The length of a year is not an even multiple of days. The year is about 365.25 days. Thus, every four years there is an extra day, February 29, provided the year is divisible by 4. Years divisible by 400 are leap years. If the year is divisible by 100, it is not a leap year. Consequently, the years 1988, 1992, 1996, and 2000 are leap years. The year 2100 will not be a leap year because it is not divisible by 400. With the addition of leap years, the calendar stays in step with the seasons.

ACCUMULATED LEAP SECOND:

Since 1 January 1972, the relationship between International Atomic Time (TAI) and Coordinated Universal Time (UTC) has been given by a simple accumulation of leap seconds occurring approximately once per year.

At any instant (i), T_i = TAI time

U_i = UTC time expressed in seconds

$$T_i = U_i + L_i,$$

where (L_i) is the accumulated leap second additions between the epoch and the instant (i).

The following table contains a reference list of the accumulated leap second additions (L_i) between 1972.0 and 1988.0:

Table 11: Reference list of the accumulated leap second

TIME PERIOD	L_i
1972 Jan 1 --- 1972 Jul 1	10.000 000 0 s
1972 Jul 1 --- 1973 Jan 1	11.000 000 0 s
1973 Jan 1 --- 1974 Jan 1	12.000 000 0 s
1974 Jan 1 --- 1975 Jan 1	13.000 000 0 s
1975 Jan 1 --- 1976 Jan 1	14.000 000 0 s
1976 Jan 1 --- 1977 Jan 1	15.000 000 0 s
1977 Jan 1 --- 1978 Jan 1	16.000 000 0 s
1978 Jan 1 --- 1979 Jan 1	17.000 000 0 s
1979 Jan 1 --- 1980 Jan 1	18.000 000 0 s
1980 Jan 1 --- 1981 Jul 1	19.000 000 0 s
1981 Jul 1 --- 1982 Jul 1	20.000 000 0 s
1982 Jul 1 --- 1983 Jul 1	21.000 000 0 s
1983 Jul 1 --- 1985 Jul 1	22.000 000 0 s
1985 Jul 1 --- 1986 Jan 1	23.000 000 0 s
1986 Jan 1 --- 1988 Jan 1	24.000 000 0 s

5 Algorithms

The algorithm of G-TMOC briefs the different monitoring and controlling functions of transformers in physical domains, the algorithm module of G-TMOC consists of 6 different sub modules

- Load Monitoring
- Thermal Model
- Dissolved Gas analysis
- Moisture Analysis
- Life cycle estimation
- Cooling Monitoring and Control
- Automatic Voltage Regulator – OLTC

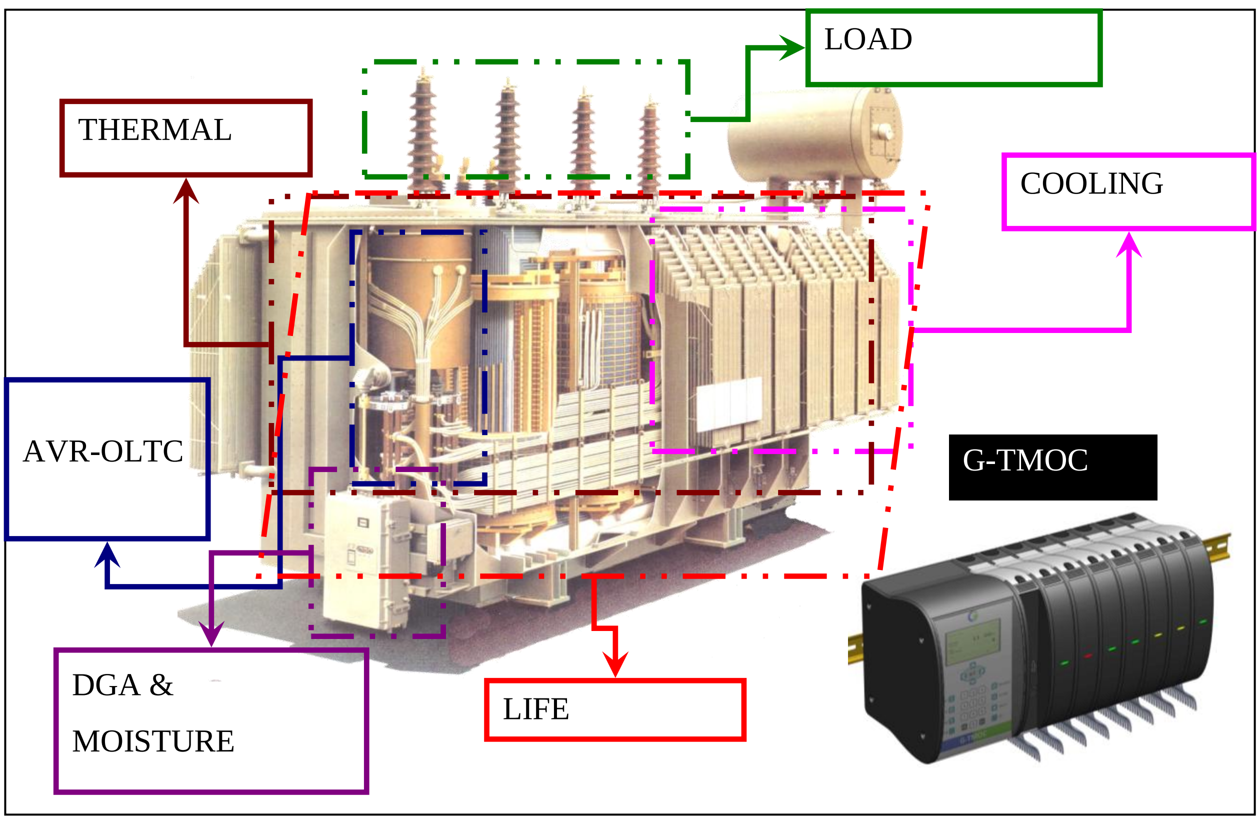


Figure 24: G-TMOC Application model

5.1 Load Monitoring

The Load monitoring module measures and computes the electrical parameters Current, Voltage, Apparent power and % Utilization of Transformer.

5.1.1 Current

Transformer Current can be measured using 4-20mA sensor or current transformer. The channel samples at 5000 samples per second, the sampled values per second will be averaged to compute the average current.

$$I_{avg} = \frac{I_1 + I_2 + I_3 + \ldots\ldots\ldots\ldots\ldots + I_n}{n} \times CTR$$

Equation 1: I_{avg} Computation

Where

I_{avg} - load Current

I_1, I_2, I_3, I_n - sampled values

CTR – CT ratio

5.1.2 Voltage

Transformer Voltage can be measured using 4-20mA sensor or potential transformer. The channel samples at 5000 samples per second, the sampled values per second will be averaged to compute the average Voltage.

$$V_{avg} = \frac{V_1 + V_2 + V_3 + \ldots\ldots\ldots\ldots\ldots + V_n}{n} \times VTR$$

Equation 2 V_{avg} Computation

Where

V_{avg} - System Voltage

V_1, V_2, V_3, V_n - sampled values

VTR – VT ratio

5.1.3 Apparent Power

The power Transformed by the transformer will be computed using Voltage and Current parameters

$$S_{Load} = V_{avg} \times I_{avg}$$

Equation 3: Power Computation

Where

S_{Load} – Apparent Power

I_{avg} - load Current

V_{avg} – system voltage

Based on the Rating of the Transformer and power computed % utilization will be computed

$$\%U = \left(S_{Load} / S_{Rated}\right) \times 100$$

Equation 4: % MVA Utilization Computation

Where

% U – % power under utilization

S_{rated} – Power rating of transformer

S_{Load} – Apparent power utilized

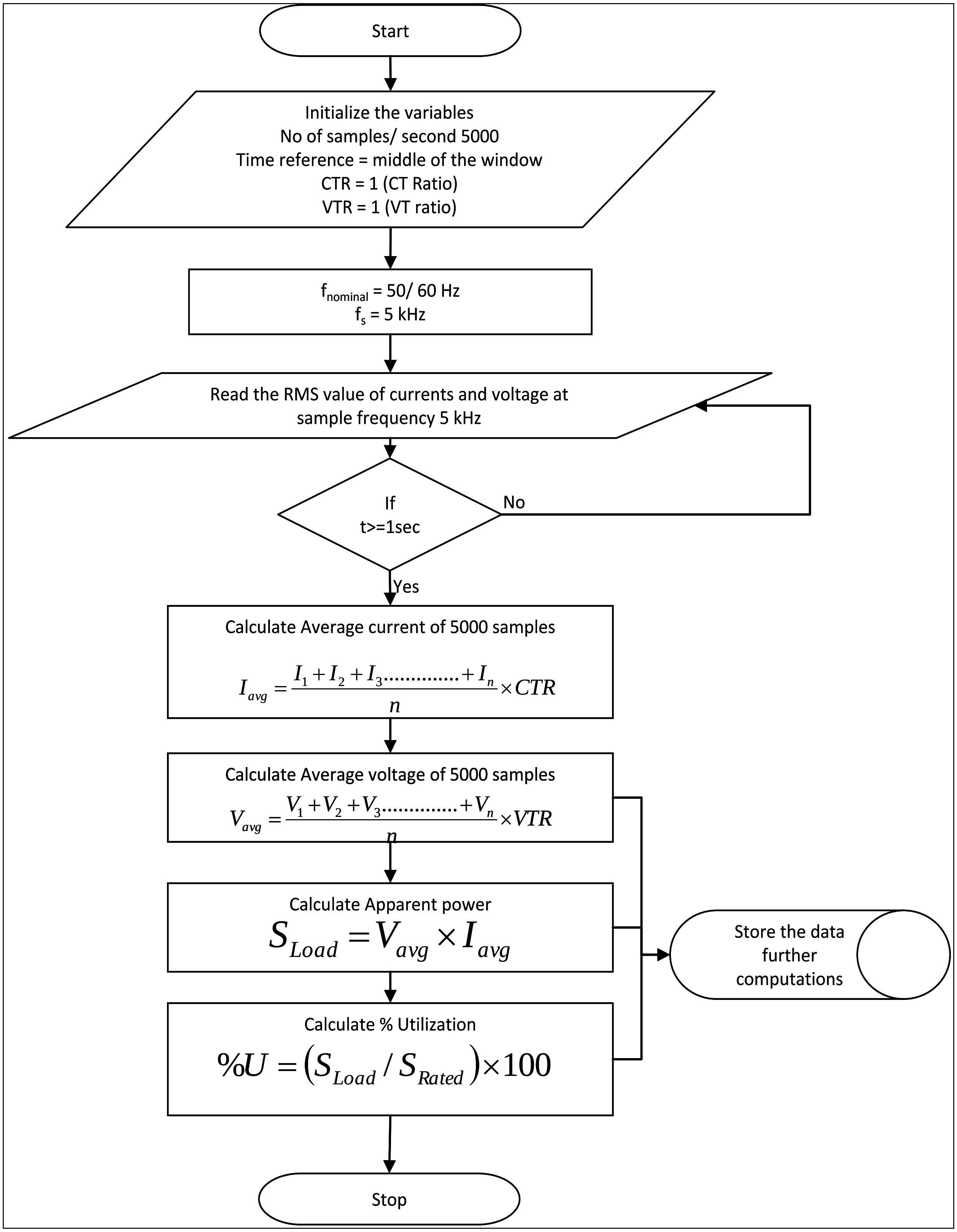


Figure 25: Load Monitoring Flow Chart

5.1.4 Alarms

Alarms will be provided, if the actual value exceeds the alarm settings

Table 12: Load monitoring module alarms

Sl No	Alarm	Parameter	Setting	Message
1	Utilization	% Utilization	> $\%U_{th}$	% Utilization exceeds the alarm settings
2	Over Current	I_{rms}	> I_{th}	Load Current exceeds the Over current setting
3	Under Current	I_{rms}	< I_{th}	Load Current exceeds the Under current setting
4	Over Voltage	V_{rms}	> V_{th}	System Voltage exceeds the Over Voltage setting
5	Under Voltage	V_{rms}	< V_{th}	System Voltage exceeds the Under Voltage setting

5.2 Thermal Analysis

The Thermal module measures the temperature at different locations of transformer and computes the hot-spot temperature using IEEE and IEC standards. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the temperature.

$$T_{avg} = \frac{T_1 + T_2 + T_3 + \ldots\ldots\ldots\ldots\ldots + T_n}{n}$$

Equation 5 Average Temperature

Where

T_{avg} - Average Temperature of particular channel

T_1, T_2, T_3, T_n – Sampled values

5.2.1 Top Oil Temperature

The Top oil temperature will be measured using PT100 RTD/ 4-20mA sensor at different locations on the top of the transformer, based on the manufacturers design. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the Top oil temperature.

Symbol - θ_{TO}

5.2.2 Bottom Oil Temperature

The Bottom oil temperature will be measured using PT100 RTD/ 4-20mA sensor at different locations on the Bottom of the transformer, based on the manufacturers design. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the Bottom oil temperature.

Symbol – θ_{BO}

5.2.3 Ambient Temperature

The Ambient temperature will be measured using PT100 RTD/ 4-20mA sensor in open space next to transformer, based on the manufacturers design. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the ambient temperature.

Symbol - θ_A

5.2.4 Winding Temperature

The Direct Winding temperature will be measured using fiber optic to 4-20mA sensors as per design of the transformer. The 4-20mA sensor output will be connected to G-TMOC. The channels samples at 50 samples per second, the sampled values per second will be averaged to compute the 3 phase winding temperature.

Symbol - θ_W

5.2.5 OLTC Temperature

The OLTC Chamber temperature will be measured at the top of chamber using PT100 RTD/ 4-20mA sensor, based on the manufacturers design. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the OLTC temperature.
Symbol - θ_{OLTC}

5.2.6 Cooling Bank Temperature

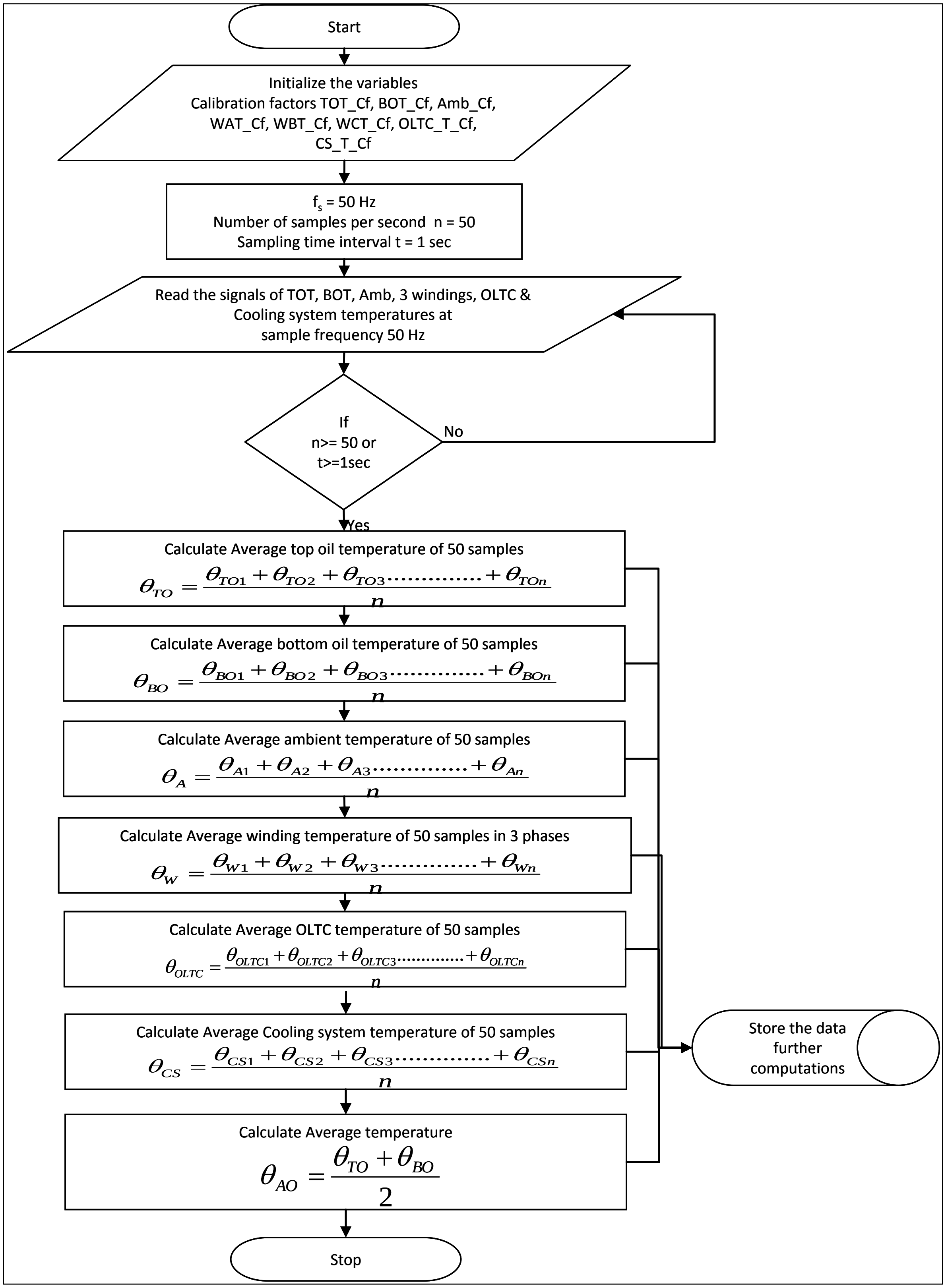
The Cooling bank temperature will be measured at the top using PT100 RTD/ 4-20mA sensor based on the manufacturers design. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the Cooling bank temperature.
Symbol - θ_{CST}

5.2.7 Average Oil Temperature

The average temperature is the average temperature exists in the transformer at any time of measurement; average temperature will be derived from top oil, bottom oil temperatures.

$$\theta_{AO} = \frac{\theta_{TO} + \theta_{BO}}{2}$$

Equation 6 Average Temperature Calculation



$$\theta_{TO} = \frac{\theta_{TO1} + \theta_{TO2} + \theta_{TO3} \ldots\ldots\ldots\ldots + \theta_{TOn}}{n}$$

$$\theta_{BO} = \frac{\theta_{BO1} + \theta_{BO2} + \theta_{BO3} \ldots\ldots\ldots\ldots + \theta_{BOn}}{n}$$

$$\theta_{A} = \frac{\theta_{A1} + \theta_{A2} + \theta_{A3} \ldots\ldots\ldots\ldots + \theta_{An}}{n}$$

$$\theta_{W} = \frac{\theta_{W1} + \theta_{W2} + \theta_{W3} \ldots\ldots\ldots\ldots + \theta_{Wn}}{n}$$

$$\theta_{OLTC} = \frac{\theta_{OLTC1} + \theta_{OLTC2} + \theta_{OLTC3} \ldots\ldots\ldots\ldots + \theta_{OLTCn}}{n}$$

$$\theta_{CS} = \frac{\theta_{CS1} + \theta_{CS2} + \theta_{CS3} \ldots\ldots\ldots\ldots + \theta_{CSn}}{n}$$

$$\theta_{AO} = \frac{\theta_{TO} + \theta_{BO}}{2}$$

Figure 26: Flowchart for thermal module

5.2.8 Hot Spot Temperature

The Hot spot temperature is the maximum temperature exists in the transformer at any time of measurement; Hot spot temperature will be derived from top oil, bottom oil, ambient and transformer factors. There were standards available in IEEE and IEC for computation of Hot spot temperature.

- IEEE – C57.91 – 1995
- IEC – 60076-2 – 2011

5.2.8.1 IEEE Hot Spot Computation

IEEE standard uses the Top oil, bottom oil, ambient temperature and load current to compute the hot spot temperature.

$$IEEE\_\theta_H = \theta_{To} + \Delta\theta_H$$

Equation 7 Hot Spot Temperature

Where

θ_H – hot spot temperature

θ_{TO} – top oil temperature

$\Delta\theta_H$ - Hot spot temperature rise

5.2.8.2 IEC Hot Spot Computation

IEC standard uses the Top oil, bottom oil, ambient temperature and load current to compute the hot spot temperature.

$$\theta_H = \theta_{To} + \Delta\theta_H$$

Equation 8 Hot Spot Temperature

Where

θ_H – hot spot temperature

θ_{TO} – top oil temperature

$\Delta\theta_H$ - Hot spot temperature rise

5.2.9 Alarms

Alarms will be provided, if the actual value exceeds the alarm settings

Table 13: Thermal Module Alarms

Sl No	Alarm	Parameter	Setting	Message
1	Top oil temperature	θ_{TO}	θ_{TOTh}	Top oil temperature exceeded alarm settings
2	Winding temperature	$\theta_{WA,}$ θ_{WB}, θ_{WC}	θ_{WTh}	Winding temperature exceeded alarm settings
3	OLTC temperature	θ_{OT}	θ_{OTTh}	OLTC temperature exceeded alarm settings
4	Cooling Temperature	θ_{CS}	θ_{CSTh}	Cooling temperature exceeded alarm settings
5	Hot spot temperature	θ_{H}	θ_{HTh}	Hot spot temperature exceeded alarm settings
6			θ_{HT}	Hot spot temperature exceeded Trip settings

5.3 Life cycle

5.3.1 Ageing acceleration factor

From existing hottest-spot temperature, the rate at which transformer insulation aging[20] is accelerated compared with the aging rate at a reference hottest-spot temperature. The reference hottest-spot Temperature is 110 °C for 65 °C average winding rise and 95 °C for 55 °C average winding rise transformers (without Thermally upgraded insulation). For hottest-spot temperatures in excess of the reference hottest-spot temperature the aging acceleration factor is greater than 1. For hottest-spot temperatures lower than the reference hottest-spot Temperature, the aging acceleration factor is less than 1.

$$F_{AA} = e^{\left[\frac{15000}{\theta_{HR}+273} - \frac{15000}{\theta_H + 273}\right]}$$

Equation 9 Ageing Acceleration Factor As Per IEEE C57.91

Where

F_{AA} – Ageing acceleration factor

θ_{HR} – Winding hot spot rise at rated load

θ_H – winding hot spot temperature

$$V = e^{\left[\frac{15000}{110+273} - \frac{15000}{\theta_H + 273}\right]}$$

Equation 10 Relative Ageing Rate As Per IEC 60076-7 For Thermally Upgraded Paper

$$V = 2^{(\theta_H - 98)/6}$$

Equation 11 Relative Ageing Rate As Per IEC 60076-7 For Non- Thermally Upgraded Paper

Where

V – Relative ageing rate

θ_H – winding hot spot temperature

5.3.2 Loss of life

The equivalent aging in hours at the reference hottest-spot temperature over a time period (usually 24 h) times 100 divided by the total normal insulation life[21] in hours at the reference hottest-spot temperature. The equivalent aging in hours at different hot-spot temperatures is obtained by multiplying the aging acceleration factors for the hottest-spot temperatures times the time periods of the various hottest-spot temperatures.

$$L_l = \sum_{n=1}^{N} F_{AA_n} \times \Delta t_n$$

Equation 12 Loss Of Life As Per IEEE C51.91

Where

L_l - loss of life

F_{AAn} – Ageing acceleration factor at n interval

t_n – Time interval, hours

$$L_l = \sum_{n=1}^{N} V_n \times \Delta t_n$$

Equation 13 Loss Of Life As Per IEC 60076-7

Where

L_l - loss of life

V_n – Ageing acceleration factor at n interval

t_n – Time interval, hours

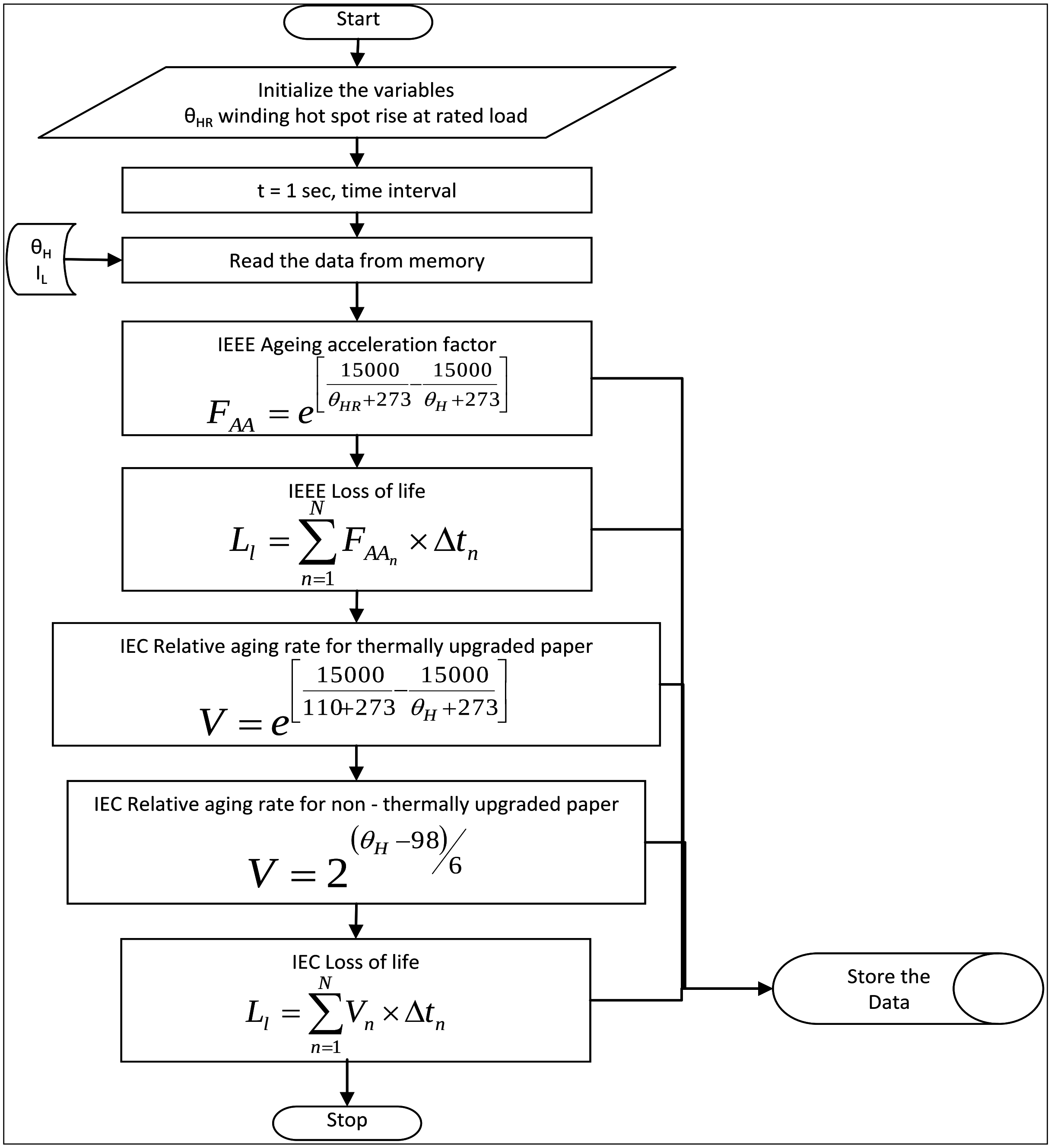


Figure 27: Flowchart For Life Calculation

5.4 Dissolved Gas Analysis

The Gas module collects the gas information of different gases from sensors like, Hydran, Kelman etc. The module collects information of different gases like

- Hydrogen – H_2
- Carbon Monoxide – CO
- Carbon dioxide – CO_2
- Acetylene – C_2H_2
- Ethylene – C_2H_4
- Methane – CH_4
- Ethane – C2H6

The collected gas information will be stored for trending and different analytical methodologies were used to analyze the system state as per gas information

- IEEE C57 – 104 state estimation analysis
- IEC 60599 state estimation analysis
- Rogers's ratio state estimation analysis
- Dornenburg's state estimation analysis
- Duval's triangle state estimation analysis

5.4.1 IEEE Analysis

The IEEE analysis uses the Total Dissolved Combustible gases (TDCG), rate of rise of TDCG and trend data of individual gases to analyze the state of the gases in the transformer. The fault types were divided into 4 types as normal condition, low decomposition, where individual gases has to be analyzed for their levels, High decomposition, where individual gases has to be analyzed and transformer has to be removed from service and excessive decomposition, danger to operate transformer.

Table 14: Status Information Of IEEE Analysis

Condition 1	TDCG below this level indicates Normal Operation, If any individual gas increases, additional investigation required. Then go for key gas and ratio methods.
Condition 2	TDCG in this limit indicates low level decomposition, requires individual gas Investigation, load dependency to be determined, If any individual gas increases, additional investigation required. Then go for

	key gas and ratio methods. TCG and TDCG to be determined Establish trend
Condition 3	TDCG in this limit indicates high level decomposition, requires individual gas investigation, Immediate trend needs to establish, Plan outage
Condition 4	TDCG above this limit indicates excessive decomposition, operation may result in failure, removal from service

$$TDCG = H_2 + CH_4 + C_2H_2 + C_2H_4 + C_2H_6 + CO$$

Equation 14 TDCG Calculation

Where

TDCG – Total Dissolved Combustible gases, ppm

H_2 – Hydrogen, ppm

CH_4 – Methane, ppm

C_2H_2 – Acetylene, ppm

C_2H_4 – Ethylene, ppm

C_2H_6 – Ethane, ppm

CO - Carbon Monoxide, ppm

5.4.1.1 Rate of rise of TDCG

The rate of rise of TDCG will be estimated hourly, daily, weekly, monthly, quarterly and annual. Based on the TDCG limits rate of raise limits will be checked.

$$R_{TDCG} = \frac{TDCG_n - TDCG_{n-m}}{m}$$

Equation 15 Rate Of Rise Of TDCG

Where

R_{TDCG} – rate of rise

$TDCG_n$ – Value of TDCG at nth iteration in minuets, present iteration

$TDCG_{n-m}$ – Value of TDCG at m iterations before n

n – Present iteration number

m – No of iterations, 60 for hourly, 24 for daily, 7 for weekly, 30 for monthly, 90 for quarterly, 365 for yearly

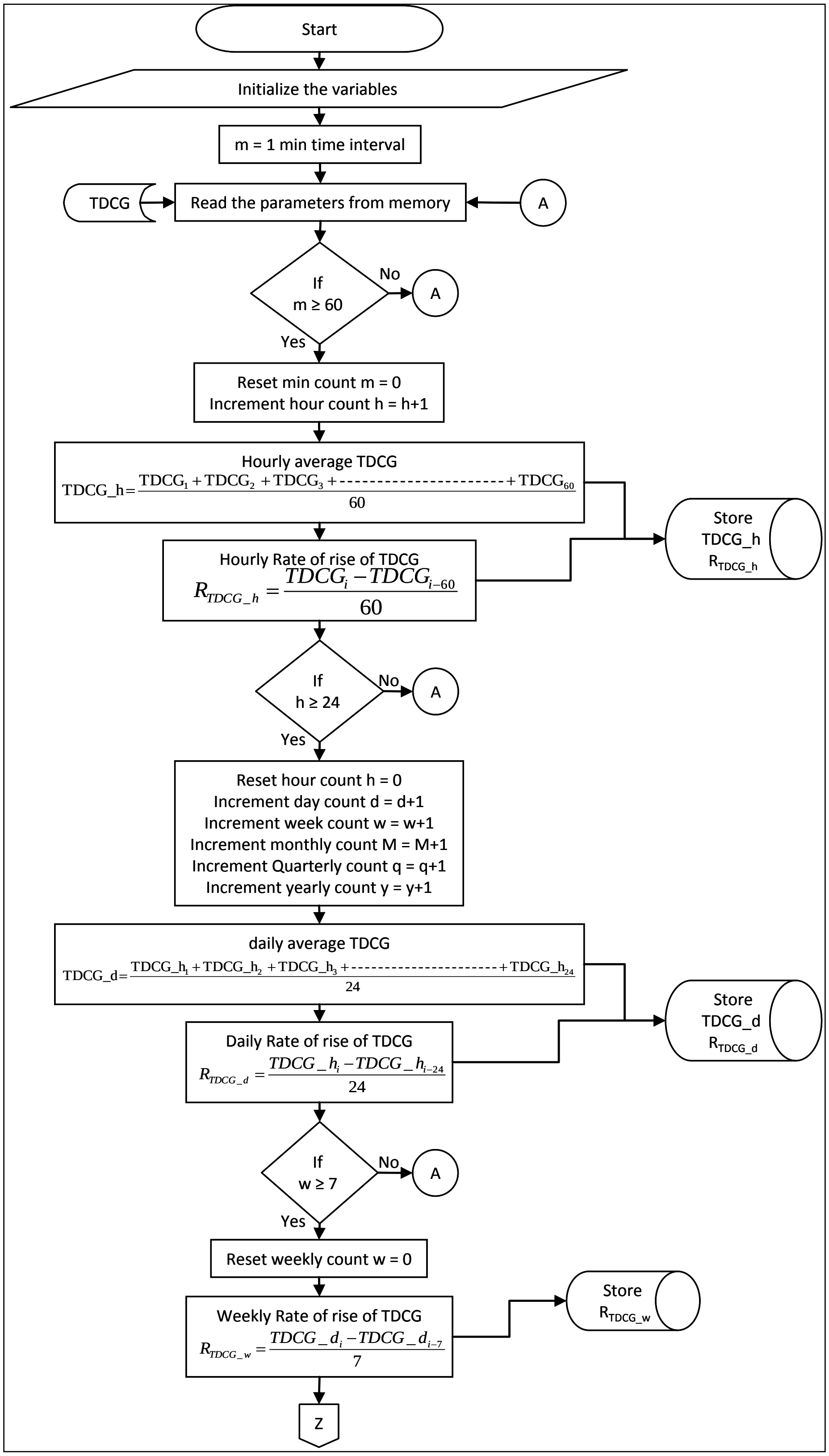


Figure 28: Flowchart for calculating TDCG

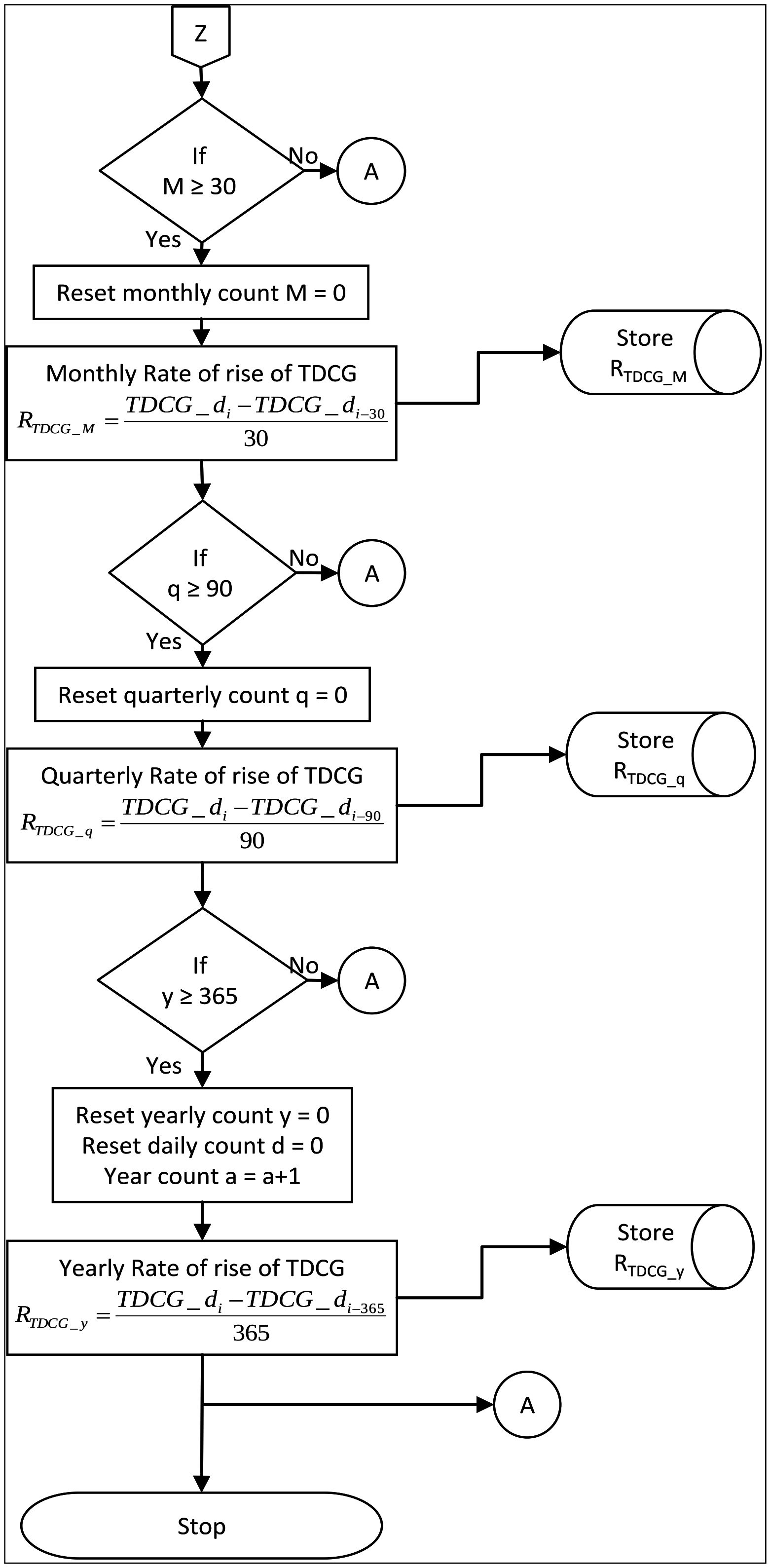


Figure 29: Flowchart For Calculation Of TDCG Monthly

Table 15: Analysis On Rate Of Rise Of TDCG

TDCG	Rate of rise of TDCG	Sampling interval	Status
> 4630	>30	Daily	Consider removal from service, contact manufacturer (4)
	10 – 30	Daily	
	< 10	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Contact manufacturer. (3)
1921 - 4630	>30	Weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Contact manufacturer. (3)
	10 – 30	Weekly	
	< 10	Monthly	
721 - 1920	>30	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence. (2)
	10 – 30	Monthly	
	< 10	Quarterly	
< 720	>30	Monthly	Exercise caution. Analyze for individual gases. Determine load dependence (2)
	10 – 30	Quarterly	Continue normal operation. (1)
	< 10	Annual	

5.4.1.2 Key Gas Analysis

The IEEE key gas analysis will be used if individual gas analysis suggested or the rate of rise trend data available is less than one year. It uses the TDCG value and individual gas values to analyze the system state, detailed investigation will be done on particular gas which exceeded certain limits.

Table 16: Key Gas Analysis TDCG And Gases

TDCG	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	Status
<=720	<100	<120	<1	<50	<65	<350	<2500	Condition 1
721 – 1920	101 -700	121 - 400	2 – 9	51 - 100	66 - 100	351 - 570	2500 - 4000	Condition 2
1921 – 4630	701 - 1800	401 - 1000	10 – 35	101 - 200	101 - 150	571 - 1400	4001 - 10000	Condition 3
> 4630	>1800	> 1000	> 35	> 200	> 150	> 1400	> 10000	Condition 4

Table 17: Key Gas Fault Analysis

Sl No	Fault	Principle gas	CO	H2	CH4	C2H6	C2H4	C2H2
1	Overheated oil	Ethylene C2H4	-	2%	16%	19%	63%	-
2	Overheated cellulose	Carbon monoxide CO	92%	-	-	-	-	-
3	Corona in oil	Hydrogen H2	-	85%	13%	1%	1%	
4	Arcing in oil	Acetylene C2H2	-	60%	5%	2%	3%	30%

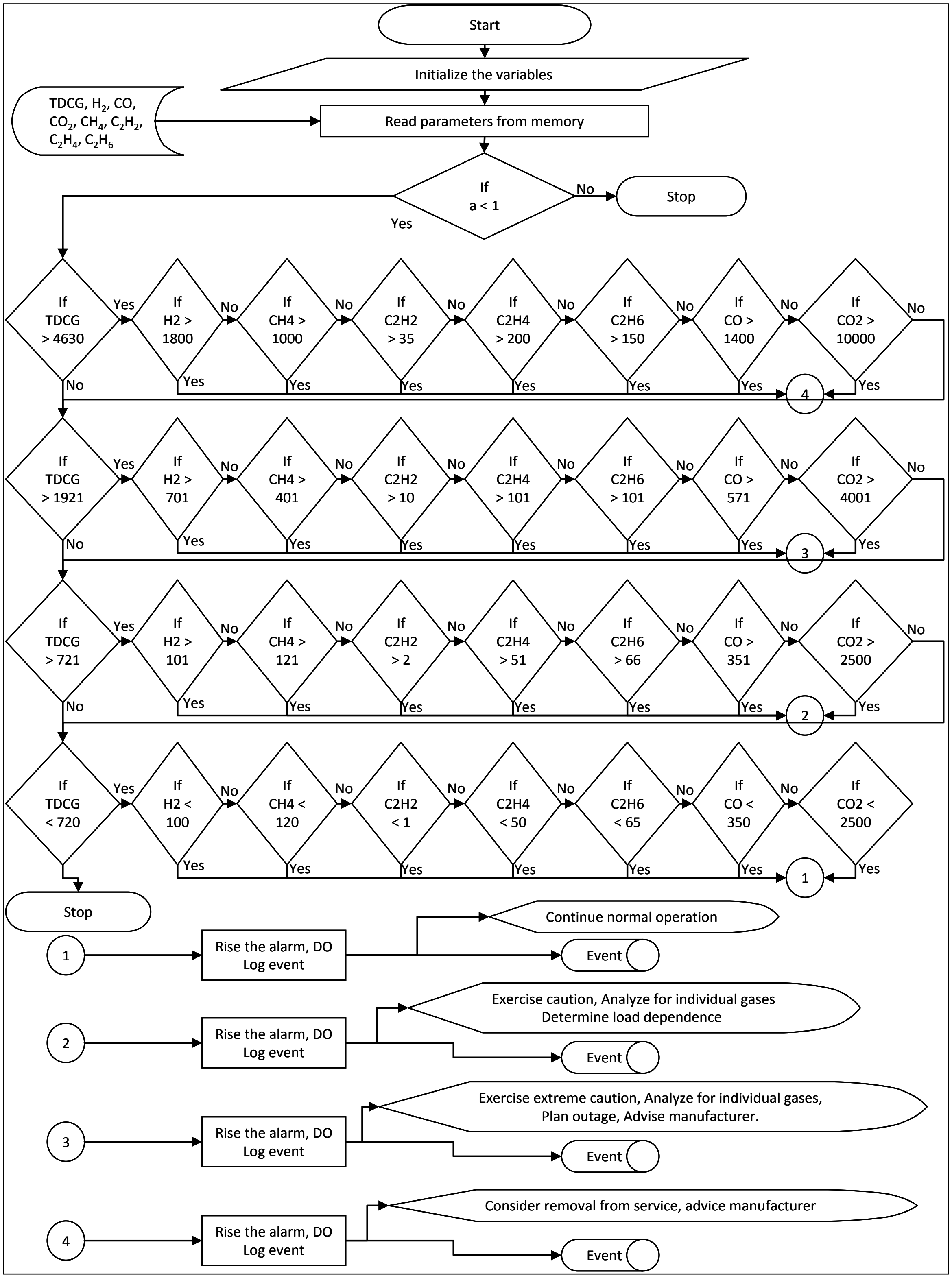


Figure 30: Flowchart For Gas State Analysis For Individual Gases

5.4.2 IEC Analysis

IEC analysis uses an advancer scenario of fault matrix where faults were classified as 7 different types Partial discharge, Low energy discharge, high energy discharge, thermal fault <300 deg C, 300 to 700 deg C, > 700 deg C.

Table 18: Status Information Of IEC Analysis

Type	Fault	Remarks
PD	Partial Discharge	Discharges in gas filled cavities resulting incomplete impregnation, high-humidity in paper, oil super saturation or cavitation's and leads to X-wax formation
D1	Low Energy Discharges	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroid's, adjacent disks or conductors of winding, broken brazing or closed loops in the core. Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls. Tracking in wooden blocks, glue of insulating beam, winding spacers, Breakdown of oil, selector breaking current.
D2	High Energy Discharges	Flashover, tracking or arcing of high local energy or with power follow-through. Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs.
T1	Thermal Fault < 300 deg C	Overloading of the transformer in emergency situations. Blocked item restricting oil flow in windings. Stray flux in damping beams of yokes.
T2	Thermal Fault 300 to 700 deg C	Defective contacts between bolted connections (particularly between aluminum bulbar), gliding contacts, contacts within selector switch (paralytic carbon formation), connections from cable and draw-rod of bushings.

		Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields. Abraded insulation between adjacent parallel conductors in windings.
T3	Thermal Fault > 700 deg C	Large circulating currents in tank and core. Minor currents in tank walls created by a high uncompensated magnetic field. Shorting links in core steel laminations.

The IEC state estimation uses a boundary limits for different gases and 3 different gas ratios to analyze the system state. The boundary limits vary as per the OLTC design for internal and external OLTC as mentioned in table.

Table 19: IEC Limits For Individual Gases

Gas	Limit (external OLTC)	Limit (Internal OLTC)
H_2	60 - 150	75 – 150
CH_4	40 - 110	35 – 130
C_2H_2	3 - 50	80 – 270
C_2H_4	60 - 280	110 – 250
C_2H_6	50 - 90	50 – 70
CO	540 - 900	400 – 850
CO_2	5100 - 13000	5300 – 12000

Table 20: IEC Gas Ratios

Ratio	Gas
Ratio 2	C_2H_2/ C_2H_4
Ratio 1	CH_4/H_2
Ratio 5	C_2H_4/C_2H_6

Table 21: IEC Analysis Ratio Limits

Case	**Characteristic fault**	**C_2H_2/ C_2H_4**	**CH_4/H_2**	**C_2H_4/C_2H_6**
PD	Partial Discharge	-	< 0.1	< 0.2
D1	Low Energy Discharges	> 1	0.1 - 0.5	> 1
D2	High Energy Discharges	0.6 - 2.5	0.1 - 1	> 2
T1	Thermal Fault < 300 deg C	-	> 1	< 1
T2	Thermal Fault 300 to 700 deg C	< 0.1	> 1	1 - 4
T3	Thermal Fault > 700 deg C	< 0.2	> 1	> 4

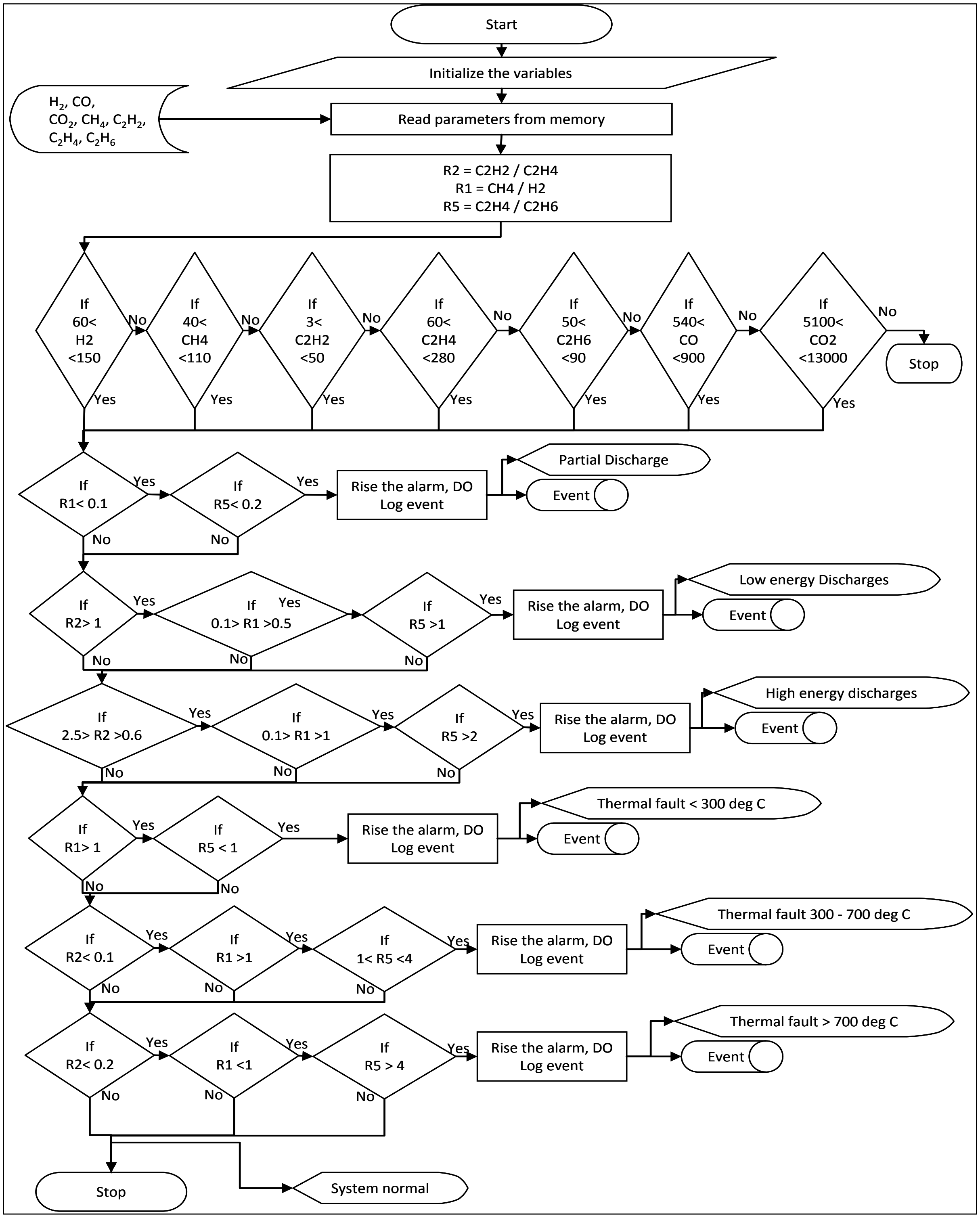


Figure 31: Flowchart For Gas State Analysis As Per IEC For External OLTC Transformer

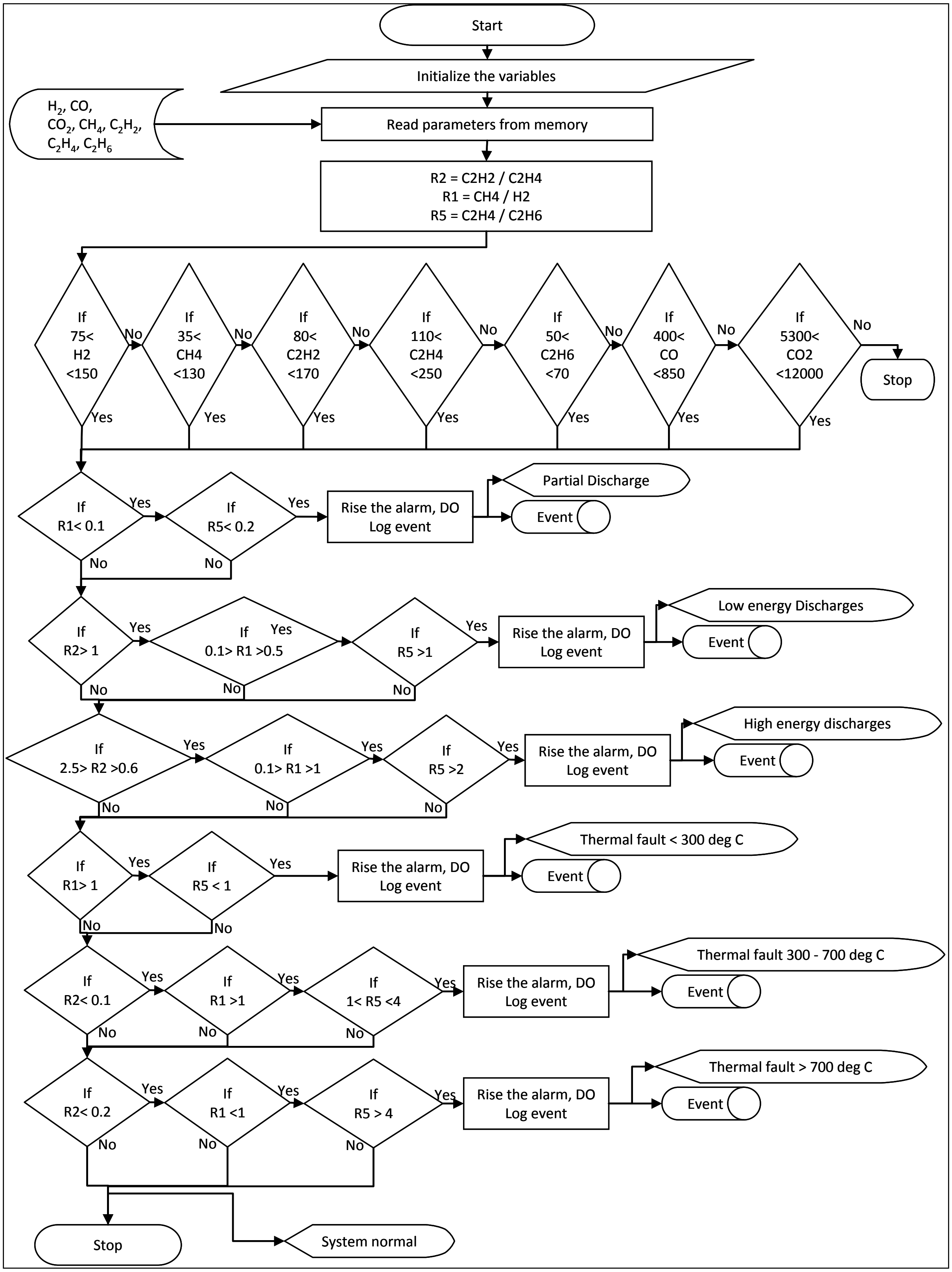


Figure 32 Flowchart For Gas State Analysis As Per IEC For Internal OLTC Transformer

5.4.3 Rogers's ratio state estimation analysis

Rogers's ratio[22,23] uses three gas ratios to analyze the system state with 6 types of fault states.

Table 22: Rogers Gas Ratios

Ratio	Gas
Ratio 2	C_2H_2/ C_2H_4
Ratio 1	CH_4/H_2
Ratio 5	C_2H_4/C_2H_6

Table 23: Roger's Ratio Limits

Case	Fault diagnosis	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
0	Unit Normal	< 0.1	0.1 - 1.0	< 1.0
1	Low energy density arcing	< 0.1	< 0.1	< 1.0
2	High energy discharge arcing	0.1 - 3.0	0.1 - 1.0	> 3.0
3	low temperature thermal	< 0.1	0.1 - 1.0	1.0 - 3.0
4	thermal fault < 700 deg C	< 0.1	> 1.0	1.0 - 3.0
5	thermal fault > 700 deg C	< 0.1	> 1.0	> 3.0

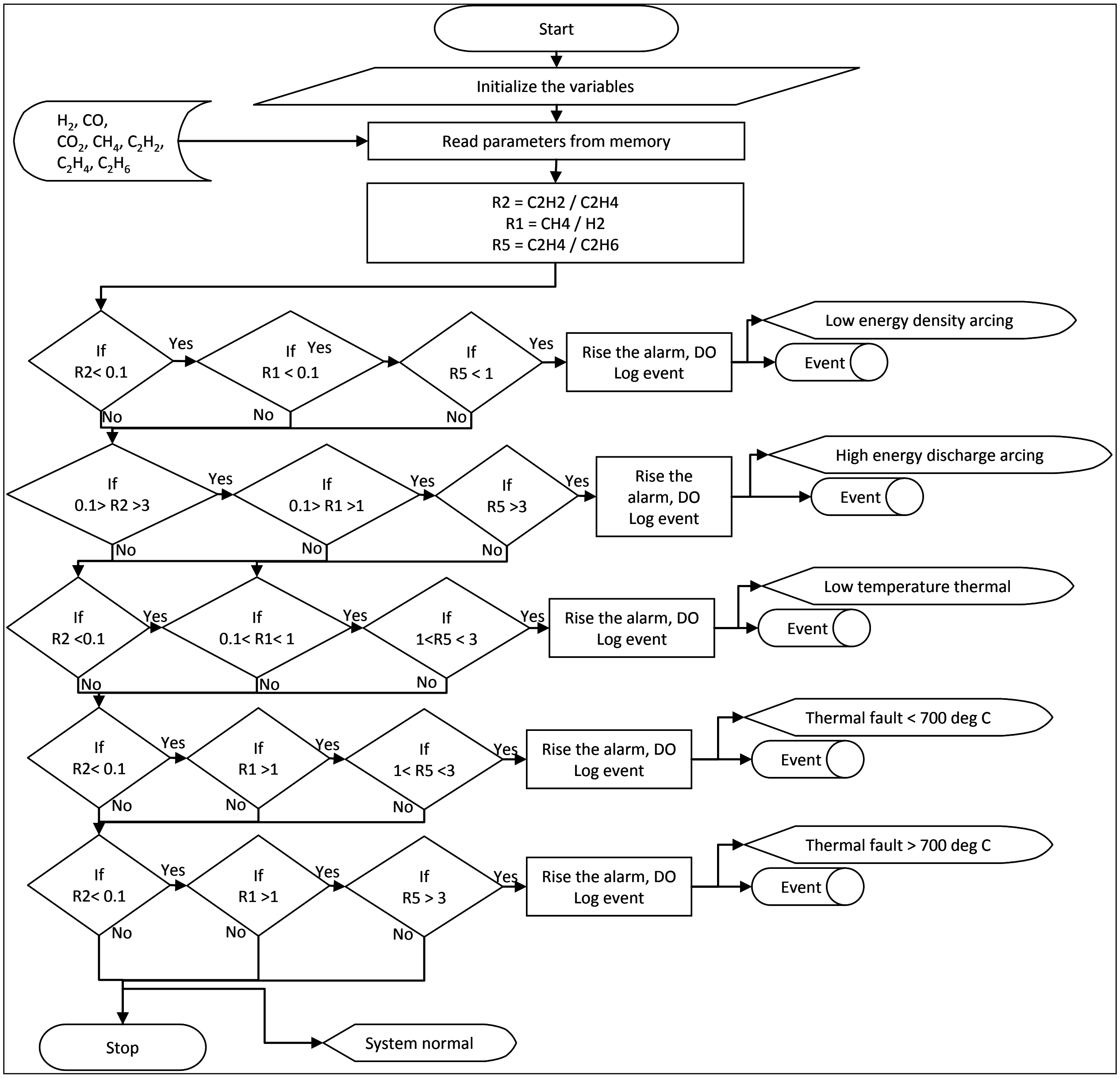


Figure 33 Flowchart For Gas State Analysis As Per Roger's Ratio

5.4.4 Dornenburg's state estimation analysis

Dornenburg's analysis uses 4 different gas ratios to analyze 3 different faults in gases. This methodology sets boundary limits of individual gases, if any gas exceeds the limits, than fault diagnosis limits will be employed to gas ratios to diagnose the fault type.

Table 24: Dornenburg's Limits For Individual Gases

Gas	Limit
H_2	100
CH_4	120
C_2H_4	50
C_2H_2	35
C_2H_6	1
CO	350

Table 25: Dornenburg's Gas Ratios

Ratio	Gas
Ratio 1	CH_4 / H_2
Ratio 2	C_2H_2 / C_2H_4
Ratio 3	C_2H_2 / CH_4
Ratio 4	C_2H_6 / C_2H_2

Table 26: Dornenburg's Limits For Fault Diagnosis

Fault diagnosis	**CH_4/H_2**	**C_2H_2/C_2H_4**	**C_2H_2/CH_4**	**C_2H_6/C_2H_2**
Thermal Decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Corona (Low Intensity PD)	< 0.1	-	< 0.3	> 0.4
Arcing (High intensity PD)	0.1 - 1.0	> 0.75	> 0.3	< 0.4

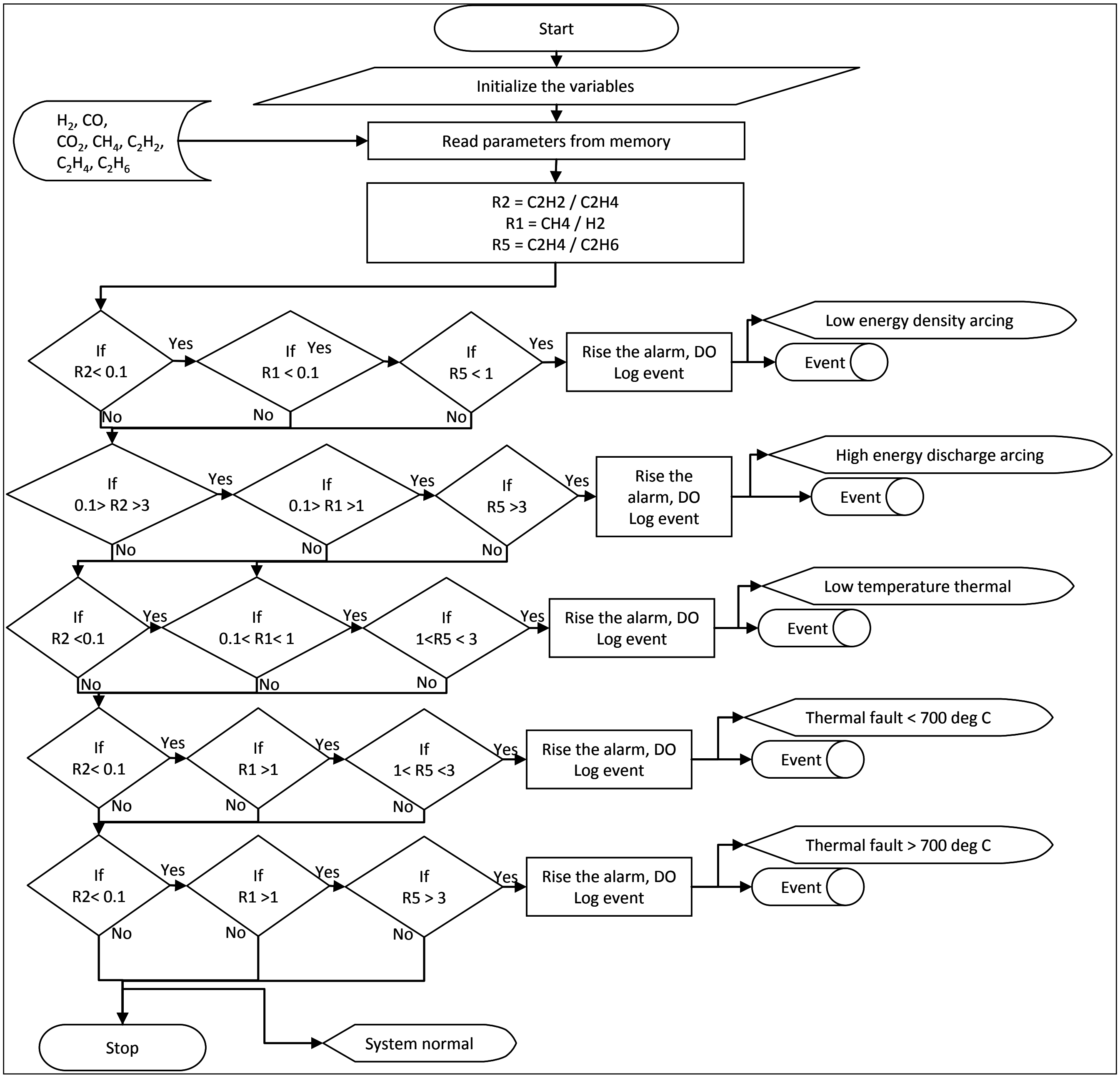


Figure 34 Flowchart For Gas State Analysis As Per Dornenburg's

5.4.5 Duval's triangle state estimation analysis

Duval's triangle[24] employs triangular phenomenon between 3 gases CH_4, C_2H_4, C_2H_2, uses % gas ratios of 3 gases to analyze system state. Duval's triangle analyzed the faults into 7 different types.

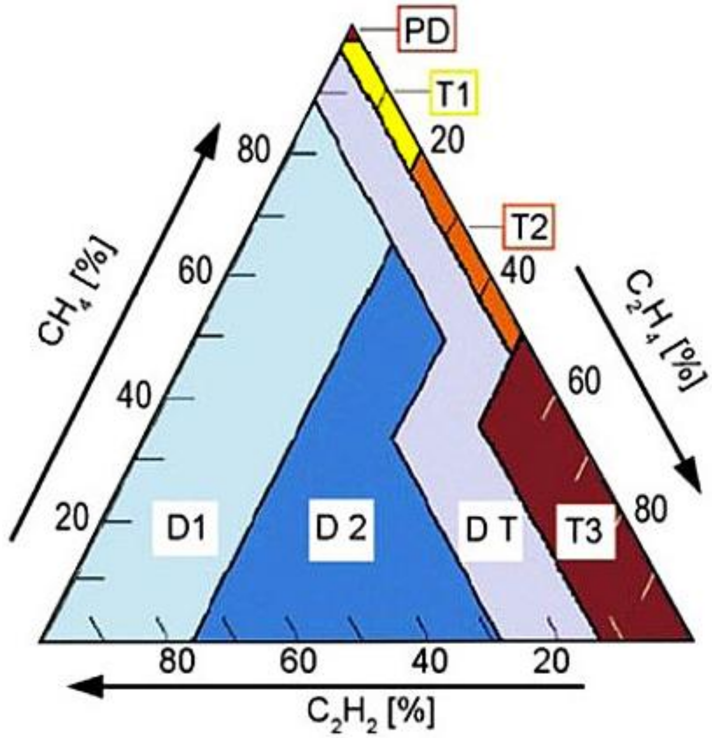


Figure 35 Duval's Triangle

$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

Equation 16 % CH_4

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

Equation 17 % C_2H_2

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

Equation 18 % C_2H_4

Table 27: Duval’s Triangle Fault Zones

Case	Fault Diagnosis	$\%CH_4$	$\%C_2H_2$	$\%C_2H_4$
PD	Partial Discharge	98%		
D1	Low energy discharge		> 13%	< 23%
D2	High energy discharge		%13 - %29	23% - 38%
			> 29%	> 23%
T1	Thermal fault < 300 deg C		< 4%	< 20%
T2	Thermal fault 300 - 700 deg C		< 4%	20% - 50%
T3	Thermal fault > 700 deg C		< 15%	> 50%
DT	Thermal & electrical fault	rest area		

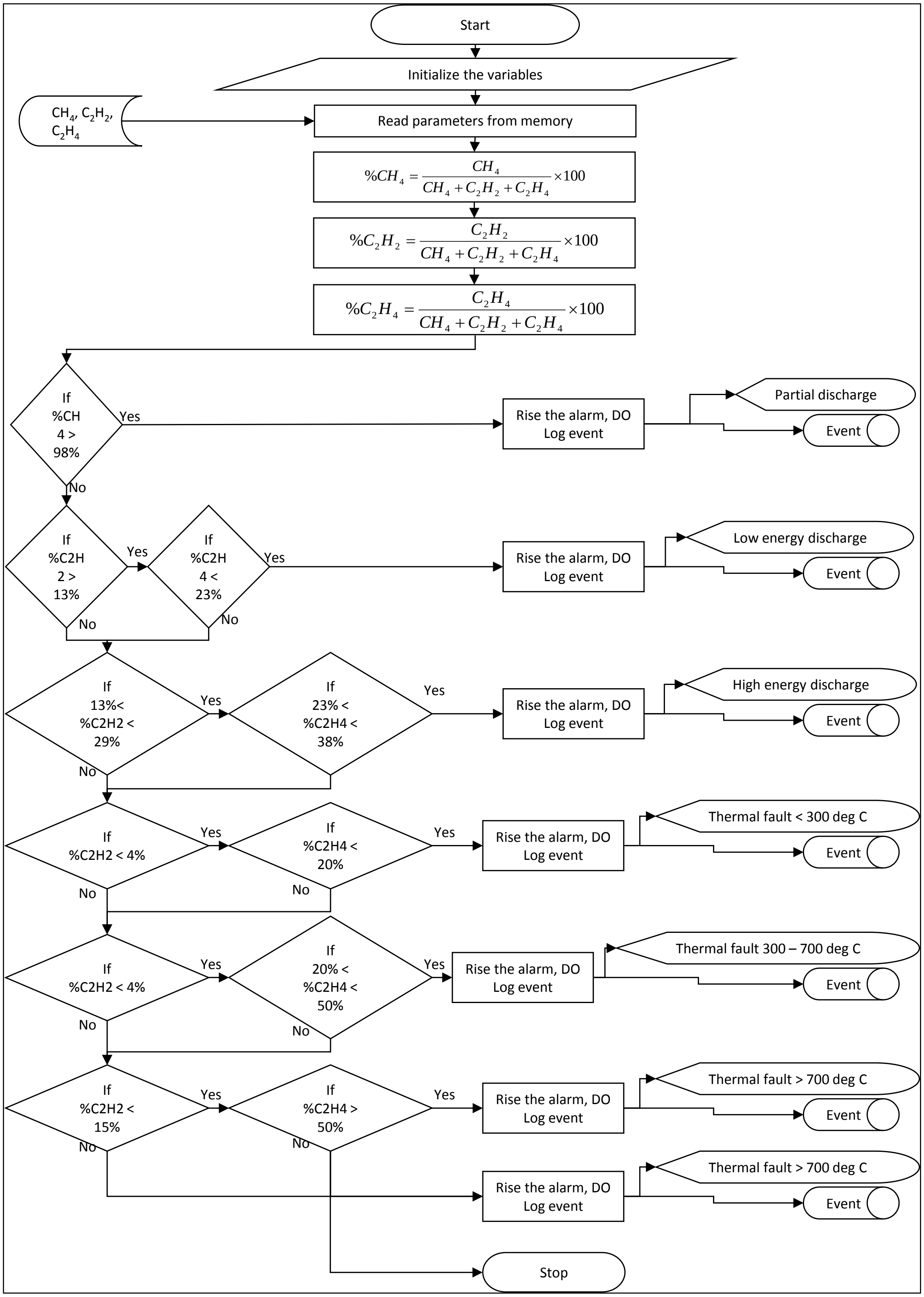


Figure 36 Flowchart For Gas State Analysis Using Duval’s Triangle

5.4.6 Alarms

Table 28: Gas Analysis Alarm Settings

Sl No	Alarm	Parameter	Setting	Message
1	NO	As per the analysis system and fault zone		NO Normal Operation
2	D1			D1 Low energy discharge
3	D2			D2 High energy discharge
4	DT			DT Thermal and electrical fault
5	T1			T1 Thermal Fault < 300 deg C
6	T2			T2 Thermal Fault 300 to 700 deg C
7	T3			T3 Thermal Fault > 700 deg C
8	PD			PD Partial discharge
9	Total dissolved combustion gas	TDCG	$TDCG_{th}$	TDCG exceeds alarm settings
	Hydrogen	H_2	H_{2th}	Gas exceeds alarm settings
	Methane	CH_4	CH_{4th}	Gas exceeds alarm settings
	Acetylene	C_2H_2	C_2H_{2th}	Gas exceeds alarm settings
	Ethylene	C_2H_4	C_2H_{4th}	Gas exceeds alarm settings
	Ethane	C_2H_6	C_2H_{6th}	Gas exceeds alarm settings
	Carbon Monoxide	CO	CO_{th}	Gas exceeds alarm settings
	Carbon dioxide	CO_2	CO_{2th}	Gas exceeds alarm settings

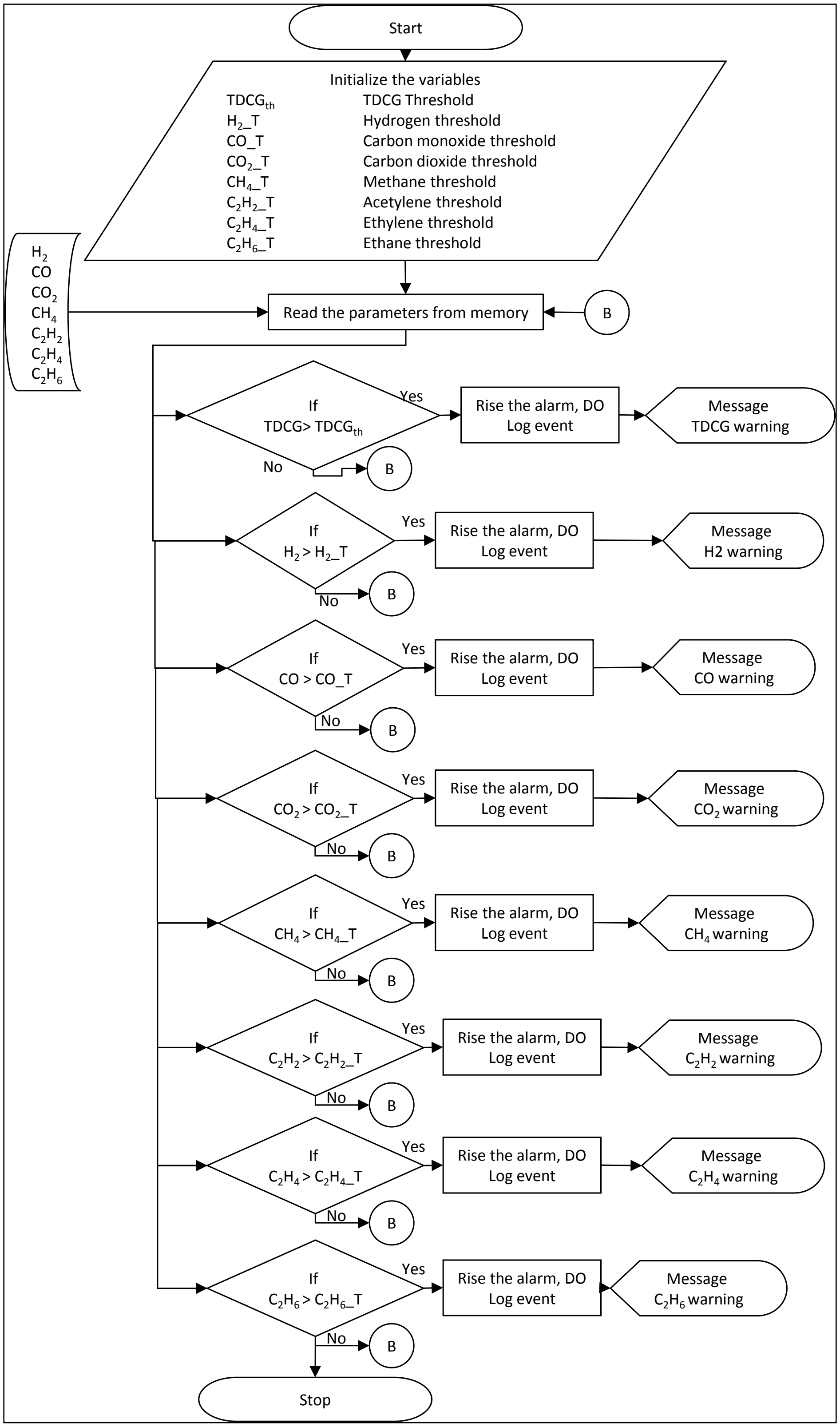


Figure 37 Flowchart For Gas Analysis Alarms

5.4.7 Moisture Analysis

The Moisture module measures the moisture content in transformer through sensor. The channel samples at 50 samples per second, the sampled values per second will be averaged to compute the Moisture value.

$$M_{avg} = \frac{M_1 + M_2 + M_3 + ... + M_n}{n}$$

Equation 19 Average Moisture

Where

M_{avg} - Average Moisture

M_1, M_2, M_3, M_n – Sampled values

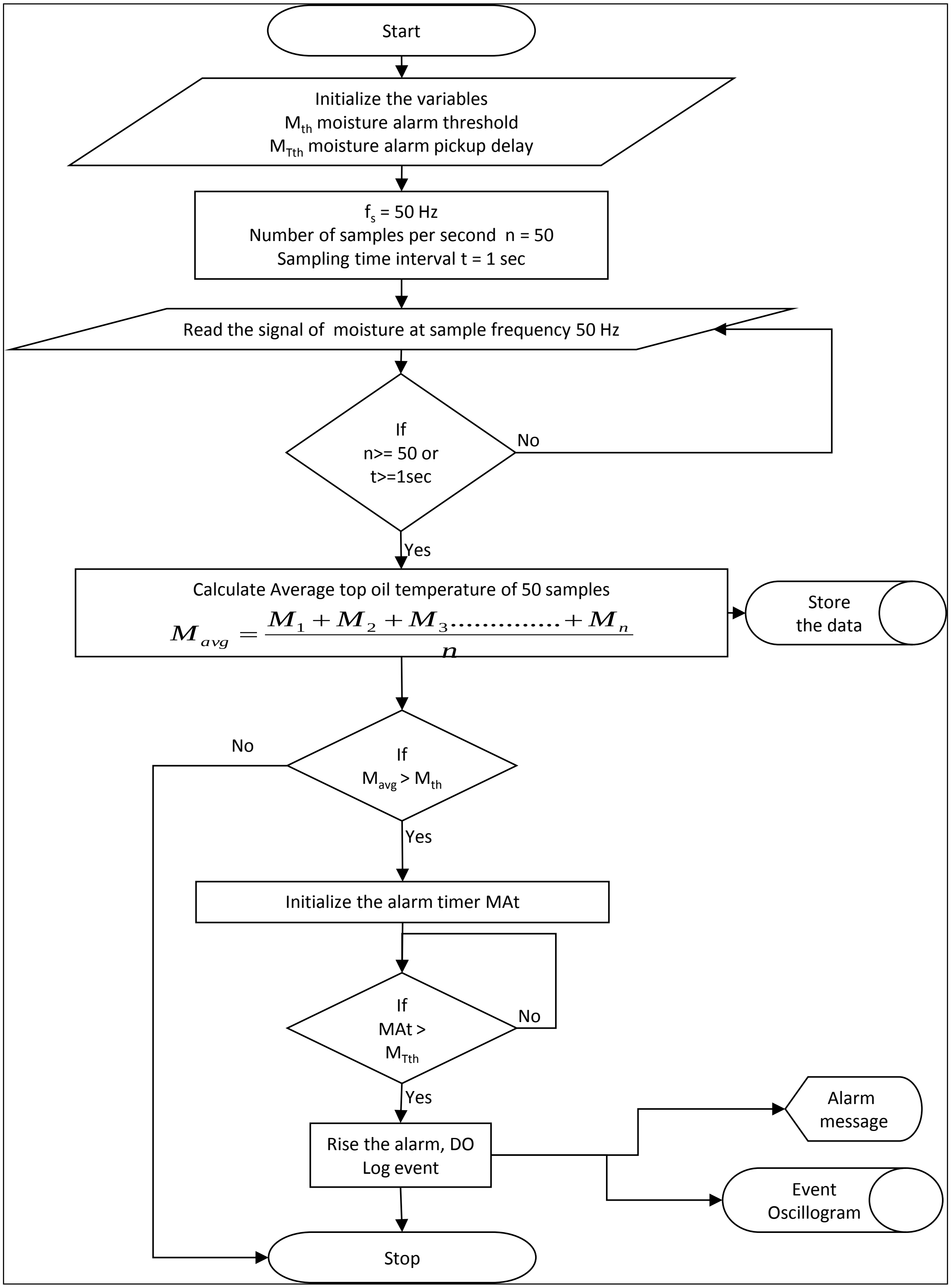


Figure 38: Flowchart For Moisture Analysis

5.5 Automatic Voltage Regulator

AVR module used to monitor and control OLTC automatically or manually from marshaling box/ remote location, it operates in 3 different modes. It monitors the tap position, tap voltage, and tap counter, tap counter per tap, cumulative tap counter, last tap operation duration, switching current during tap operation, cumulative switching current and inrush current interval.

Voltage regulation of transformers with on load tap changer is an important issue in transformers. According to DIN-IEC 38 the 230/ 400 V voltage in the public low voltage grid has to be kept constant with an accuracy of at least $\pm$ 10%. G-TMOC continuously compares the system voltage V_{actual} with a predefined desired voltage $V_{desired}$. Depending on the difference between actual and desired value, G-TMOC provides the actuating pulse for the OLTC of transformer if the actual value falls outside the predefined bandwidth $\pm$ B%. The voltage at the transformer is thus kept constant. Fluctuations with in the permissible bandwidth have no influence on the control response or the tap-change operation.

G-TMOC enables you to set and monitor the OLTC positions directly in automatic and manual mode.

5.5.1 Operating Modes

The operation of OLTC using AVR will be in two different modes, Automatic mode and Manual mode.

5.5.1.1 Automatic

If the Automatic mode is selected, the controller continuously monitors the tap step and voltage level, whenever the voltage level exceeds the bandwidth of predefined user set value AVR takes and raise or lower operation of tap step based on voltage level.

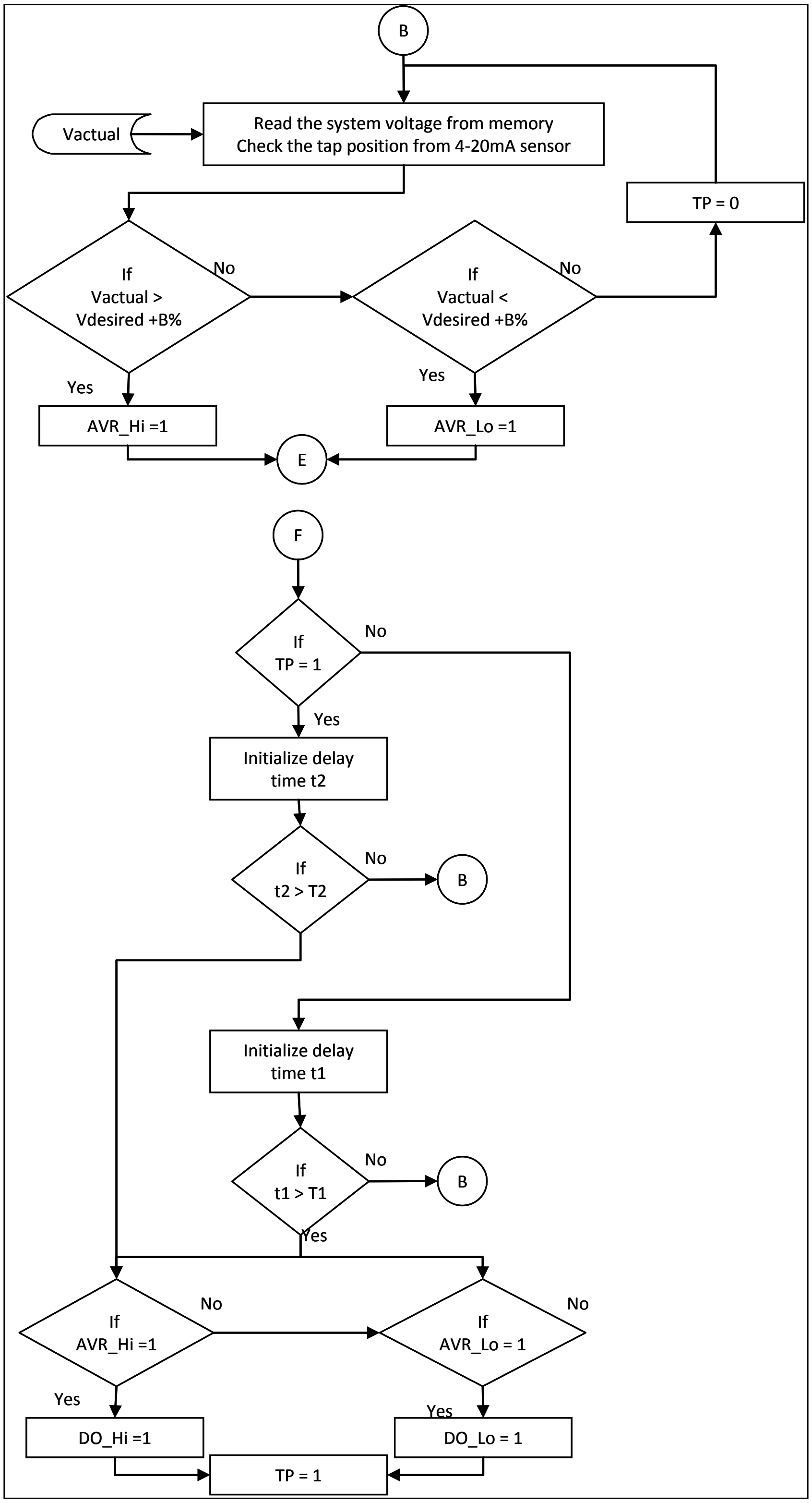


Figure 39: Flowchart For AVR Automatic Mode

5.5.1.2 Manual

If the manual mode is selected, AVR only monitors the tap step and voltage level and send the information to control room. If any tap operation is required than control person has to raise or lower the step from HMI or remote location depending on the voltage level.

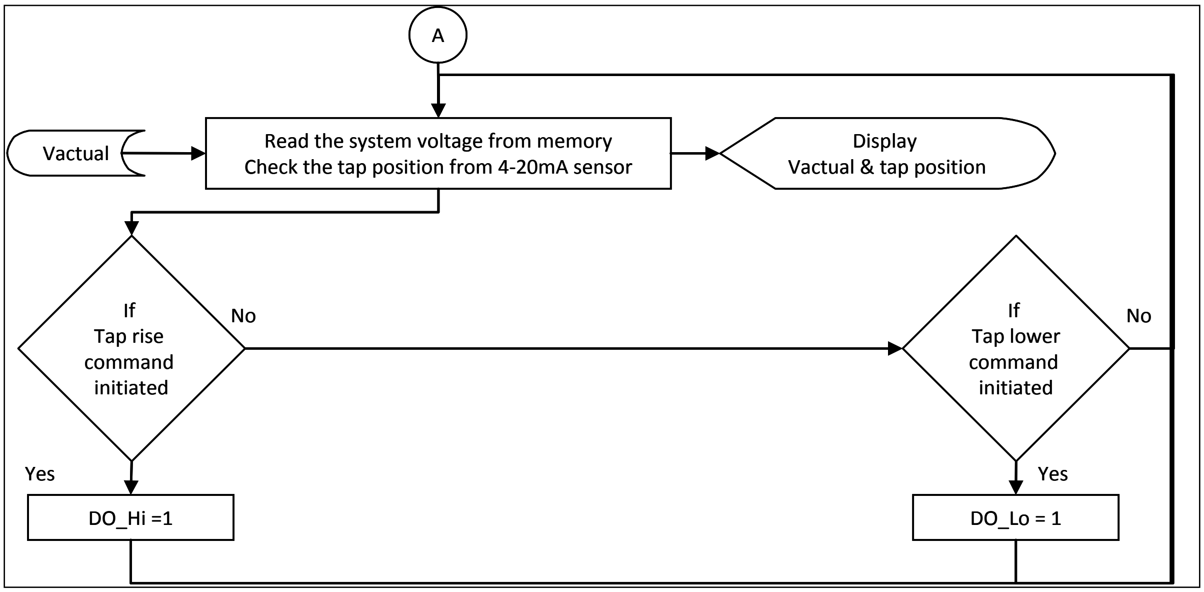


Figure 40: Flowchart For AVR Manual Operation

5.5.2 Parallel Operation

Transformer control is relatively clear and easy to handle. The situation is less clear if transformers are operated in parallel. Safe and economic parallel operation of transformers can only be ensured of their performance capability, i.e. their rated power, can be utilized fully and without overloading an individual transformer. on the primary side, the transformers must be connected to the same voltage, and the voltage on the secondary side must have the same magnitude and angle. Parallel operating transformers should be of same vector group, with comparable output, voltages, voltage ratios and short circuit impedance.

5.5.2.1 Master/ Follower

Master mode is a communication protocol based mode, whenever one controller set to Master mode, and others as followers, the controller takes on a master function. The regulator is assigned overall control while the other regulators execute its control commands.

Via the IEC-60870-5-101 protocol the master compares the tap position of the followers with its own tap position. If a tap position deviation is detected, the master ensures that the followers are brought to the same tap position.

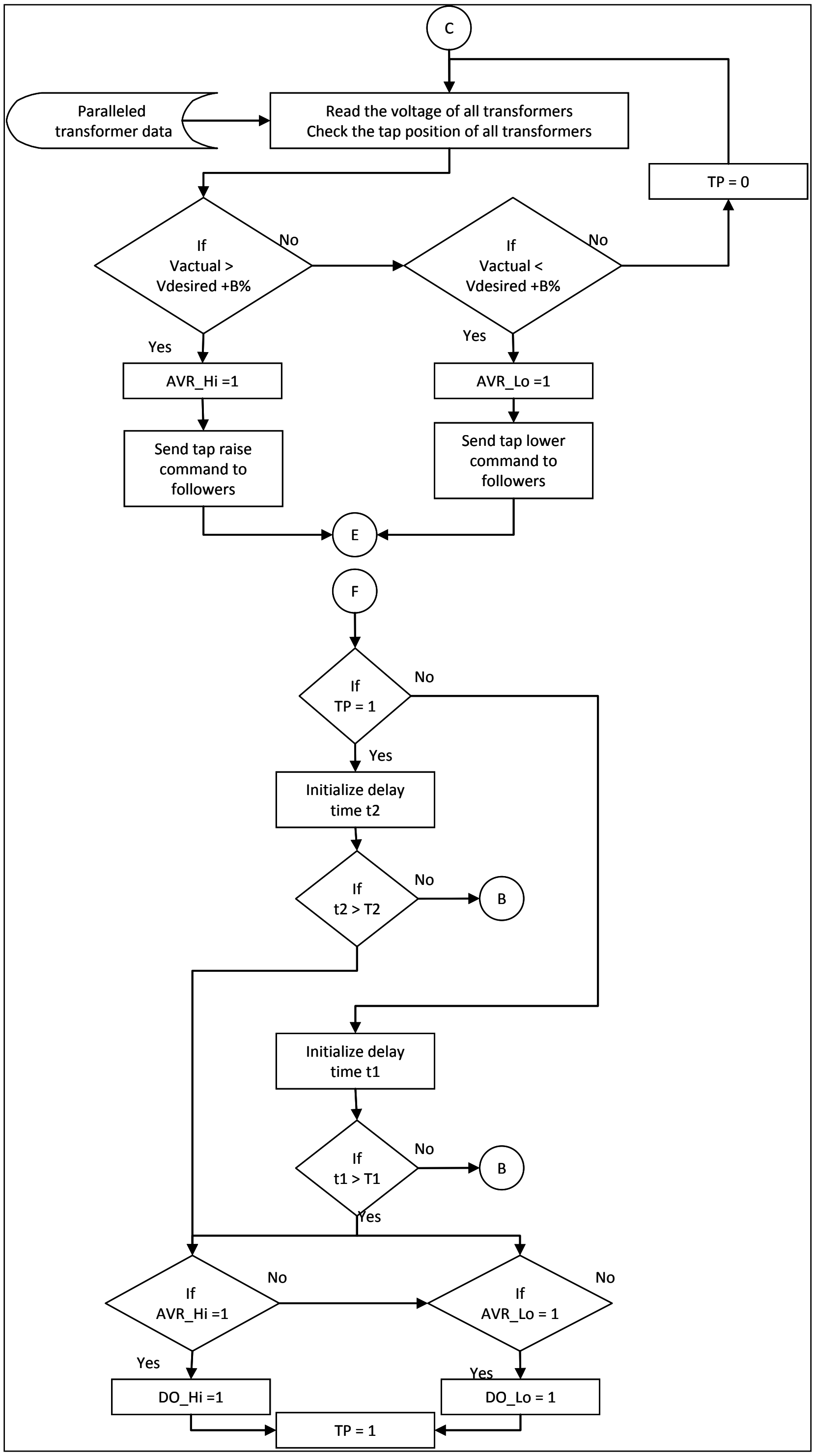


Figure 41: Flowchart For Master Mode Parallel Operation

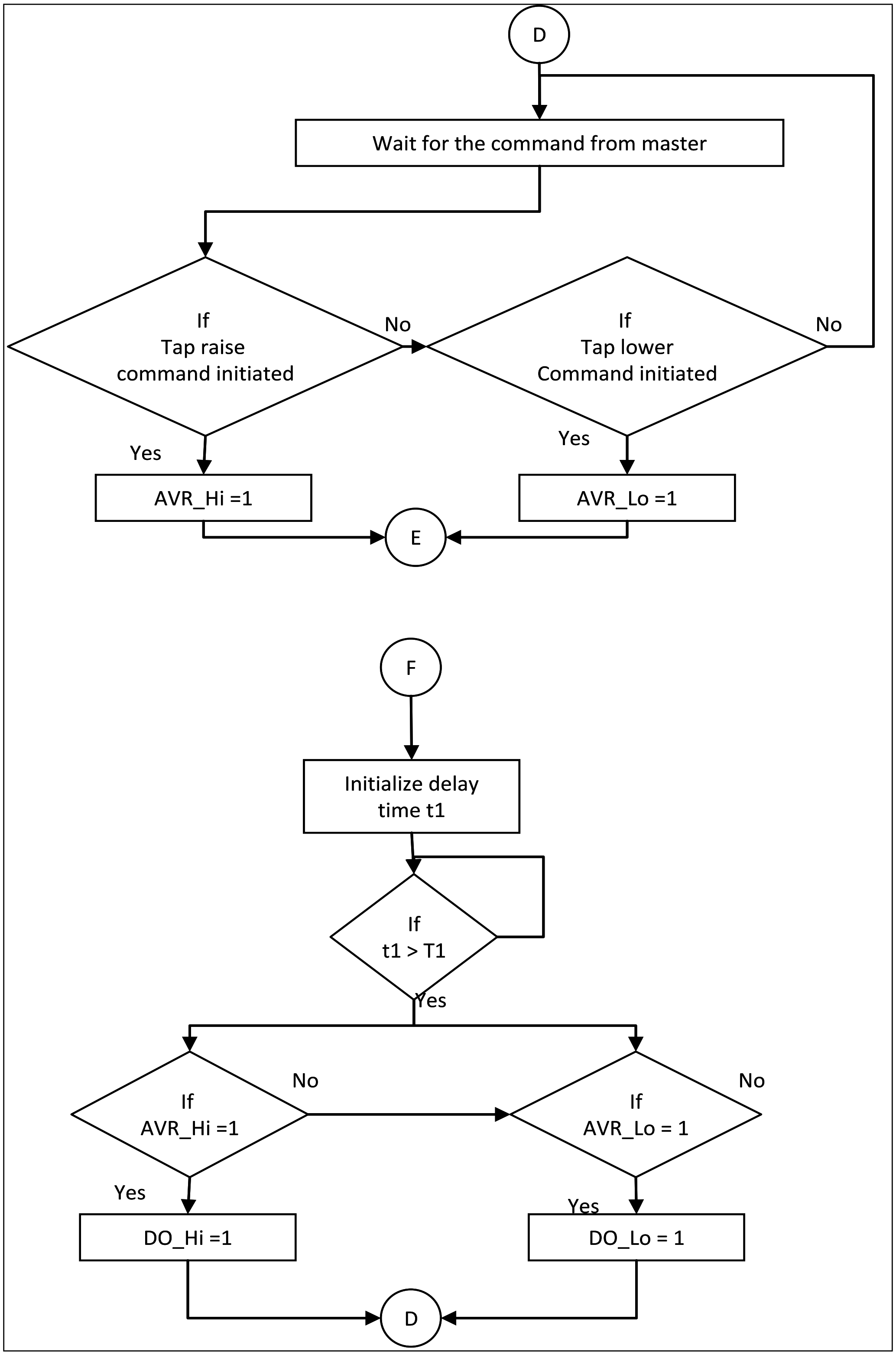


Figure 42: Flowchart For Follower Mode

5.5.3 Monitoring and Measurement

5.5.3.1 Desired Voltage

The desired voltage level is specified as a fixed value, the desired voltage level can be configured via user interface, voltage level can be set to kV or V. The desired voltage level can be set via standard protocols such as IEC-61850, IEC 60870-5-101, and DNP 3.0.

$$\Delta V = V_{actual} - V_{desired}$$

Equation 20 Regulation Deviation

Where

ΔV regulation deviation

V_{actual} actual system voltage measured

$V_{desired}$ Desired system voltage

5.5.3.2 Bandwidth

If the measured voltage i.e. the measured actual value falls outside the specified bandwidth, after the set delay time T1 an out put pulse is issued, and the OLTC switched up or down accordingly. The bandwidth, i.e. the positive and negative percentage deviation from the desired voltage level should be chosen such that the output voltage of the transformer does not exceed the specified bandwidth limits after the tap operation.

$$V_B = \frac{V_{desired} \times B\%}{100}$$

Equation 21 Bandwidth Voltage

Where

V_B bandwidth voltage

$V_{desired}$ desired system voltage

B% predefined bandwidth %

5.5.3.3 Delay Time T1

A violation of the specified bandwidth, in which case the duration of this time delay is specified via the delay timer parameter T1. A gradually filling time bar indicates the time left until the start of the control operation. If the deviation is still present after the delay time is elapsed an output pulse is issued, and the OLTC initiates a switching operation. If the deviation returns to within bandwidth limits during the delay time T1, the delay time is decremented. No tap changer operation occurs. The timer is not pre-set to 0 only decremented to ensure if the bandwidth exceeded regularly. Instead, the time already elapsed is used as a measure for the start of the subsequent delay time.

5.5.3.4 Delay time T2

In rare cases, more than one tap change operation is required for returning the transformer output voltage to within the specified bandwidth. However particularly with integral control response this would mean that the time until an output pulse is issued would increase with each tap change operation. This behavior can be counteracted by using delay time T2. the first output pulse is issued after specified time delay T1. Further pulses required for stabilization are issued after the specified delay time T2.

Chapter 6

6 RESULTS

6.1 CAN tested with all the cards communicating with each other

All the cards are put on the CAN bus with termination of 60E. All cards are communicating with each other perfectly data on the CAN high and low signal is captured by DSO.

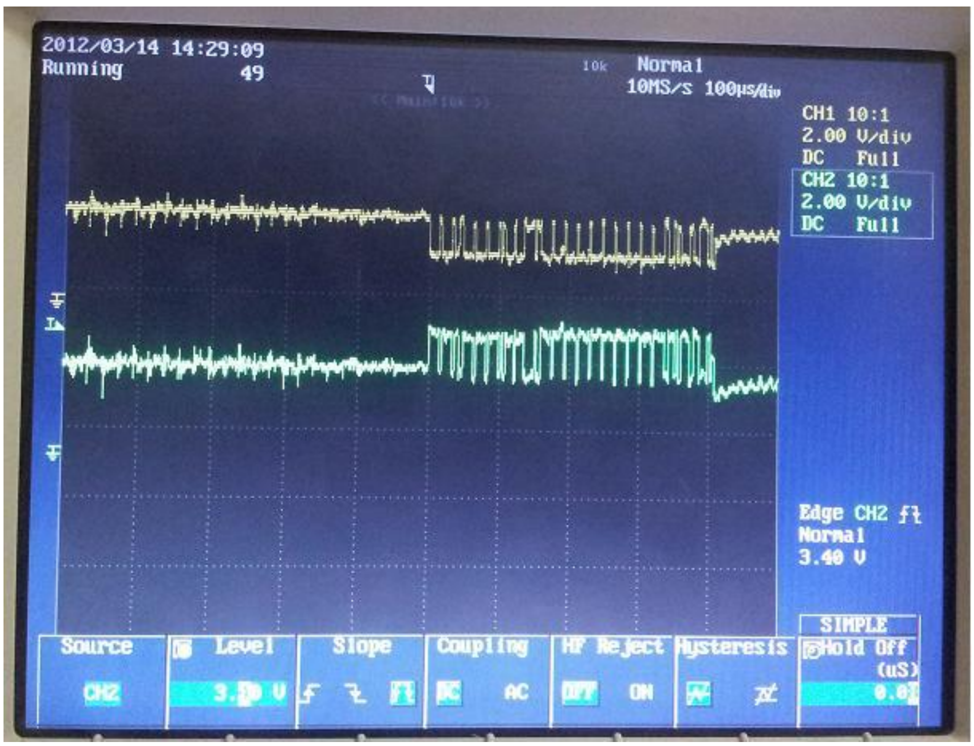


Figure 43: CAN Waveform

6.2 SPI Interface between AM1808 and dsPIC33F.

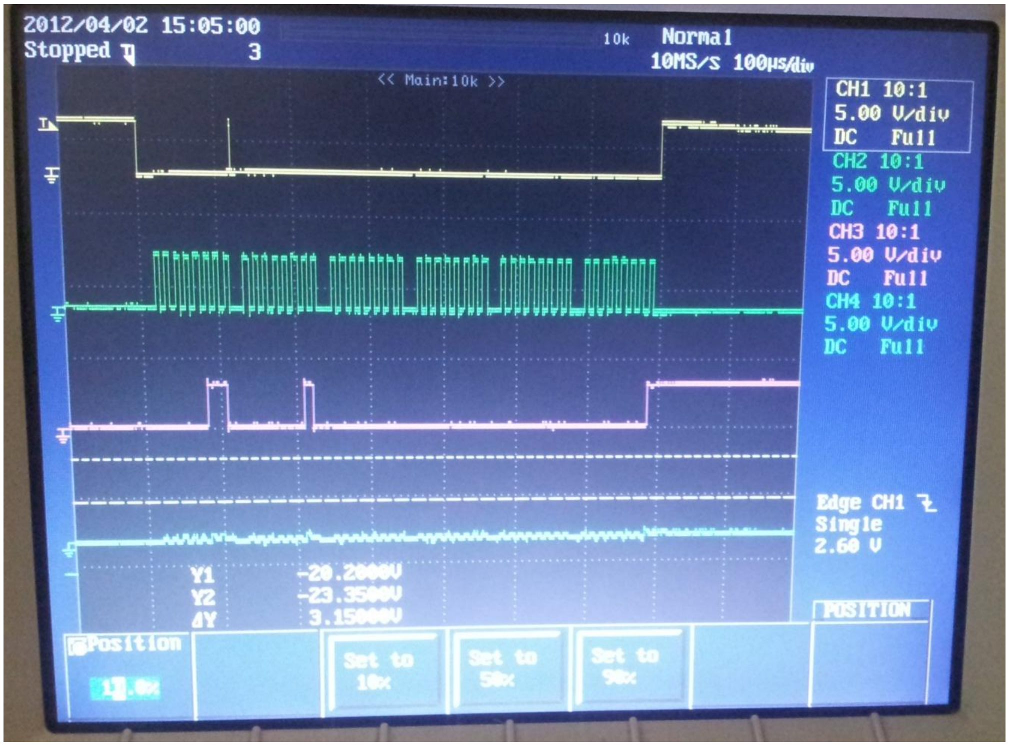


Figure 44: SPI Interface Waveform

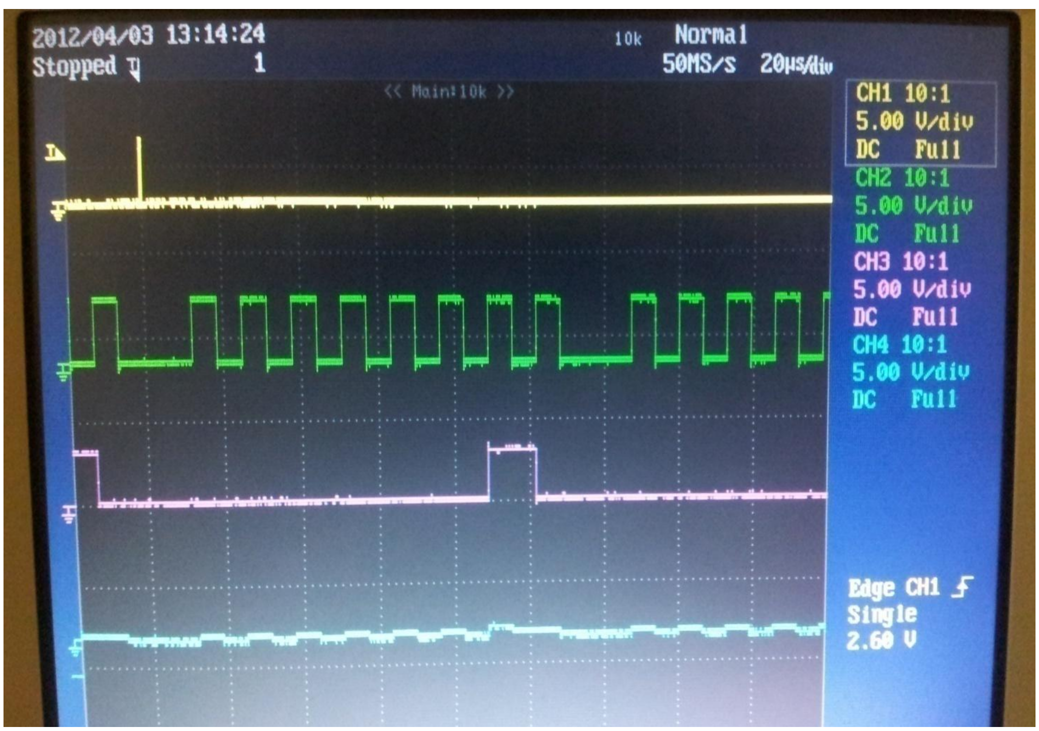


Figure 45: SPI Interface Waveform With MISO

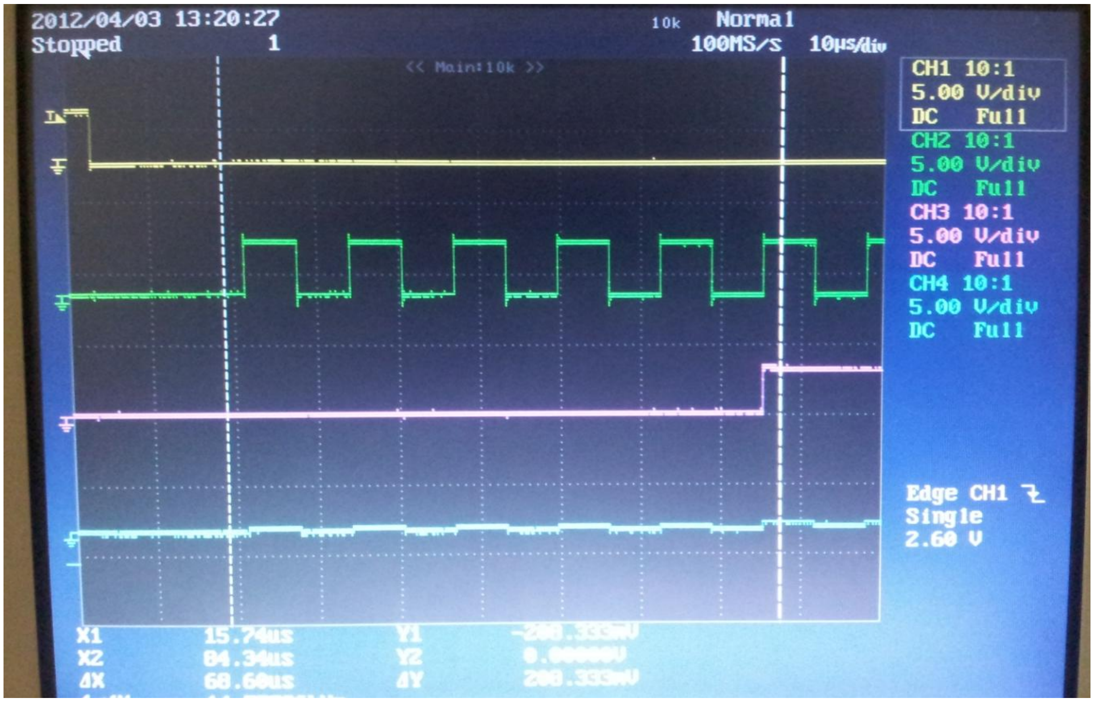


Figure 46: SPI Waveform Showing Data With Synchronized Clock Pulse

6.3 Calculated Results

Table 29 : Load Calculation Results For Star And Delta Configuration

Inputs				Star Configuration Outputs				Delta Configuration Outputs			
R Phase (A)	Y Phase (A)	B Phase (A)	Voltage (V)	Load Current (A)	Voltage (V)	Apparent Power (W)	% Utilization	Load Current (A)	Voltage (V)	Apparent Power (W)	% Utilization
27.5	27.5	27.5	420000	27.5	420000	20005186.83	10.00259341	47.63139721	420000	34650000	17.325
41.25	41.25	41.25	420000	41.25	420000	30007780.24	15.00389012	71.44709581	420000	51975000	25.9875
151.25	151.25	151.25	420000	151.25	420000	110028527.6	55.01426378	261.9726846	420000	190575000	95.2875
165	165	165	420000	165	420000	120031121	60.01556048	285.7883832	420000	207900000	103.95
178.75	178.75	178.75	420000	178.75	420000	130033714.4	65.01685719	309.6040819	420000	225225000	112.6125
192.5	192.5	192.5	420000	192.5	420000	140036307.8	70.0181539	333.4197805	420000	242550000	121.275
206.25	206.25	206.25	420000	206.25	420000	150038901.2	75.0194506	357.2354791	420000	259875000	129.9375
220	220	220	420000	220	420000	160041494.6	80.02074731	381.0511777	420000	277200000	138.6
233.75	233.75	233.75	420000	233.75	420000	170044088	85.02204402	404.8668763	420000	294525000	147.2625
247.5	247.5	247.5	420000	247.5	420000	180046681.4	90.02334072	428.6825749	420000	311850000	155.925
261.25	261.25	261.25	420000	261.25	420000	190049274.9	95.02463743	452.4982735	420000	329175000	164.5875
275	275	275	420000	275	420000	200051868.3	100.0259341	476.3139721	420000	346500000	173.25
288.75	288.75	288.75	420000	288.75	420000	210054461.7	105.0272308	500.1296707	420000	363825000	181.9125
302.5	302.5	302.5	420000	302.5	420000	220057055.1	110.0285276	523.9453693	420000	381150000	190.575
316.25	316.25	316.25	420000	316.25	420000	230059648.5	115.0298243	547.7610679	420000	398475000	199.2375

Table 30: Thermal Calculation Results

Inputs				Thermal Calculation		Life Calculation			
Ambient (^oC)	**Top Oil (^oC)**	**Bottom Oil (^oC)**	**Winding (^oC)**	**IEEE Hot Spot (^oC)**	**IEC Hot Spot (^oC)**	**Faa**	**IEEE_L**	**V**	**IEC_L**
20	20	20	20	20	20	0.001096271	0.001096271	5.96E-06	5.96E-06
20	20	20	20	20	20	0.001096271	0.002192542	5.96E-06	1.19E-05
20	20	20	20	20	20	0.001096271	0.003288812	5.96E-06	1.79E-05
20	20	20	20	20	20	0.001096271	0.004385083	5.96E-06	2.38E-05
20	20	20	20	20	20	0.001096271	0.005481354	5.96E-06	2.98E-05
20	20	20	20	20	20	0.001096271	0.006577625	5.96E-06	3.58E-05
20	20	20	20	20	20	0.001096271	0.007673896	5.96E-06	4.17E-05
20	20	20	20	20	20	0.001096271	0.008770167	5.96E-06	4.77E-05
20	20	20	20	20	20	0.001096271	0.009866437	5.96E-06	5.37E-05
20	20	20	20	20	20	0.001096271	0.010962708	5.96E-06	5.96E-05
20	20	20	20	21.26021119	239.5530491	0.001365011	0.012327719	19914.97897	19914.97903
20	20	20	20	22.03394641	374.3526189	0.00156025	0.013887969	8825832.992	8845747.971
20	20	20	20	22.50899868	457.1158694	0.001693128	0.015581098	122033556.3	130879304.2
20	20	20	20	22.80066779	507.9302426	0.001780028	0.017361125	464573011	595452315.2
20	20	20	20	22.97974464	539.1288785	0.001835487	0.019196612	1.36E+22	1.36E+22
20	20	20	20	23.08969294	558.283988	0.001870356	0.021066968	1.24E+23	1.37E+23
20	20	20	20	23.15719819	570.0447015	0.001892079	0.022959047	4.82E+23	6.20E+23
20	20	20	20	23.19864456	577.2654581	0.001905536	0.024864583	1.11E+24	1.73E+24
20	20	20	20	23.2240915	581.6988053	0.001913844	0.026778426	1.85E+24	3.58E+24
20	20	20	20	23.23971523	584.4207592	0.001918962	0.028697388	2.54E+24	6.12E+24
20	40	20	20	45.80934254	825.6450136	0.0691577	0.097855089	3.21E+36	3.21E+36
20	40	20	20	47.38702345	961.4706578	0.087188977	0.185044065	2.10E+43	2.10E+43
20	40	20	20	48.3556764	1044.86389	0.100403911	0.285447976	3.20E+47	3.20E+47
20	40	20	20	48.95040283	1096.065055	0.109445447	0.394893423	1.19E+50	1.19E+50
20	40	20	20	49.3155486	1127.50117	0.11537739	0.510270813	4.49E+51	4.60E+51
20	40	20	20	49.53973812	1146.802085	0.119170591	0.629441404	4.17E+52	4.63E+52
20	40	20	20	49.67738436	1158.65232	0.121558336	0.75099974	1.64E+53	2.10E+53
20	40	20	20	49.76189538	1165.928039	0.123046958	0.874046698	3.80E+53	5.90E+53
20	40	20	20	49.81378284	1170.395133	0.123969557	0.998016255	6.37E+53	1.23E+54
20	40	20	20	49.84564032	1173.137806	0.124539284	1.122555539	3.19317E+12	1.23E+54

20	40	20	20	53.35360693	1394.374781	0.205210905	1.327766444	1.26454E+13	1.23E+54
20	40	20	20	55.50740252	1530.208236	0.277378219	1.605144663	2.49024E+13	1.23E+54
20	40	20	20	56.82977413	1613.606263	0.333102036	1.938246699	3.597E+13	1.23E+54
20	40	20	20	57.64167414	1664.810372	0.372456923	2.310703623	4.43793E+13	1.23E+54
20	40	20	20	58.14015856	1696.248295	0.398781621	2.709485243	5.02168E+13	1.23E+54
20	40	20	20	58.44621436	1715.55032	0.415815618	3.125300862	5.40704E+13	1.23E+54
20	40	20	20	58.63412425	1727.401236	0.426616262	3.551917124	5.65415E+13	1.23E+54
20	40	20	20	58.74949579	1734.677374	0.433379863	3.985296987	5.80991E+13	1.23E+54
20	40	20	20	58.82033076	1739.144724	0.43758318	4.422880167	5.90709E+13	1.23E+54
20	40	20	20	58.8638215	1741.887555	0.440183176	4.863063343	5.96734E+13	1.23E+54
20	60	40	40	83.16269085	1983.124627	9.612972136	14.47603548	1.32277E+14	1.23E+54
20	60	40	40	85.80207911	2118.958141	13.10403773	27.58007321	1.92955E+14	1.23E+54
20	60	40	40	87.42259134	2202.356205	15.81383588	43.39390909	2.38349E+14	1.23E+54
20	60	40	40	88.41754155	2253.560336	17.73349753	61.12740662	1.41E+108	1.41E+108
20	60	40	40	89.02841377	2284.998273	19.01990903	80.14731565	5.31E+109	5.45E+109
20	60	40	40	89.40347262	2304.300307	19.853223	100.0005386	4.94E+110	5.49E+110
20	60	40	40	89.6337485	2316.151228	20.38194818	120.3824868	1.94E+111	2.49E+111
20	60	40	40	89.77513159	2323.427369	20.71318146	141.0956683	4.50E+111	6.99E+111
20	60	40	40	89.86193694	2327.894721	20.91908098	162.0147493	7.54E+111	1.45E+112
20	60	40	40	89.91523306	2330.637553	21.04646111	183.0612104	1.04E+112	2.49E+112
20	80	40	40	114.9170339	2571.874626	302.0631232	485.1243336	1.31E+124	1.31E+124
20	80	40	40	117.9880029	2707.70814	409.2596226	894.3839562	8.58E+130	8.58E+130
20	80	40	40	119.8734939	2791.106204	491.9952847	1386.379241	1.31E+135	1.31E+135
20	80	40	40	121.0311338	2842.310336	550.3972905	1936.776531	4.86E+137	4.87E+137
20	80	40	40	121.741893	2873.748273	589.4467918	2526.223323	1.84E+139	1.88E+139
20	80	40	40	122.1782798	2893.050306	614.7074665	3140.93079	1.71E+140	1.90E+140
20	80	40	40	122.4462093	2904.901227	630.7213382	3771.652128	6.71E+140	8.61E+140
20	80	40	40	122.6107108	2912.177369	640.7483713	4412.400499	1.56E+141	2.42E+141
20	80	40	40	122.7117101	2916.644721	646.979312	5059.379811	9.25886E+14	2.42E+141
20	80	40	40	122.773721	2919.387553	650.8333308	5710.213142	9.29635E+14	2.42E+141
20	100	60	60	148.417588	3160.624626	6532.534082	12242.74722	1.29E+15	2.42E+141
20	100	60	60	162.9606143	3296.45814	3249.121779	15491.869	1.53E+15	2.42E+141
20	100	60	60	171.8896349	3379.856204	6481.392578	21973.26158	1.68E+15	2.42E+141
20	100	60	60	177.3718095	3431.060336	9770.307503	31743.56908	1.78E+15	2.42E+141
20	100	60	60	180.7377148	3462.498273	12508.59822	44252.16731	1.84E+15	2.42E+141
20	100	60	60	182.8042886	3481.800306	14531.25019	58783.41749	1.88E+15	2.42E+141

20	100	60	60	184.0731084	3493.651227	15921.26163	74704.67913	1.90E+15	2.42E+141
20	100	60	60	184.8521291	3500.927369	16835.56073	91540.23986	1.92E+15	2.42E+141
20	100	60	60	185.3304265	3505.394721	17421.10283	108961.3427	1.93E+15	2.42E+141
20	100	60	60	185.624088	3508.137553	17790.02677	126751.3695	1.93E+15	2.42E+141
20	120	60	60	215.1004645	3749.374626	128224.7158	254976.0852	2.45E+15	2.42E+141
20	120	60	60	220.9187006	3885.20814	184157.6345	439133.7197	2.77E+15	2.42E+141
20	120	60	60	224.4909385	3968.606204	229031.5167	668165.2363	1.57E+194	1.57E+194
20	120	60	60	226.6841949	4019.810336	261439.3399	929604.5763	5.80E+196	5.82E+196
20	120	60	60	228.0307944	4051.248273	283406.7057	1213011.282	2.19E+198	2.25E+198
20	120	60	60	228.8575696	4070.550306	297735.1137	1510746.396	2.04E+199	2.26E+199
20	120	60	60	229.365187	4082.401227	306864.3085	1817610.704	8.02E+199	1.03E+200
20	120	60	60	229.6768503	4089.677369	312598.0872	2130208.791	1.86E+200	2.89E+200
20	120	60	60	229.8682029	4094.144721	316167.8314	2446376.623	3.11E+200	6.00E+200
20	120	60	60	229.9856883	4096.887553	318378.3621	2764754.985	4.27E+200	1.03E+201
20	140	60	60	260.1879287	4338.124626	1724155.513	4488910.498	5.42E+212	5.42E+212
20	140	60	60	266.4518253	4473.95814	2390261.016	6879171.514	3.54E+219	3.54E+219
20	140	60	60	270.2976866	4557.356204	2910235.366	9789406.881	5.41E+223	5.41E+223
20	140	60	60	272.6589403	4608.560336	3279556.954	13068963.83	2.01E+226	2.01E+226
20	140	60	60	274.1086856	4639.998273	3527365.863	16596329.7	7.58E+227	7.78E+227
20	140	60	60	274.9987895	4659.300306	3687999.062	20284328.76	7.05E+228	7.83E+228
20	140	60	60	275.545289	4671.151227	3789955.543	24074284.3	2.77E+229	3.55E+229
20	140	60	60	275.8808247	4678.427369	3853841.964	27928126.27	4.93E+15	3.55E+229
20	140	60	60	276.0868345	4682.894721	3893559.496	31821685.76	4.95E+15	3.55E+229
20	140	60	60	276.2133189	4685.637553	3918132.582	35739818.35	4.96E+15	3.55E+229
20	200	80	80	336.2909768	4747.321577	57894832.52	93634650.86	5.14E+15	3.55E+229
20	200	80	80	353.1638547	4748.355521	112394639	206029289.9	5.15E+15	3.55E+229
20	200	80	80	363.5233405	4748.990335	165984233.3	372013523.2	5.15E+15	3.55E+229
20	200	80	80	369.8837815	4749.380093	209566434.7	581579958	5.15E+15	3.55E+229
20	200	80	80	373.7889184	4749.619394	241269684.6	822849642.5	5.15E+15	3.55E+229
20	200	80	80	376.1865657	4749.766318	262846103.3	1085695746	5.15E+15	3.55E+229
20	200	80	80	377.6586556	4749.856526	276952154.3	1362647900	5.15E+15	3.55E+229
20	200	80	80	378.5624786	4749.911911	285951952.2	1648599852	5.15E+15	3.55E+229
20	200	80	80	379.1174011	4749.945916	291609077.5	1940208930	5.15E+15	3.55E+229
20	200	80	80	379.4581084	4749.966794	295132836.2	2235341766	5.15E+15	3.55E+229

7 REFERENCES

[1] C. Bengtsson, "Status and Trends in Transformer Monitoring", *IEEE Transactions on Power Delivery,* July 1996, Vol. 11, No. 3, p. 1379-84.

[2] J. Reason, "On-line Transformer Monitoring", *Electrical World*, October 1995, Vol. 209, No. 10, p. 19-20.

[3] Syprotec, Inc., *Instruction Manual Version 2.11*, Hydran® 201i System, June 1995.

[4] C. Bengtsson, "Status and Trends in Transformer Monitoring", *IEEE Transactions on Power Delivery*, July 1996, Vol. 11, No. 3, p. 1379-84.

[5] Performance Based Monitoring and Control: Off-Line Model-Based Analysis of Transformer Data, *LEES Technical Report, TR 96-001, Massachusetts Institute of Technology*, Cambridge, MA, July 15, 1996.

[6] C. Bengtsson, "Status and Trends in Transformer Monitoring", *IEEE Transactions on Power Delivery*, July 1996, Vol. 11, No. 3, p. 1379-84.

[7] M. Domun, "Oil Analyses as a Condition Monitoring Technique", *IEE Colloquium, IEE Science, Education and Technology Division Colloquium on Monitoring Technologies for Plant Insulation*, London, UK, Nov. 22, 1994, Num. 227.

[8] F. Li, Z. Qi, H. Huang, "On-line Monitoring of the Static Electrification in Power Transformer", 1996 Asian *International Conference on Dielectrics & Electrical Insulation Diagnosis*, 1996 AICDEI & 4th JCCEID, Oct, 8-11, 1996, p. 397-400.

[9] C. Bengtsson, "Status and Trends in Transformer Monitoring", *IEEE Transactions on Power Delivery*, July 1996, Vol. 11, No. 3, p. 1379-84.

[10] *ieeexplore.ieee.org/iel1/24/9132/00406570.pdf?arnumber=406570*
by J Mi - 1995

[11] http://www.wtc.com.au/OBU/dynamic_ratings.aspx

[12] www.gedigitalenergy.com/MD/catalog/**intellixmo150**.htm

[13] www05.**abb**.com/global/.../1zsc000857-abk%20en%20rev%201.pdf

[14] www.alstom.com/grid/**MS3000**/

[15] M.F.Barnes, "QualiTROL SENTRY Transformer Monitoring System", IEE Colloquium on Monitors and Condition Assessment Equipment, Leatherhead, UK, December 5, 1996.

[16] QualiTROL CORPORATION, SENTRY Substation Transformer Monitors, "New *Product Release*", 1385 Fairport Road, Fairport, New York, 14450.

[17] http://qualitrolcorp.thomasnet.com/compare/intelligent-transformer-monitors/qualitrol-509-itm-intelligent-transformer-monitors?bc=100|1003|1054|1059&forward=1&itemids=1100+1109+1110+1111+

[18] Ron Cytron, ‘‘Doacross: Beyond Vectorization for Multiprocessors (Extended Abstract),’’ *International Conference on Parallel Processing*, pp. 836-844, 1986.

[19] SIM18 datasheet

[20] C. Summereder, M. Muhr and B. Körbler, “Life Time Management of Power Transformers”, *e & i Elektrotechnik und Informationstechnik*, 120(12):420-423, 2003

[21] L.M. Geldenhuis, “Power Transformer Life Management”, *CIRED 18th International Conference on Electricity Distribution*”, Turin, Italy, 2005.

[22] R. R. Rogers, "Concepts Used in the Development of the IEEE and IEC Codes for the Interpretation of Incipient Faults in Power Transformers by Dissolved Gas in Oil Analysis", *Technical Report, Central Electricity Generating Board*, Transmission Development and Construction Division, Guilford, England.

[23] R. R. Rogers, "IEEE and IEC Codes to Interpret Incipient Faults in Transformers, Using Gas in Oil Analysis", *IEEE Transactions on Electrical Insulation*, Vol. EI- 3, No. 5, pp. 349-354, October 1978.

[24] M. Duval, “The Duval Triangle for Load Tap Changers, Non-Mineral Oils and Low Temperature Faults in Transformers,” *IEEE Electrical Insulation Magazine*, Vol.24, No6, 2008.