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HIF & LIF ARC FAULT DETECTOR POINT SENSOR MODULE

Combined High Impedance and Low Impedance Arc Fault Detection System

Technology

2014

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ABSTRACT

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Low and medium voltage switchgears are usually protected from low impedance (high current) arc fault incidents using varies standard detection technologies. Currently, over-current plus light detection method is widely implemented system due to its performance in speed and security. However, because it’s not always possible to implement this method especially in existing installations, a demand exists for other standalone technologies with similar or better performance. On the other hand, any of these standard protection devices are not capable of detecting high impedance (low current) arc faults, and available technologies to recognize such low current faults entirely rely on determination of current signal signature and hence are subjected to risk of false positives due to load conditions which creates similar current signal characteristics.

In an attempt to produce possible alternative, a new approach was taken to develop an arc fault detection point sensor module capable of detecting both low and high impedance arc faults with an adequate performance in speed and security. This was done, by implementing a low field (high sensitive) on board magnetic field sensor to recognize strong magnetic field presented during high current fault condition in the vicinity of the fault point. In addition, a software algorithm was developed to identify arc signature through the measured light signal by adapting previously developed high impedance arc fault current signal pattern recognition approaches.

The paper focuses on the development of the prototype module. Accordingly, necessary backgrounds to support understandings about basic ideas and objectives used for implementation are provided, also the system design details and validation test results are discussed.

Keywords Arc Fault detection, High impedance, Low impedance

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ABBREVIATIONS

HIF High impedance fault

LIF low impedance fault

CT current transformer

DSP digital signal processing unit

LV low voltage

MV medium voltage

1 INTRODUCTION

An arcing fault is a type of electrical fault which occurs when current flows through air medium between phase conductors, phase to neutral, phase to ground, or within the same phase conduction path when an air gap is introduced due to contamination or loss connection.

In electrical power substation the fault can be the most devastating event. It might cause safety hazard to operation personnel through radiation, thermal convection, arc blast, flying particles, and toxic impact. In addition, the economic consequences can be very significant. Depending on the strength and duration of the arc, one field or the entire substation can be affected. That is, in spite of the direct maintenance cost imposed to the utility, the failure of the power distribution can create significant indirect costs. Moreover, it may also happen that because of the strong release of heat energy the entire substation could be damaged and has to be replaced completely.

Arc fault prevention is naturally the primary objective. Different prevention systems and guidelines has been put forth by varies institutions. However, arc faults are still present in accident statistics. It is thus, a vital investment for an electrical utility to employ both arc flash prevention and protection mechanisms as a part of a complete safety program.

Among the number of technologies introduced for mitigation of arc fault impacts includes: reducing arc time, personal protective equipment, encapsulating arc-flash energy in arc resistant enclosures and channel the energy where it is less dangerous. Currently, the most feasible and effective mitigation option is to reduce the arcing time via a fast protection system. Within the past decade considerable advancement has been achieved in this area. Today, protection devices can operate within 1-2ms and isolate the faulty zone selectively depending on the speed of the breaker operating time. In addition, quenching devices which divert the arc energy into a bolted fault until the breaker operates, makes it possible to reduce the arcing time by a factor of ten, resulting in significant reduction of the incident energy as well as the extent of the damage.

1.1 Problem Statement

The speed and security performance of an arc fault protection systems is influenced by the mechanism employed on the detection devices. Different arc fault detection approaches has been compared in varies research papers, the fastest possible protection achieved so far is by using optical detection system [1],[2],[8]. The use of light only sensory mechanism will reduce the system security due to possible risk of nuisance tripping via changing ambient light condition. For this reason most protection devices employ dual-sensing principle. Among these alternatives the most widely accepted system is light plus over current detection system due to its moderate price and superior performance in terms of speed and security. However, it is not always possible to implement this particular system in all situations especially in existing installations due to lack of current transformers and also in new installations when current transformers are required for other purpose. For this reason power system engineers show interest into other standalone sensor modules, such as pressure plus light with reduced speed performance. In addition to this, despite the fact it is mostly accepted that low current arc faults can exist in switchgear due to contact interruption in the bus-bar or due to contamination of insulation material [3],[4], the field is rarely addressed and widely used detection systems are not designed to detect such low current faults. In general, although different systems already exist to address the problem, none of these systems has provided a complete solution for all situations.

Throughout the years, a number of researches have been done separately addressing both low impedance (high current) and high impedance (low current) faults, which provide notable insight about the physical characteristic and signatures presented during the fault condition. In addition, alternative methods to improve the existing detection mechanism have been introduced. The scope of this thesis is to build on these previous studies by applying today’s new technology and see if any advancement can be made with new sensors and algorithms to produce an improved standalone complete arc fault detection system.

1.2 Arcteq Oy

Arcteq Oy is a Finnish Company offering a wide range of power system protection devices for high-voltage transmission, sub-transmission and medium voltage distribution systems. The company is headquartered in Vaasa, Finland with research development centers based in Finland and Poland. In addition, currently the company operates in over 40 countries world-wide, via local offices and a partner network.

The development teams at Arcteq are manly consists of industry experts with decades of experience in protection relay platform, and as per ISO 9001:2009, ISO 14000 all products are continuously upgraded based on customer feedback as well as scheduled internal procedures. Main product lines provided by Arcteq include:

AQ100 Series Relays: Arc protection relays designed with special focus on simplicity while maintaining both flexibility and functions. Suitable for LV and MV switchgear and control-gear applications as standalone or for varies AQ100 standard arc schemes (AQ-SAS).

Figure 1. AQ100 Series Relays

AQ200 Series Relays: Medium voltage or back-up high voltage: protection, control and monitoring application IEDs. These devices integrate protection control, monitoring, communication and extensive diagnostics information in a compact package with fully modular hardware construction which is easily customizable for different application needs.

Figure 2. AQ200 Series Relays

AQ300 Series Relays: Medium voltage feeder protection and high voltage line, bus-bar and transformer protection application. These devises include a wide range of protection functions also additional control, measurement, and monitoring features.

Figure 3. AQ300 Series Relays

Arc flash sensors: Arcteq provides different types of Arc fault Sensors to be used in different situations according to specific application requirements. Basic sensor types include: Arc light only point sensors, Pressure plus light point sensors and arc light fiber optic loop sensors.

Figure 4. Arc flash sensors

AQ-SIM F215 simulator: Feeder protection simulator unit suitable for basic hands-on training including most demanding application specific trainings and simulations. Different fault types and protection stages can be simulated, including sequence protections functions, directional protection functions, auto-reclosing, circuit breaker failure protection and fast acting arc protection along with other AQ F215 functions. In addition, the simulator can be connected to the substation automation/SCADA system using AQ F215 feeder protection IED's and built in breaker and disconnector or switches allow for full control system simulations.

Figure 5. AQ-SIM F215 simulator

Arcteq also provides a full range of services to its customers via skilled staff and global network of partners. The services include: power system protection training courses, power system simulations, short-circuit analysis, protection setting calculations and arc flash hazard calculation (according to IEEE 1584).

2 LITERATURE REVIEW

This chapter provides the reader with background information, which is considered necessary to support the discussion within the presented document and helps to understand the basic idea behind the development made as part of this thesis work.

2.1 Types of Arc fault

2.1.1 Low impedance faults

Low impedance faults are usually the result of short circuit between phase conductors or phase to neutral or ground having different potential that is enough to maintain current flow through a medium in between.

Often the fault is initiated when a foreign conducting object is introduced between the two potentials, though it could also be started due to insulation failure. The high heat energy release causes the surrounding air to ionize setting-up plasma formation which is able to conduct arc current. Depending on the available energy a very high current could be drawn to the fault point and establish a plasma channel between the two potential with a very low impedance current path for the arc to reignite easily every cycle.

Since the energy involved in this state is very high, this kind of fault creates easily recognizable abnormal physical phenomena, such as:

- Over current
- Strong magnetic field
- Rise in temperature,
- High intensity luminous discharge,
- Pressure rise,
- and explosive sound,

Most current available arc fault detection systems use two or more of the above physical phenomena to safely recognize this type of faults. The speed at which these physical phenomena appear is in the order listed. However, the sensing technology affects the time it takes for the protection device to recognize the event. For instance, most light sensors (e.g. photodiodes) have a rise time in nano-second range, whereas temperature sensors (e.g. thermopiles) have a time constant in tenth of millisecond.

2.1.2 High impedance faults (HIF)

The main difference between an arc fault of this kind and the other type discussed in the previous section is that the arc current is limited by impedance introduced within the current path. Usually the fault appears as series arc fault type, an arc fault category where the load impedance is limiting the arc current. However, it can also appear as a parallel arc fault type between two phases or phase to ground when sufficient impedance is introduced within the current path. Despite the fact that there is no official statics available about how often this type of fault occurs, research papers suggest that series arc faults occur more often than parallel faults (LIF is usually parallel) [3],[4].

The fault can be initiated due to a loosened screw or rivet connections in an electrical bus-bar and or due to contamination of insulation material. Then the failure can result in a local heating-up of the bus-bar material and insulation material creating local carbonization and low current arcing. After a certain time this process can develop into low impedance fault scenario and may create a larger damage.

The only abnormal physical phenomena formed by this type of faults are temperature rise and flashing light which is presented only at the fault point. The fault current is within the range of rated value. Hence, protection device that uses fault current as criteria will not recognize the event as a valid fault condition. As a result, the arc may burn for too long before thermal safety devices or protection relays recognize the fault and cut off the current supply. Therefore, these kinds of faults are considered especially dangerous because it might involves worst-case incident energy [1],[8].

Although, infrared cameras and light sensors could be used to recognize hot spots or changing light conditions, the systems are not widely implemented on protection devices due to cost or security reasons. Hence, the detection of high impedance faults on electrical distribution systems has been one of the most challenging problems facing the industry. However, recent advancement in digital technology sets practical solutions for the problem by using signal recognition software which identifies special current signal characteristics in time domain or frequency domain to recognize an arc fault form other load condition.

Figure 6 Illustrates a time domain characteristic of arc current signal which is widely regarded as signature of high impedance arc fault [3] [4] [5] [6] [7]. Thus, initially the arc is ignited at the highest current density level (point 1), then interrupted as the driving voltage drops below the breakdown value of the electrode gap (point 2) and reignite after zero cross when the required ignition voltage is reached (point 3). In between there is a short dead time where no relevant current flows through the air gap. This is well known phenomenon termed as arc extinguishing after current zero [6], shouldering phenomenon or zero Hugh [5] and it exists in all voltage levels. The duration of the current gap mostly depends on the electrode gap and on the condition of the plasma between the electrodes. Thus the property may blur or occasionally absent if conductive path forms which prevents current interruption and arc re-ignition (point 4).

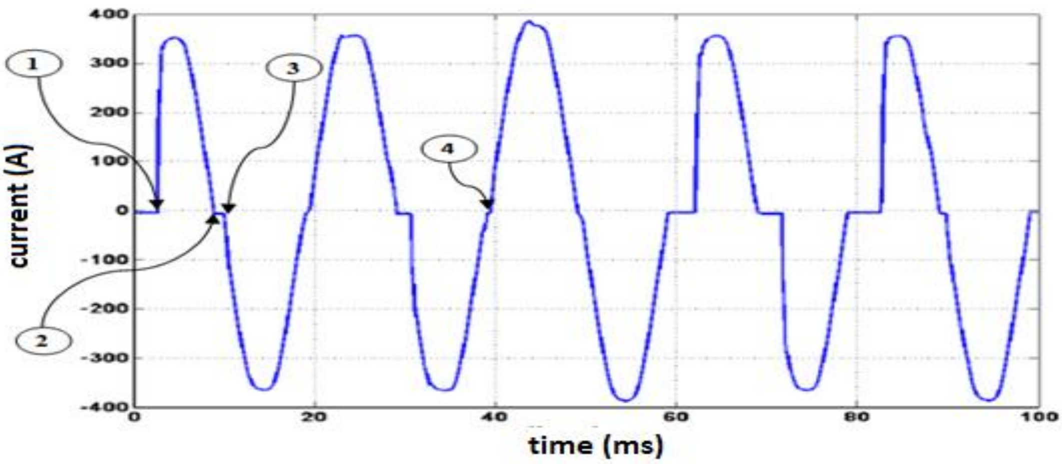

Figure 6. Typical arc current time domain characteristic

For reasons described above, the frequency spectrum translation of the arc current may not have similar property in frequency domain for all cases. However, several papers suggest that the elevated 3rd harmonic as a relevant indicator for both series and parallel type faults. Another arc fault current signature is that in the range of 2 to 5 kHz the arc current spectrum is slightly increased due to the rising current edge after the arc re-ignition and somehow forms an elevation. A typical case frequency distribution of arc current copied from [4] is illustrated in Figure 7 & Figure 8 to support the discussion.

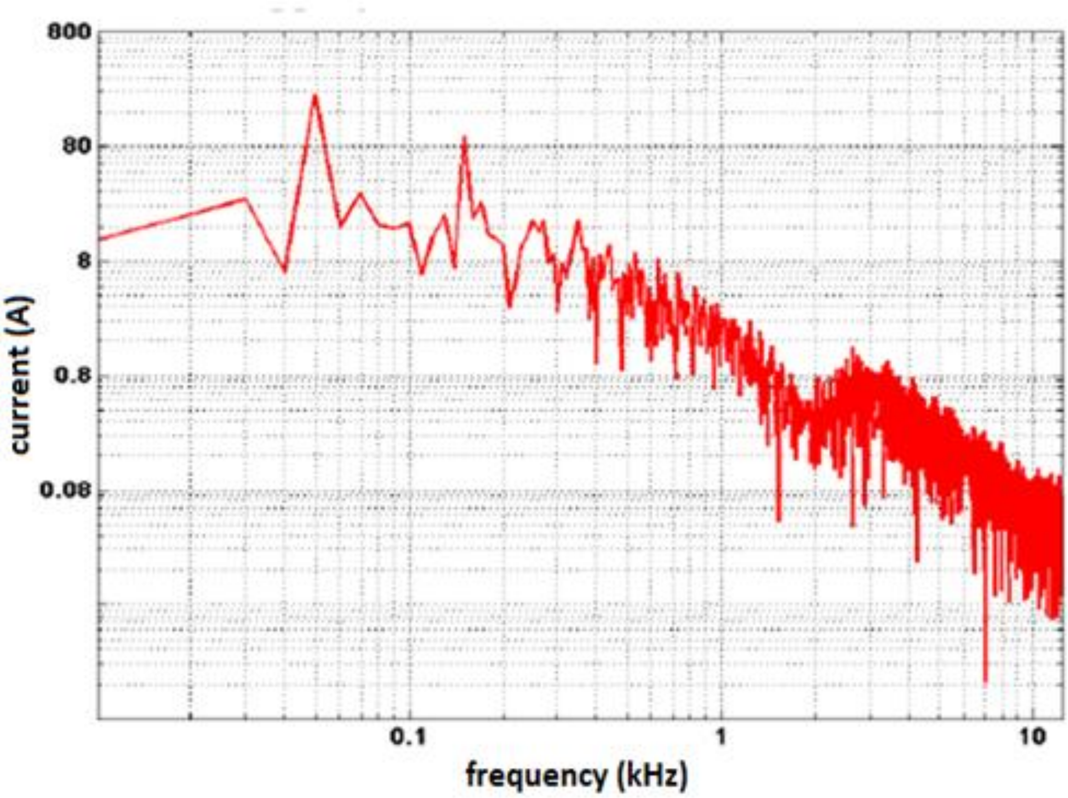

Figure 7. Typical frequency spectral distribution for parallel arc fault. Here, highest peak is 50 Hz, 3rd harmonic is comparably high. The area between 2 kHz and 5 kHz is a result of fast rising edge due to arc re-ignition.

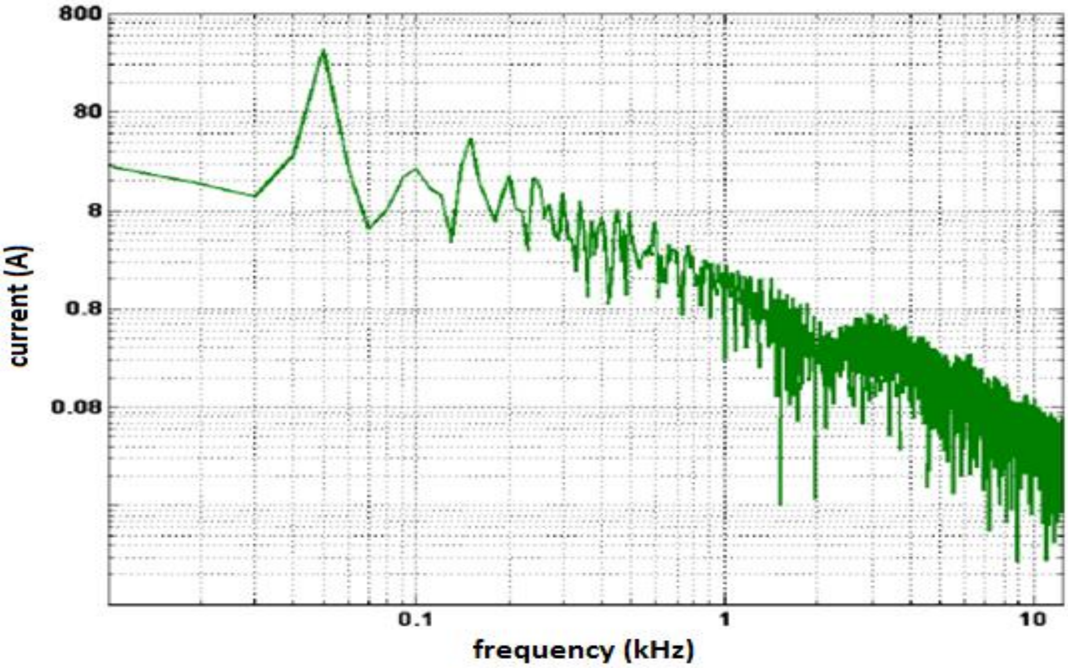

Figure 8. Typical frequency spectral distribution for series arc current. Here, highest peak is 50 Hz, 3rd harmonic is comparably high. The increased amplitudes from 2 to 5 KHz spectral range is comparable characteristics with parallel arc current spectral distribution.

2.2 Arc light characteristics

The main property of an arc flash incident is the strong luminous intensity discharge as compared to the normal case substation background. A typical arc flash light intensity measured 3 meter away from the fault point ranges from 108klux to more than 250klux [9].

Figure 9 illustrates typical characteristics of arc flash radiation spectrum taken form collaboration research work publication [2]. According to the paper, the test is performed on various material, current magnitudes and standard switchgears. The result shows that the spectrum rang 330nm to 530nm and 770nm to 870 nm are important characteristics of arcing light. In addition to this, although it is not shown in this particular test result, it is widely accepted that an electric arc flash contains shorter wavelength radiation as low as 200nm in UVC range, which is a characteristically only reflected by abnormal case light sources. That is, including sun light under the atmosphere, most light sources doesn't have such property.

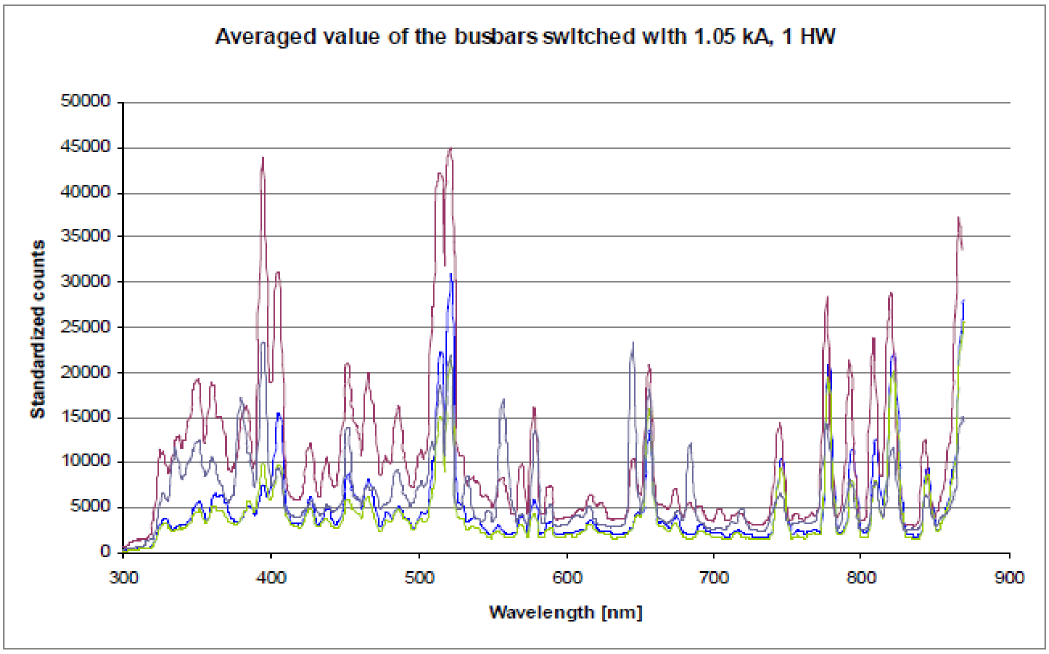

Figure 9. Measurement result from of arc light spectrum distribution.[2]

Another essential characteristic of an arc flash light worth to mention is that the luminous intensity varies proportionally with the arc current. Figure 10 taken from measurement result [8] illustrates this attribute of the arc light. Thus, at this point it is important to notice that it is possible to obtain details about the driving force of the light signal from the arc light itself.

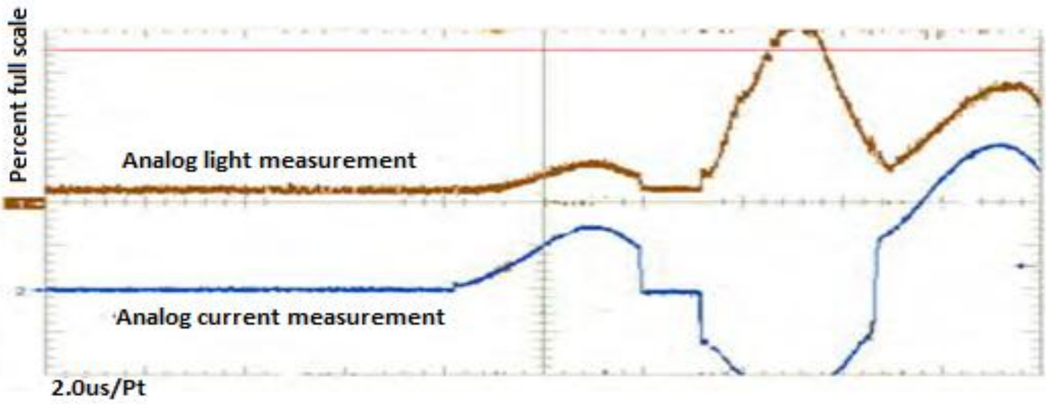

Figure 10. Analog light measurement plotted with current

2.3 Arc fault Hazard magnitude

In relation to arc flash hazarded assessment there are two worldwide used guidelines put forth by institutions like Institute of Electrical and Electronic Engineers (IEEE), and NFPA National Fire Protection Association.

IEEE Standard 1584 “Guide for Performing Arc-Flash Hazard Calculations” is a guideline for performing arc flash hazard analysis to determine boundary distances for unprotected personnel and the incident energy at the working distance for operating personnel working on energized equipment [10]. However, the calculated incident energy level is also used in estimating damage to equipment when different protection approaches are compared.

NFPA 70E “Standard for Electrical Safety in the Workplace” assigns hazard level from 0 to 4 based on the calculation result of IEEE 1584 standard to incident energy levels up to 40cal/cm^2 in an efferent to help employers meet different regulations [11].

2.4 Mitigation Approach

According to IEEE 1584 Empirical equation [10] (example calculation is also provided in [8],[9]) the incident energy of an arc-flash event is directly proportional to voltage, distance, current and arcing time. As a result, the three factors namely distance, current and arcing time are widely used as arc fault mitigating strategy.

In practice, the main approaches implemented on protection devices are arcing current and arcing time. However, as explained in [12] current limiting approach includes many uncertainties and risks related especially to the impact on arcing time. Hence, reducing arc time as mitigation strategy is widely used operation principle in the industry for reactive safety devices.

The arc time is defined as the sum of the operation time of the protection relay and the time in which the primary device (breaker or quenching device) operates. The relay time includes arc detection time, relay tripping element time and coordination time. The coordination time varies depending on the implemented protection scheme. The total detection and tripping time varies from 1ms to more than 8ms based on the sensing technology and tripping element employed on the protection system. Quenching devices can operate in less than 4ms duration, limiting the arc time to about 5ms. According to IEEE Standard 1584, LV and MV breaker operating times vary from 1.5 cycles to 5 cycles depending on the class of breaker involved.

3 PROJECT MOTIVE

After looking through various physical phenomena caused by an arc fault and studying the performance of corresponding sensing technologies currently available on the market, two alternative approaches were devised to construct a complete arc fault detection system with the ability to detect both low and high impedance faults aiming for relatively similar performance or price index of existing and widely accepted detection methods. This chapter provides an insight on the basic ideas behind the chosen system.

3.1 Magnetic Field Sensing

As discussed in the previous section, during a low impedance arc fault almost all available energy will be drawn to the fault point and the current magnitude becomes in the range of many kilo amps. As a result, both the arc current as well as bolted fault current sets-up a very strong magnetic field in the vicinity of the fault point. Thus, the assumption considered is that a magnetic sensor positioned near the fault point will be able to sense this large change and could be used as a fault indicator.

Today various magneto resistive sensor technologies with the sensitivity ranging from 1mV/V/G as high as 12mV/V/Oe (1G ≈ 1Oe for air medium) and dynamic range up to +/-90 Oe are available in the market at a relatively low price. Most manufacturers also provide these sensors as 2 or 3 axis arrangement in a very small size package which makes it suitable to be easily incorporated into existing arc light point sensor modules.

Incorporating such a field sensor in an existing arc flash light point sensor is useful to supervise the optical system output in order to enhance trip security with an added advantage of having a standalone device with comparable performance to light plus current detection method. Such an arrangement also gives the detection module the ability to analyze the two signals simultaneously and may provide relatively small improvement on detection speed.

The magnetic field distribution study within switchgear during short circuit or arc fault incident is essential to determine the sensor placement and suitable field strength threshold levels. Although this not covered within this thesis work due to time constraint and resources required for the test, on the bases of theoretical assumption possible placement for the detection modules is provided in Figure 11 for typical case illustration purpose. Here, the main consideration taken in this arrangement is that the sensor modules are placed near to one of the phase conductor with the field of view covering most of the area within the compartment. In addition to this, it’s also assumed that two or more sensors will work together exchanging over-current (or strong field) binary information. For this reason, two or more sensors are placed near to different phase conductors. For instance, as shown in the figure, if a sensor in cable compartment is placed near to phase1 conductor the corresponding sensor in the same switchgear cell main bus bar compartment could be placed near to phae2 or phase3 conductor. Also, if third additional sensor is used it can be placed near to another uncovered phase conductor. Here, it’s important to notice that the approach is not in any way intended to measure the current within the phase conductors. That is, only unusually strong magnetic field strength simultaneously detected with light signal is used as fault indicator.

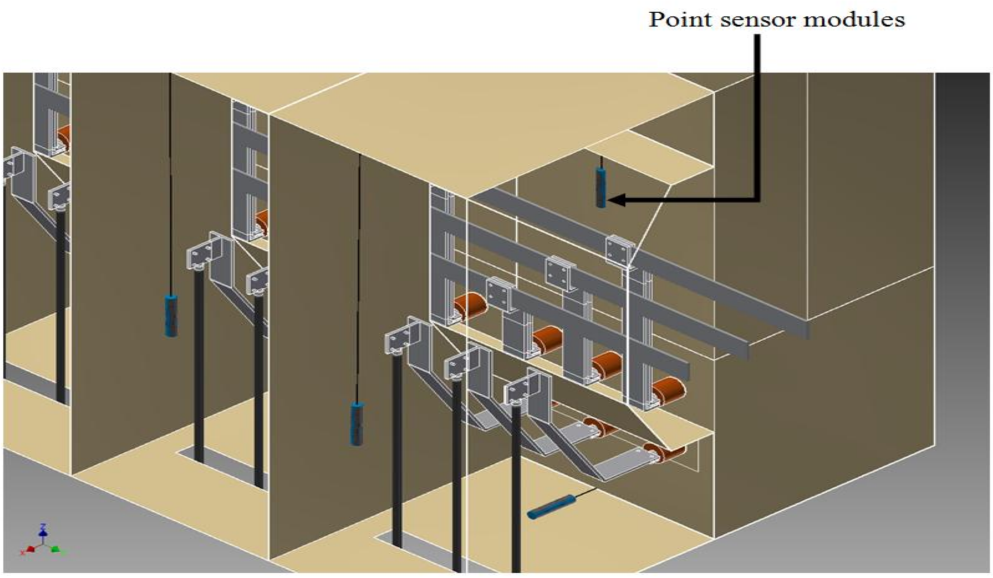

Figure 11. Possible placement of the devised sensor modules inside switchgear

3.2 Measured light signal evaluation

The main purpose in which this approach devised is to be able to recognize high impedance fault incidents taking place within the detection system field of view. Thus, as mentioned in section 2.2 the light signal itself provides indirect details about the nature of the driving force. One possible and practical approach to extract this information from the flashing incident is to analyze the waveform property of the measured light signal.

Another important but not mandatory approach taken to enhance the performance of the system is to exclude the visible light spectrum range from the measured light signal and make a decision based on the luminous strength present within a properly selected spectral range (ultraviolet (UV) and infrared (IR) region). This method is very common in flame detection systems and is selected because most artificial light sources are designed to operate in the visible spectrum and also most similar light sources with extended spectrum distribution will not satisfy both conditions (i.e. UV & IR) or will have insignificant strength in this region. Therefore, the approach will create the opportunity to increase the sensitivity of the detection module by reducing the threshold level and be able to operate even under obstruction via reflected light.

Table 1. Potential false positive sources, characteristic comparison

Source	**Intensity at 457 nm**	**Spectral distribution**		**Light signal Waveform**	**Signal Duration**
		UV	IR		
Camera Flash	234klux	High	High	Exponential decaying	< 5ms
Direct sunlight (at any distance)	100klux	High	High	Constant	-
High-intensity AA LED flash-light	28klux	High	Zero	Constant	-
Common AA LED flashlight	4.56klux	High	Zero	Constant	-
Arc Light escaping from cir-cuit breaker	-	High	High	Sinusoidal	< 100ms MV CB

Table 1 compares the essential characteristics of other typical high intensity light sources which are usually considered as causes of false positive [9] (i.e. regarding light only detection scheme). Here, it can be seen that the only concerning source of light after implementing such a system is the arc light itself which is escaping from breakers during normal operation. The problem is present only on older air magnetic breakers and it could easily be overcome by increasing the observation time length in which the detection module analyzes the data to make decision. LV and MV barker operating time varies from 1.5cycle to 5cycle.Therefore, by configuring the detection device to react in a time above the breaker operating duration the fault incident could be identified safely in less than 100ms time depending on the operating voltage. At this point, it should be recognized that since the incident energy is a function of time and available current, the introduced delay is within the acceptable range when considering a high impedance arc fault.

4 SENSOR DEVELOPMENT

As part of this thesis, an arc fault detection point sensor module was developed on the bases of alternatives described in Chapter 3. The sensor was designed under consideration of the following requirements:

- Able to identify a low impedance arc fault in less than 1ms and a high impedance arc fault within 25ms (1.25 cycle).
- Performs self-supervision.
- Adaptive threshold level tuning for changing light level.
- Disturbance record: pre activation 1 cycle & post activation 4 cycle
- Non-volatile storage for configuration and disturbance record data.
- Data transfer on serial request: current self-supervision result, current signal level of all inputs, disturbance record and device configuration data.
- Accepts serial configuration parameters.

The sensor modules are designed to work with Arcteq AQ100 series protection relays. Figure 12 illustrates the overall arrangement of the system under discussion. Here, because the current signal is used for communication and trip output signal, it is possible to connect multiple sensors in series at any of the four relay sensor input channels. The protection relay supervises the sensor status and also coordinates communication when the sensor user interface software attempts to communicate with a specific sensor.

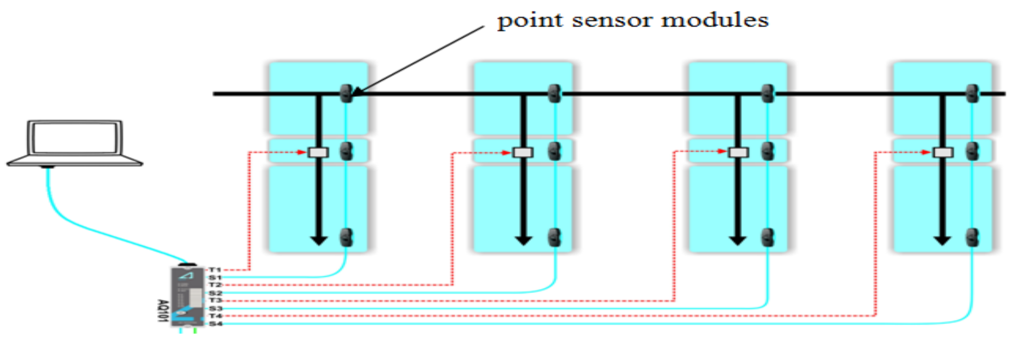

Figure 12. Overall arrangement of the system under discussion

4.1 Hardware Implementation

The section discusses the sensor hardware construction. Figure 13 illustrates essential parts of the implemented hardware in block diagram. For more detailed description of the hardware a complete schematic diagram is also provided under APPENDIX 1.

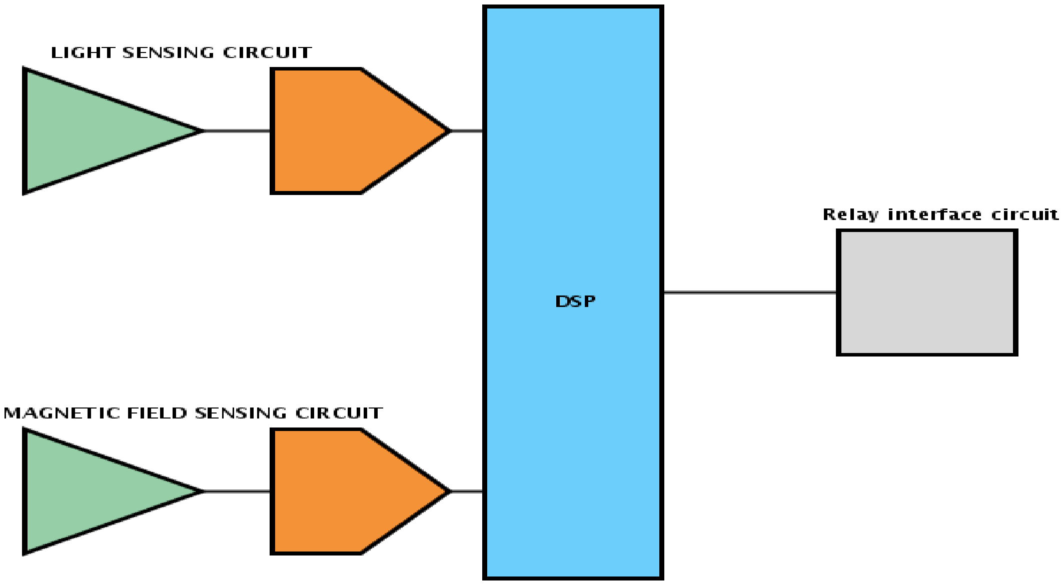

Figure 13. Block diagram illustration of sensor module hardware essential components

4.1.1 Processing unit (DSP)

Microchip dsPIC33EP128MC202 was selected as a signal processing unit, for the reason that it satisfies the following specifications:

- Good Price/Performance Index.
- CPU Speed 70MIP
- Data Memory 16KB (for temporary storage of large system data)
- Support native arithmetic operation (used to speed up calculation).
- Four channel simultaneous sampling future

4.1.2 Light sensing circuit

As light sensory elements two sensors were chosen for measuring ultraviolet and infrared intensity level.

ML8511-00FCZ05B: Measures ultraviolet radiation intensity within spectral bandwidth range 280nm to 400nm. Because the sensor package consists of an amplifier circuit the output swings between 1 to 3 volts with respect to the measured intensity. Therefore, this signal is directly feed into the DSP unit ADC input.

BPW41N (PIN photodiode): Measures infrared radiation intensity within spectral bandwidth range 870nm to 1050nm. The signal needs to be amplified to be used by the DSP unit. Hence an LMV324 rail-to-rail op-amp amplifier with gain 15000 was used to feed the DSP. Here, the reason for which this spectral range is preferred instead of one discussed in section 2.2 is that arc lights usually produce off the scale light signal. The choice is considered to have an attenuation effect without losing the light information.

4.1.3 Magnetic field sensing circuit

The main specification of the required low magnetic field sensor was expected to have high sensitivity, large dynamic range, low noise density. Honeywell HMC1022 two axis AMR (Anisotropic Magneto-Resistivity) technology low magnetic field sensor was selected solely based on local market availability and price. The stated sensitivity of this sensor is 1mV/V/gauss and dynamic range: +/-6g.

These types of sensors are simple resistive Wheatstone bridges arrangement employed to measure low magnetic fields. As a result, it only requires a supply voltage to obtain output. However, because the output signal is very low, an additional amplifier circuit is required. Here, a bridge voltage 3.3V and difference amplifier gain 82.5 provide a full dynamic range swing with overall gain of 0.274 V/gauss at the DSP analog input.

In addition to the bridge circuits, the sensor has two on-chip magnetically coupled straps; the offset strap and the set/reset strap for purpose of measured field adjustment and magnetic domain alignment respectively. The use of offset strap may not be necessary depending on the application. However, the set reset strap is essential because the sensor performance might reduce due to strong fields [13]. Hence, in this application an additional set reset driver circuit is added in order to periodically realign the magnetic domains for most sensitive performance.

The set/reset driver circuit implemented in this particular application is shown in Figure 14. The role of the circuit is to inject about 0.5A current through 4.5Ω set/reset strap resistor of the magnetic sensor to ground. The capacitor C10 is used as a charge reservoir to provide the required current magnitude and hence on the set/reset pulse high to low transition P-Channel FET Q3 conducts while the N-Channel FET Q4 is turned off providing positive current pulse through C7. Next on low to high transition of the pulse, Q3 is OFF while Q4 is ON and this provides negative current pulse. An oscilloscope screen capture of the typical current signal is provided in APPENDIX 2.

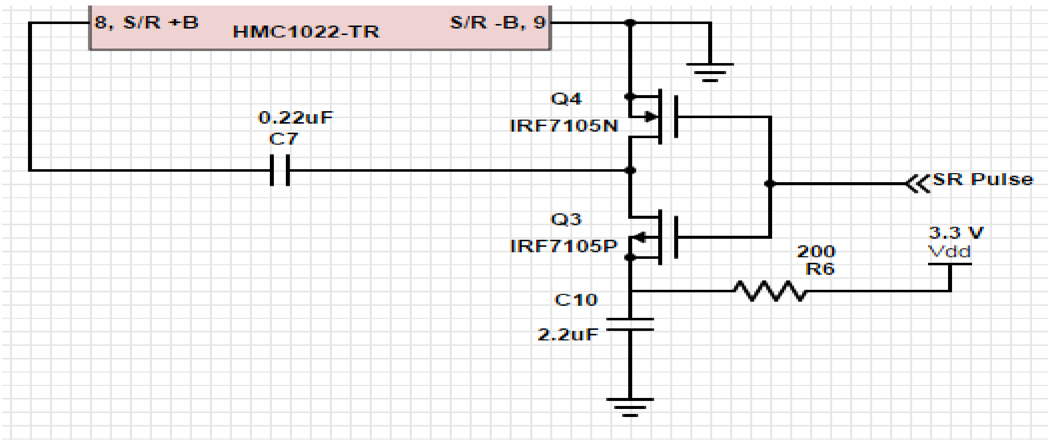

Figure 14. Set/reset driver circuit implementation

4.1.4 Relay interface circuit

The purpose of this circuit is to convert voltage signal to current signal to reduce the effect of noise and distance on communication. The circuit operates with 24V supply and consists of BJT transistor switching circuits. The relay circuit and firmware is designed to distinguish the alarm signal from communication signal using threshold settings. Therefore, single-wire transmission line (single wire method) is used both for communication and trip output.

4.2 Software Implementation

Embedded application firmware intended to run on digital signal processor with processing speed of 60MIPS or higher is prepared to implement the system under discussion. The general structure of the software is shown in Figure 15.

The software consists of three sensory modules (IR, UV and magnetic field modules) for supervising corresponding sensory element status, service modules to provide low level driver or helper functions and an algorithm module to process various s notifications from other modules and also to implement the devised protection logic filtering algorithm.

This section provides details about essential components of the software, the generic principle of the software execution and the developed protection logic algorism. For more details about the software structure please refer to the source-code or doxygen generated documentation provided with this paper.

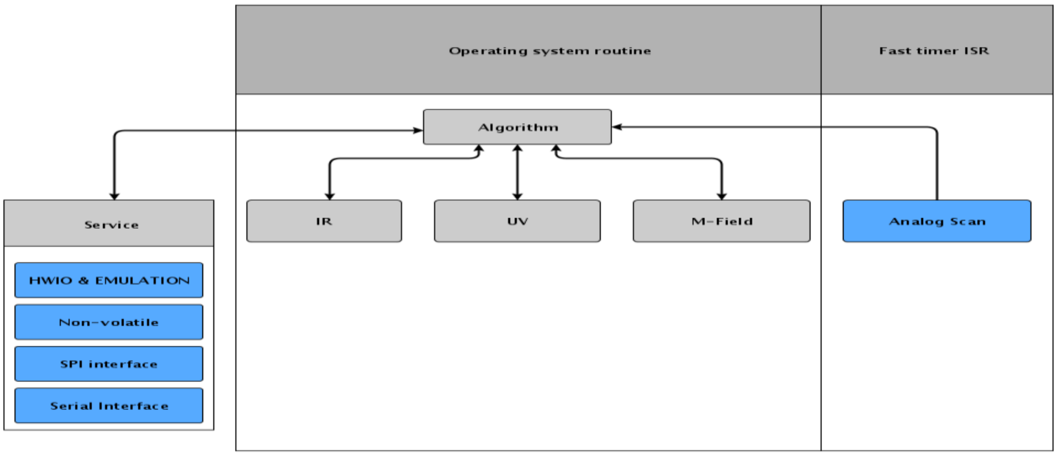

Figure 15. General Overview of implemented software structure.

4.2.1 Generic principle

The OS used in this application is a simple event based scheduler. Basically it distributes task event functions for synchronous execution and notification functions for asynchronous calls between modules. The system also provides soft timer scheduling and sends notification when such a timer expires. Moreover, interrupt functions or other functions requiring short execution length can trigger special notification calls to particular modules in order to perform extra asynchronous task after the function return.

In this application the OS is started in main function during startup procedure. Then, using task initialization function each module provides module handle variable, task event function to receive synchronous calls with events distributed by the OS and task notification function to receive asynchronous calls from other modules via notification distribution function (see e.g. main.c). Following on, the system initiates all modules by sending a system notification (see e.g. algorithm_notifyx() , all modules have a similar structure). Then, the modules prepare the system objects (event or notification objects for use during runtime see e.g algorithm_init()) and the schedule timer for periodic operation. After the OS startup procedure is completed, the algorithm module initiates non-volatile memory read procedure, calculates operation parameters, sends configuration notifications to enabled modules and then starts an analog scan timer to activate diagnosis functions (see algorithm_configure()).

The execution time of the software is generally divided into two time slots. About 70% of CPU time is consumed by 10 kHz interrupt service routine used to analyze input signals presented from sensing elements. Thus, whenever a timer interrupt occurs, the algorithm module distributes sampled values to the responsible modules. Consequently, the modules define and return their current state using this and the previous values. Then, depending on the implemented protection logic, if one or more modules are active, Algorithm module event filter function (algorithm_wake()) will be executed with message “supervision alarm” as a final trip event filtering procedure. Also, if the previously active module changes its state while the trip signal is active, algorithm_wake function will be called with message "event cleared" to clear the trip signal. In addition to this, the algorithm wake function may also use the interrupt service routine to create delays synchronous to the sampling interval for purpose of event filtering (see e.g. _T1Interrupt() and algorithm_wake()).

The rest 30% of CPU load is originated mainly from operating system routine with the exception of the time consumed when processing external interrupts. Thus, within this time, the modules designed and configured for sensory element supervision or other diagnosis operations execute the intended procedure when they receive notification or task event calls distributed by the OS. The modules send notification to the algorithm module in case of supervision error or configuration mismatch, which may arise due to threshold level adjustment performed by the calling module. The sequence diagram in Figure 16 illustrates the basic principle of the firmware operation.

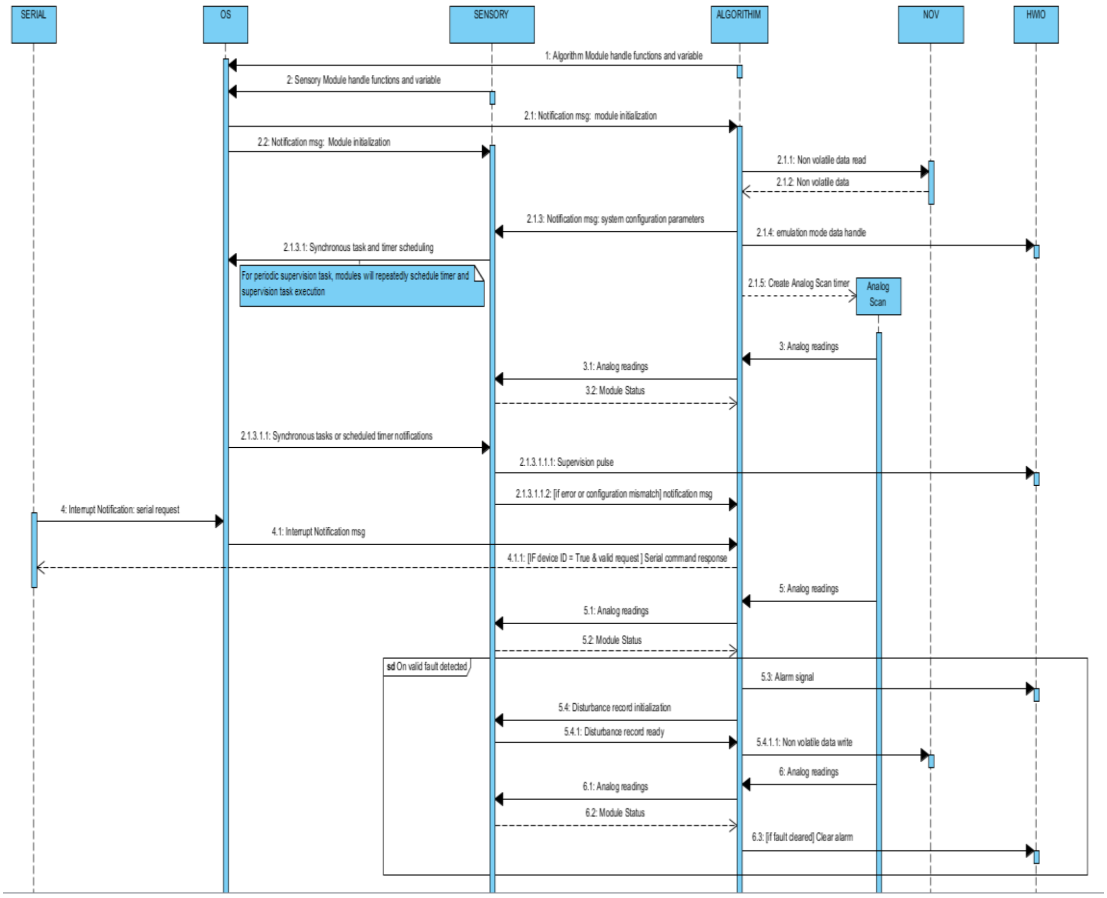

Figure 16. UML diagram shows the basic principle of the firmware operation

4.2.2 Sensing Modules

In the application firmware the sensing modules are responsible for all tasks related with corresponding sensing elements. Although the design of such modules slightly varies, basically it involves the following functionalities:

- Determining input signal status,
- Determining light signal characteristic (only IR sensor module)
- Perform sensor element supervision
- Perform adaptive tuning of threshold setting (only light sensor module)
- Disturbance record

4.2.2.1 Determining input signal status

Given that the main approach implemented to identify fault condition is to recognize the occurrence of excepted sequential events in the measured signal, the sensory modules are designed to operate in a manner similar to the mealy state machine approach.

As illustrated in Figure 17 the modules operate in State 0 as long as the first order derivative or magnitude of the input signal is below the set-value and whenever this condition is changed the module state will change to State 1 if the measured signal magnitude is above maximum value or to State 3 if fast rising signal condition is identified while the magnitude is below threshold. However, one exception is that, if the rate of change in the observed signal shows impulsive nature, the module state will change from State 0 to intermediate event filtering state (State 2).

The observation counter variables set during the initial state transition control the next operation state of the module. To be precise, primarily these variables will be used to delay the next state transition for the configured number of samples. When the required delay is expired, the observed positive event with respect to the total observation defines the probability of the expected event, as a result the module current state will change to State 4 (Active) if the calculated probability is above 80% or to initial case State 0 otherwise.

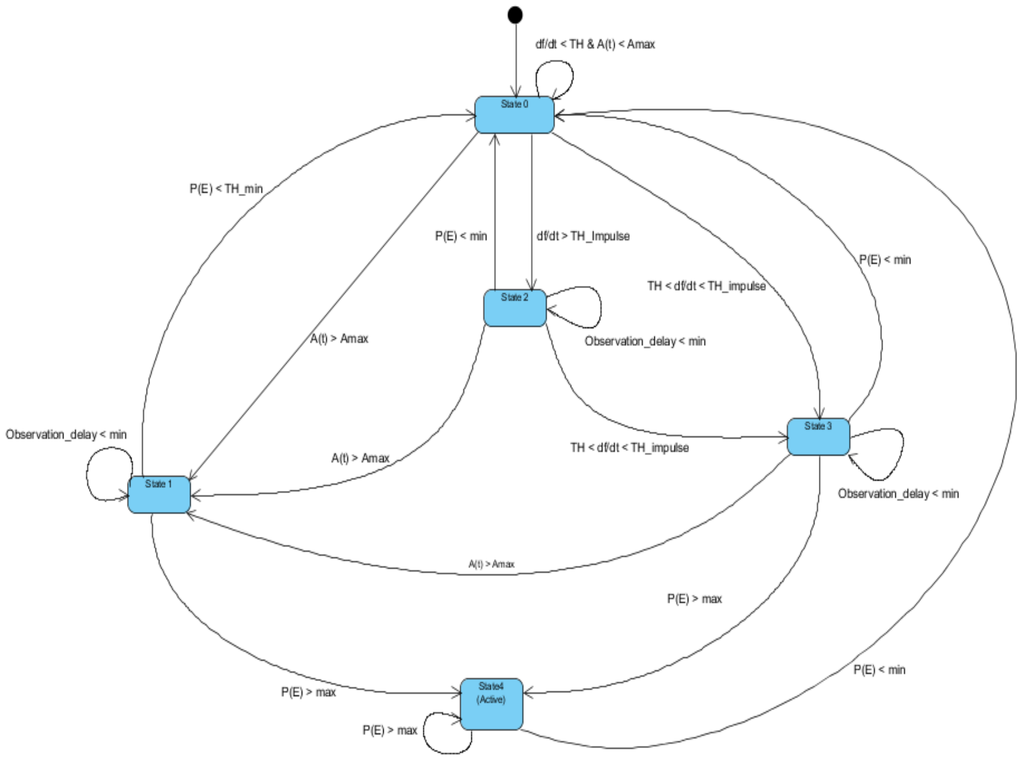

Figure 17. Typical Sensory modules operation state diagram

4.2.2.2 Determining light signal characteristic

The role of this particular case implementation was to determine whether or not the measured light signal has the characteristics of sinusoidal or shouldering sinusoidal type waveform described in section 2.2. Here, the main method used for this purpose was to examine the similarity between the input signal and pre-stored reference signal as discussed in section 1.1.1.1. However, because of the long execution time required to calculate the correlation between the two signals, the result of predetermination procedure performed by light sensor module was used to trigger cross correlation analysis.

Figure 18 demonstrates the method used by the infrared sensor module to identify the excepted arc light signal characteristics. Thus, as illustrated the time domain plot of first order derivative for light input signal which resembles arc current waveform (see section 2.2) consists of high magnitude spikes due to arc re-ignition. Hence, by setting a threshold value dependent on the system frequency and measuring the period between these pulses the module will identify this characteristic from the measured light signal (see e.g. ir_sen_get_status(,) & ir_sen_diagonesis_record()). Furthermore, because this characteristic of the arc waveform may sometimes blur for reasons pointed out in section 2.1.2, identifying the period between sinusoidal peaks is used as additional criteria to launch cross correlation analysis procedure. Here, as shown in the figure, the peak detector function is designed to identify peaks which resemble sinusoidal waveform maxima and ignores other types including local peaks occurring in sinusoidal waveform (see e.g. ir_peak_detected()).

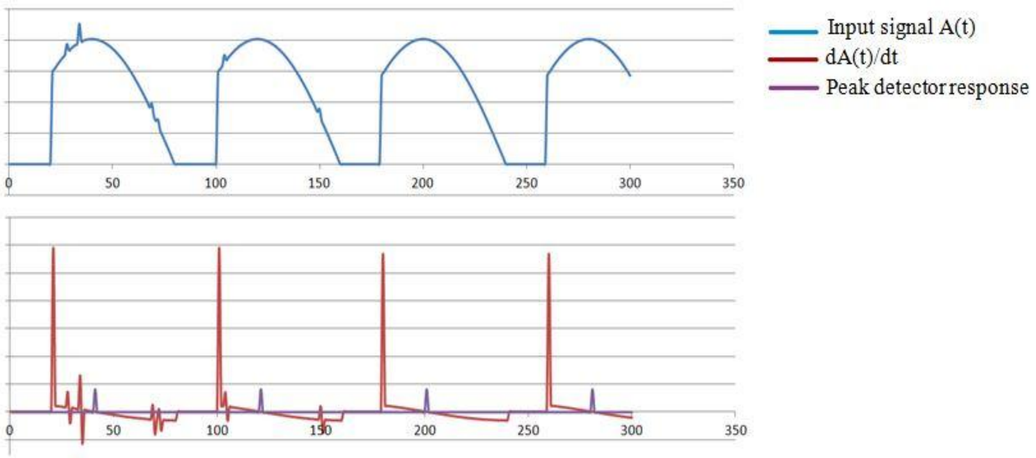

Figure 18. Arc light signal characteristic predetermination procedure, logic test result. The result is plotted when testing the implemented logic on spreadsheet software (Excel)

4.2.2.3 Sensor element supervision

The purpose of this task is to determine whether or not the corresponding sensory element controlled by the module is functioning properly. Here the method used for this function is to verify the sensor response by periodically triggering light or magnetic field sources to affect the sensor output.

The supervision task runs in about every 1ms as scheduled by the OS. Here, if the observed signal shows valid variation within this period the supervised sensor element will be considered functional without any additional assessment. However, if the value of signal does not change within the supervision time interval, in case of light sensor supervision, the magnitude will be compared when an LED installed near the light sensor turned on and off to confirm the appropriate variation or error will be marked otherwise (see e.g. ir_sen_sensor_element_sv_task()). XLMDKCBD59M LED having Luminous intensity specification 350mcd Blue at 460nm and 200mcd Red at 645nm is chosen for this purpose. However, the LED used in the implemented prototype is OVLLB8C7 (300mcd Blue at 466nm) only because it was locally available. On the other hand, regarding magnetic sensor supervision the output is expected to vary all the time except in case the current supply is turned off. Thus, under this condition when the measured field stays constant within the supervision time interval, a current pulse similar to set/reset pulse discussed in section 4.1.3 could be injected to confirm the sensor response (see e.g mfield_x_sen_sensor_element_sv_task()).

4.2.2.4 Threshold setting adaptive tuning

The functionality is implemented only on light sensor modules in order to maintain the minimum threshold setting for sensitive operation and it is enabled if the device is not configured in the manual threshold setting mode. Thus, in this operation mode, modules continuously adjust and maintain the respective threshold setting just above the recorded average maximum value of the input signal with the exception that the new setting level is outside of the predefined maximum and minimum interval.

The adjustment task is executed together with the supervision task in such a way that if the average difference between set value and measured signal is below the predefine value, the level will be reduced to maintain the required gap. On the other hand, if the average gap is above the predefined value and also the number of marked false positives issued by the algorithm module (see section 1.1.1.1) within this period exceeds the defined limit, the setting level will be increased to correct the condition (see e.g. ir_sen_diagonesis_record() and ir_sen_taskx():case X_MSG_IR_SENSOR_SV). The logical behavior of this implementation is also shown in Figure 19.

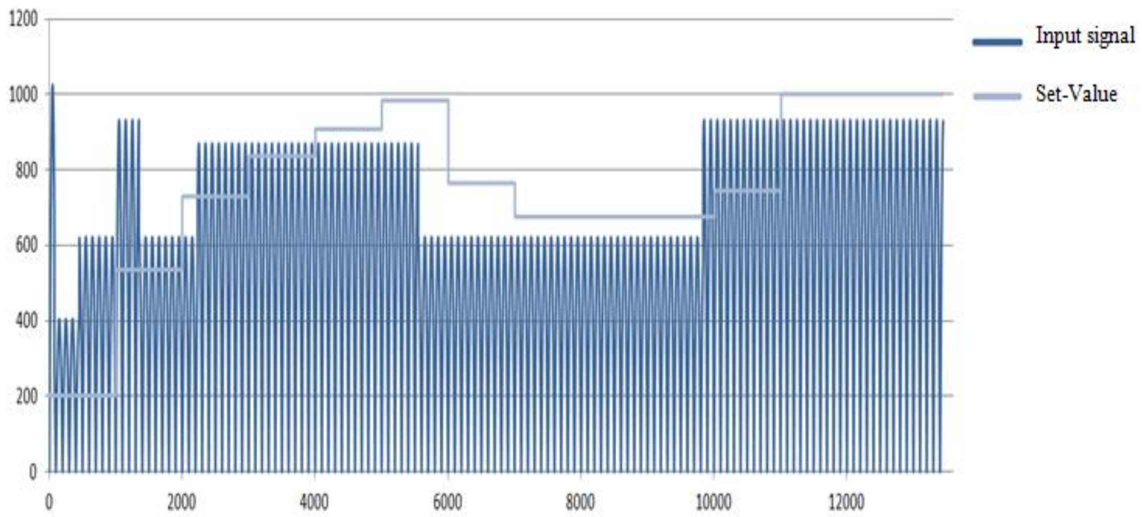

Figure 19. Threshold adjustment task logical behavior plotted when testing the implemented logic on spreadsheet software (Excel) for about 14000 sample period with variable amplitude sinusoidal input signal. Thus, every 5 cycle the system adjusts the threshold value and eventually maintain the required threshold gap.

4.2.2.5 Disturbance record

The main purpose of this implementation is to capture the signal history at the time of valid activation so as to provide details about the event causing the trip. Thus, the sensory modules are designed to collect 20ms pre-activation and 80ms post-activation with a total length of 2KB data per module. The pre-activation data is continuously recorded via a circular buffer during normal case operation. When a valid global activation is issued, the post-activation record is initiated and upon completion the whole record will be stored to non-volatile storage. The data can be accessed by means of the sensor user interface software. In addition to this, because the pre-activation record is running continuously it is made accessible at any instance using the same software in order to obtain the time capture of measured signal from the corresponding sensor.

4.2.3 Algorithm module

The algorithm module is the top most module in the sensor application firmware. Basically it is responsible for system configuration, protection logic algorithm implementation, external communication and system notification handling.

4.2.3.1 System Configuration

As mentioned earlier during the startup procedure configuration data will be retrieved from non-volatile storage and distributed to dependent operating modules in order to define the system behavior. Here the configuration data distributed by algorithm module includes:

- Threshold setting values including the upper and lower limit in which modules are allowed to adjust the set-value when configured in adaptive tuning mode (see section 4.2.2.4).
- Signal rate of change: maximum, minimum and impulse values. Calculated based on the system frequency and activation threshold set-value.

- Observation length: minimum number of observation required before the sensory module changes its operation state from state 0 to state 4 (Active).
- Probability thresholds: minimum probability value above which the event is considered positive.
- System Frequency: used by sensory moulds for diagnosis operations
- Operation mode: example threshold adjustment manual or adaptive, sensor element supervision enabled or not enabled.
- Storage locations: a pointer to the non-volatile system data structure in which modules stores (e.g. disturbance records) or retrieves (e.g. emulation data).

In this application firmware the threshold setting for light sensor modules is default or user configured value in terms of ADC unit is to be used directly without any mapping procedure. However, for the case of magnetic field sensing modules configured installation details have to be converted to the corresponding ADC unit representing magnetic field sensor output values. For this reason the following expression (1) derived from biot-savart law is used to determine the maximum activation setting for magnetic field modules (see algorithm_configure()).

$$B_{\max\_adc} = \frac{2 \times I_{rated} \times Gain \times ADC_{RESOLUTION}}{distance_{min} \times V_{ref}} \quad (1)$$

Where:

I_{rated}: *switchgear Continuous Current Rated value*

$Gain$: *overall gain of the magnetic sensor circuit* ((0.274V/gauss) see 4.1.3)

$distance_{min}$: *Minimum distance from live conductor which carriers the rated current*

V_{ref}: *ADC referance voltage* (3.3V *for this case*)

$ADC_{RESOLUTION}$: *ADC module resolution* (1024 *for this case*)

After the maximum signal threshold value is defined, the maximum and impulse rate of change settings distributed to sensory modules is calculated using the relation (2) & (3). The minimum rate of change is defined in such a way that modules will not change state due to noise (e.g. $df_{min} = 20mV/Ts$) usually noise density specification is in terms of nV/sqrtHz.

$$df_{max} = 2 \times \pi \times f_{system} \times A_{\max\_adc} \times Ts \tag{2}$$

$$df_{impulse} = 10 \times df_{max} \tag{3}$$

Where:

f_{system}: $system\ frequecy$ 50 or 60Hz

$A_{\max\_adc}$: $calculated\ amplitude\ trehsold\ value$ ($adc\ unit$)

Ts : $sampleing\ time$ (100µ$S\ for\ this\ case$)

In addition to the above configuration procedure, the algorithm module also generates a reference signal to be used for high impedance fault analysis if retrieved the reference signal is not configured by the user or in case the non-volatile storage data is not valid. The default reference waveform generated for this condition is illustrated in Figure 20. Here, the zero huge length is set to be equal to one-eighth of the period to influence the cross correlation result when comparing an actual arc signal with zero huge length varying from zero to quarter period of the signal.

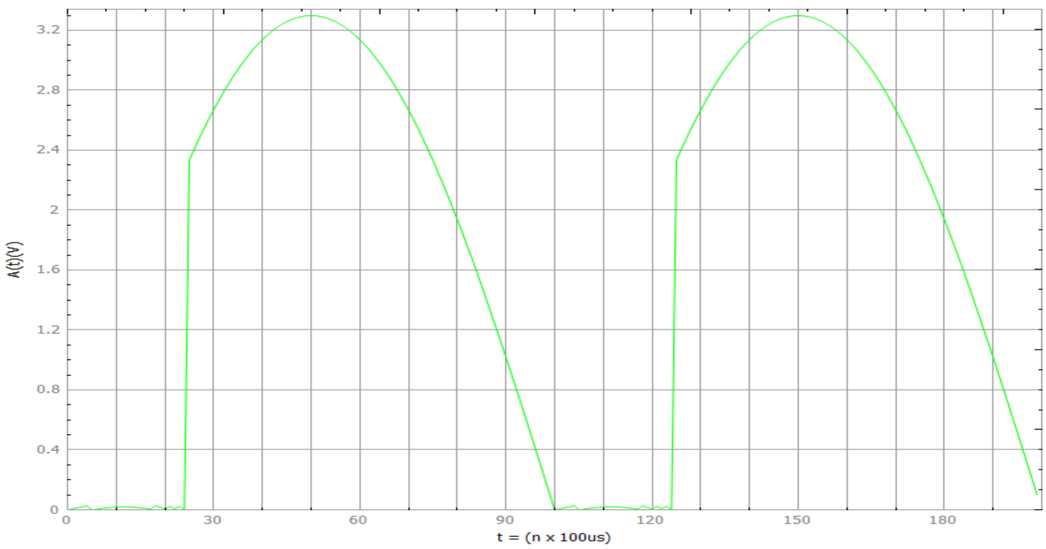

Figure 20.Default referace waveform

1.1.1.1 Protection logic

As pointed out earlier, when one or more light sensor modules change their state to state 4 (Active), the algorithm main function (algorithm_wake()) will be executed as a final event filtering procedure. The protection logic developed on the bases of the approaches described in section 0 is illustrated in Figure 21. The approach is designed to address both high impedance and low impedance faults. Thus, as illustrated in the figure under the situation in which all modules (magnetic field and light sensing modules) are active, an alarm signal is issued without any delay (U3). However, if the magnetic field module is not active the sampled infrared signal waveform will be compared with the pre-stored reference waveform and if the two waveforms have a strong similarity, the event will be considered as high impedance fault condition, hence the alarm will be enabled (U5) (see algorithm_wake(),EVENT_SV_ALARM:case default).

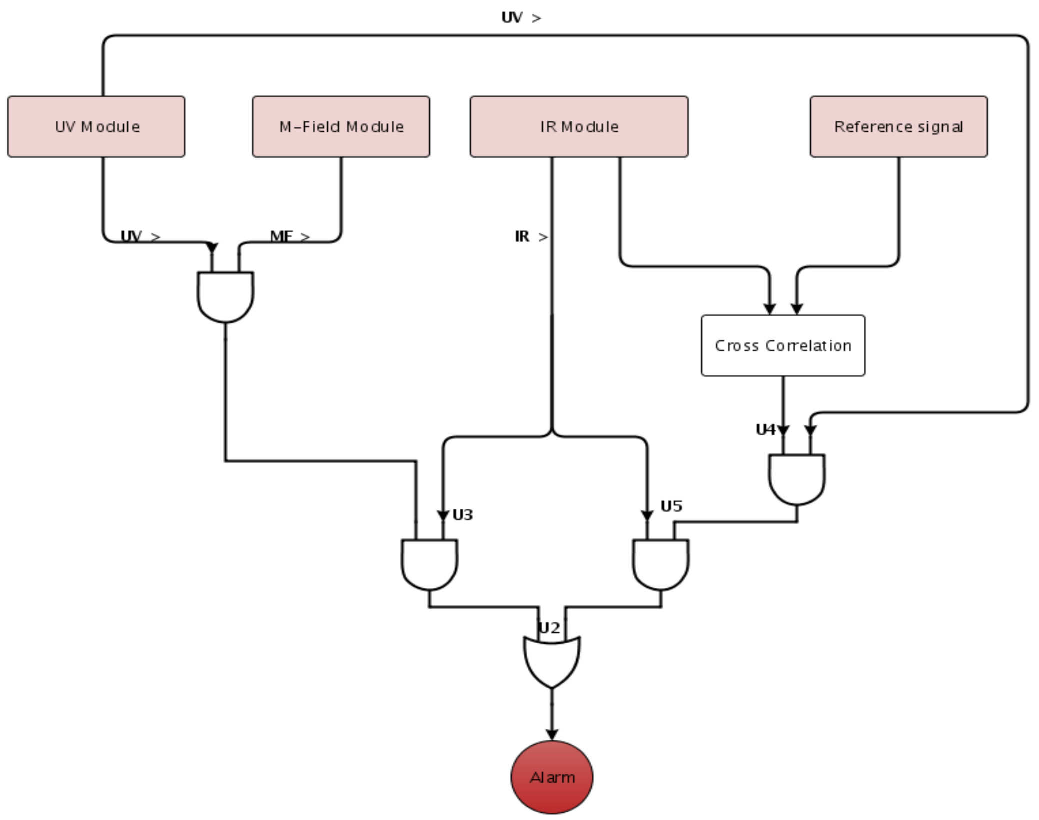

Figure 21. Implemented Protection logic

The activation time varies depending on the fault type (HIF or LIF) and configured observation length. Thus, in a low impedance fault case with the observation length four sample period (i.e. the default) the activation time is about 500us independent of the signal magnitude. Whereas in case of a high impedance fault with the same observation length, the activation time is about 25ms or 1.25 cycle, considering cross correlating analysis on 200 samples.

The correlation function is designed to operate using native arithmetic futures provided by the implemented DSP unit and is able to return the correlation coefficient of two signals with 200 sample length in 236us considering that the system instruction cycle is 60MIP (see algorithm_liner_correlation(,), algorithm_get_std_deviation(,), algorithm_get_mean(,)). The function is executed when the required data length is collected as well as the predetermination procedure performed by the light sensor (IR) module is completed, with a result showing possible HIF signal. Here, if only one expected characteristics of HIF signal (see section 4.2.2.2) is identified by the sensor module, above 80% correlation coefficient is required to consider the event as positive. Whereas, if both characteristics are indicated, a correlation result of more than 50% is considered sufficient to mark the event as positive. The reason for this type of implementation is that if the measured signal has a zero huge length about a quarter of the period, the correlation coefficient with respect to the reference signal will be less than 80%, though the signal actually has the expected characteristics. Therefore, considering the fact this type of waveform should always satisfy both characteristics evaluated by the firmware, reduced correlation coefficient is used to mark the event as positive.

Once a valid activation is issued, the device outputs an alarm signal as notification to the connected relay and at the same time a global trip flag will be set to enable disturbance record for the event. The recording process will take some time depending on the size of the data. Hence, the delay counter synchronous to the sampling interval will be armed so as to transfer the data to non -volatile storage when ready. Here, because the EEPROM write operation is performed using a low priority task running in the OS time slot, the device protection functionality will still be enabled during this period.

In the case when false positive is marked and is persistent for a period of three cycles, the algorithm module sends notification to the corresponding sensory module to clear the alarm. And as mentioned in section 4.2.2.4 the sensory module can use this information for threshold adjustment if configured in the adaptive tuning mode. Table 2 illustrates the conditions in which false positives will be marked during event filtering procedure.

Table 2. Conditions that will be considered as false positive.

IR	**UV**	**Magnetic Field**	**Correlation Result**
False	True	False	False
True	True	False	False
True	False	False	False

4.2.3.2 External communication

Algorithm module is also responsible for handling external requests. The module will receive interrupt notification from the serial module whenever a valid request arrives. The general message structure used for serial communication with external devices is summarized in Figure 22 and Figure 23 below.

<u>Request Message structure</u>

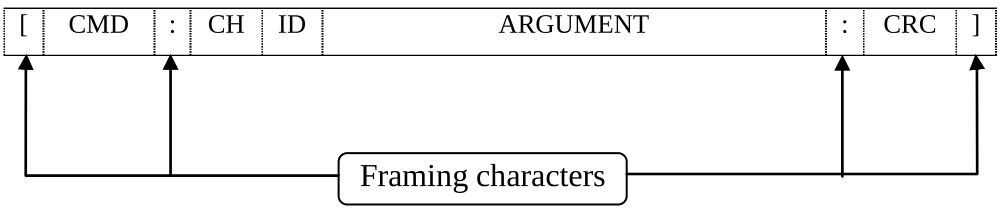

Figure 22. External Serial communication, request message structure

Response Message structure

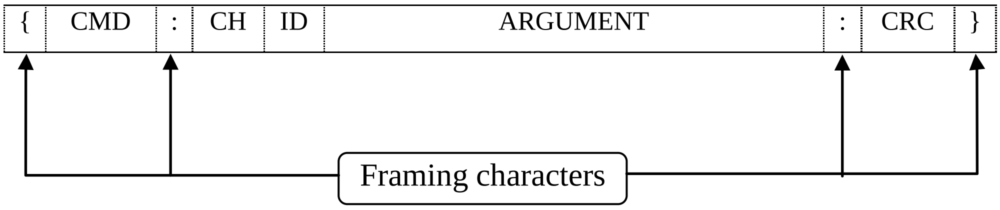

Figure 23. Serial communication, response message structure

Framing characters: single byte characters used for the purpose of message parsing

CMD: Four characters representing 16bit command used to categorize the messages. All serial devices have to use a common header file to correctly handle communication.

CH: Two characters representing 8bit channel address in which the sensor is connected. The information is only read by the connected relay when forwarding the message from the host device (running user interface software) to the channel where the target sensor is connected.

ID: Two characters representing 8bit address of the target sensor. Any sensor connected to the relay channel where a message is broadcasted will respond to the message if this ID matches the sensor configured address.

Argument: Basically this section of the message contains information, such as acknowledgment or command error response, directive messages and data. The length of the argument can vary depending on the message type and the maximum allowable packet size which is determined by the relay receiving buffer. In general the argument structure can have any form as long as the message can be retrieved by the appropriate helper function.

CRC: Four characters representing 16 bit crc (cyclic redundancy check) value for message validation. It is also possible that the sending device can replace these characters with a value 0xCCCC for manual mode crc to bypass checksum validation procedure.

Basically the commands supported in this application are categorized into four: configuration, data loading, data request and event trigger commands.

4.2.3.2.1 Configuration commands

Configuration commands are used to set the device operation parameters. The sensor graphical user interface software is designed to accept these parameters and configure the target sensor. The message argument length varies from zero to thirty characters depending of the executed command. However, all messages should follow the structure summarized below.

DIRECTIVE MSG	PARAMETER length	PARAMETER LIST

Directive MSG: bit coded argument indicating usable or not usable parameters. Thus, although all parameters are transmitted as place holder, the command handler will only copy the values of the parameters indicated by this part of the message.

Parameter Length: a message indicating the length of the parameter list.

Parameter List: a list of configuration values to be copied to the system internal structure.

Configuration commands supported by current firmware are summarized below:

Device ID: a message used to set the device address before installation.

Installation Details: the messages contain sensor installation information related with the switchgear construction, such as rated current, maximum short circuit current, system frequency and minimum distance from live conductor which carries the maximum rated current. Usage of this data is discussed in section 4.2.3.

Threshold Setting: contain threshold values directly set by the user in ADC unit to be used by the light sensor modules. The threshold setting for the magnetic field sensor module is calculated from the information provided as installation details.

Event Analysis Parameters: the message contains parameters which affect the behavior of the device concerning fault detection. The parameters include minimum observation length, maximum and minimum probability values used to distinguish false or true events and bit coded trip criteria information to alter the protection logic used by the device.

Run Time Options: the message contains bit coded information to enable or disable certain features of the firmware (e.g. sensor element supervision mode, adaptive tuning mode).

4.2.3.2.2 Data transfer commands

As mentioned earlier the device supports requests requiring transmission of large length data, such as system parameters and disturbance records. In addition, for the purpose of HIF analysis and / or input signal emulation the device is also designed to accept large length data from the user interface software. For this type of message communicating device uses a common header file which defines the system data structure implemented on sensor module with an equivalent memory alignment. Therefore, the data transferring procedure will be performed in a similar manner as copying data from memory to memory. The structure of the argument used for this type of messages is summarized below.

OFFSET	DATA LENGTH	DATA

Offset: relative offset pointer, indicating the starting address where the data is to be copied or transmitted. The user interface software will increment this value by the transferred data length amount after every successful transmission.

Data Length: the length of the data transferred to be copied or requested for transmission. Here the length of the data is limited by the relay communication buffer size. In this application a maximum of 100 byte data can be transferred in one packet.

Data: Hex characters representing binary raw data which is requested to be copied or transmitted.

4.2.3.3 Internal system notifications

As mentioned earlier, modules dependent on the algorithm module will send notification in the case of supervision error or when a change is made in the configuration data to indicate mismatch. In this application only power supply alert notification will trigger the algorism main function in order to initiate non -volatile data storage write procedure. Notifications received from the sensory modules due to a supervision error will be used to update the device status flags required when a connected relay (or master device) supervision request is received. The other case notifications received due to threshold adjustment is only used to update internal data structure in order to correct the mismatch.

4.2.4 Service modules

In the sensor application firmware low-level stateless driver modules are termed as service modules. The modules are responsible for handling: UART or SPI serial communication, analog or digital input output, non-volatile storage and watchdog timing. In this section, the construction and operation principle of modules assumed necessary for the discussion are presented.

4.2.4.1 HWIO Module

The HWIO module is responsible for the device analog and digital input output operations. Here, two interface helper functions are provided for analog level reading and digital input output operations. Thus, other modules with the privilege to access hardware functionality uses these functions for such purpose (see hwio_get_analog() and hwio_execute_gpio_task()).

The module also supports hardware reading redirection to allow the testing of firmware functionality. Thus, the user can replace real hardware reading with values supplied by serial commands so as to validate the software operation. In case of analog signal emulation the module can accept up to 400 byte (200 samples) data per input and sequentially supply the values in circular manner instead of real hardware reading, that is if the sensory module monitoring the signal is running in emulation mode (see hwio_get_analog()).

4.2.4.2 Non volatile storage (NOV) module

For non-volatile storage requirement of this application an external microchip 25LC640A series serial EEPROM is used for storing device configuration data and disturbance records. The device can store 16KB data divided into 64Byte sized pages and can be accessed using the SPI interface via provided instructions. The device supports data write operation per byte, per page size or any length data size up to 64byte can be transferred in a single write operation if stored on the same page. On the other hand, data can be read per byte or the entire memory can be fetched in a single read operation. Furthermore, the device also provides instructions to access the status registers as well as read write control registers.

The Nov module is designed to handle data storing and retrieving procedures, based on the specified read/write protocol. In this application there are three types of EEPROM data blocks: Device id, configuration data and disturbance record.

Device id includes both device serial number and device address. Four copies of each of these values are stored in the beginning address of the eeprom. Thus, on every reset the data will be retrieved and will be considered valid if two or more successive addresses contain equal values (see nov_get_serial_number()).

Configuration data contains the device configuration parameters and supervision records. Here, the data is stored in two identical copies starting from second copy and then the first copy to make sure that one copy is valid if the execution is interrupted due to a power failure. During the startup, the first copy is read and checked for proper checksum (crc 16). If valid, these parameters are used. If the copy is not valid, the module will attempt to use the second copy. If the second is also defective then this is a fatal error hence the device will be configured with factory default values.

Disturbance record mainly contains the modules disturbance record data including with the event history recording parameters (e.g. relative timestamp). However, it is possible that emulation mode data can also be preserved across reset using the same block (see typedef:post_act_record_buffer_t, nov_data.h file). Here, since this is considerably large amount of data, only a single copy is stored and retrieved when an external data transfer request is received.

4.2.5 Serial module

The serial module is responsible for external serial communications. Here, two interface helper functions are provided for data transmission and reading incoming message (see serial_send_response(), serial_get_command(,,)). In these application only algorithm module can access these functions.

Basically the implemented operation principle is that, during a receiver interrupt the module collects incoming data to receiver buffer and sends interrupt notification to algorithm module after a successful validation procedure (see _U1RXInterrupt()). On the other hand, for data transmission request the module copies the message to transmit buffer and starts sending out data on every transmit interrupt (see _U1TXInterrupt()). Here, sending can be configured in the blocking mode or the non-blocking mode. In the latter case data which cannot fit into the buffer will be lost (see serial_send(,)). Whereas, in the first case (the default) the serial message will be blocking till the transmission is completed. However, this does not affect protection functionality which is serviced by high priority interrupt function.

5 RESULT AND DISCUSSION

At the time of writing, the developed prototype module has not been tested under an actual arc fault condition. However, in order to validate the intended functionality of the system, a common approach namely camera flash and current source was used to imitate fault condition. In addition to this, an emulation signal editor tool added to the sensor user interface software was used to supply various type of signals with different magnitude to evaluate the responses from the sensor module.

5.1 Firmware testing using camera flash and current

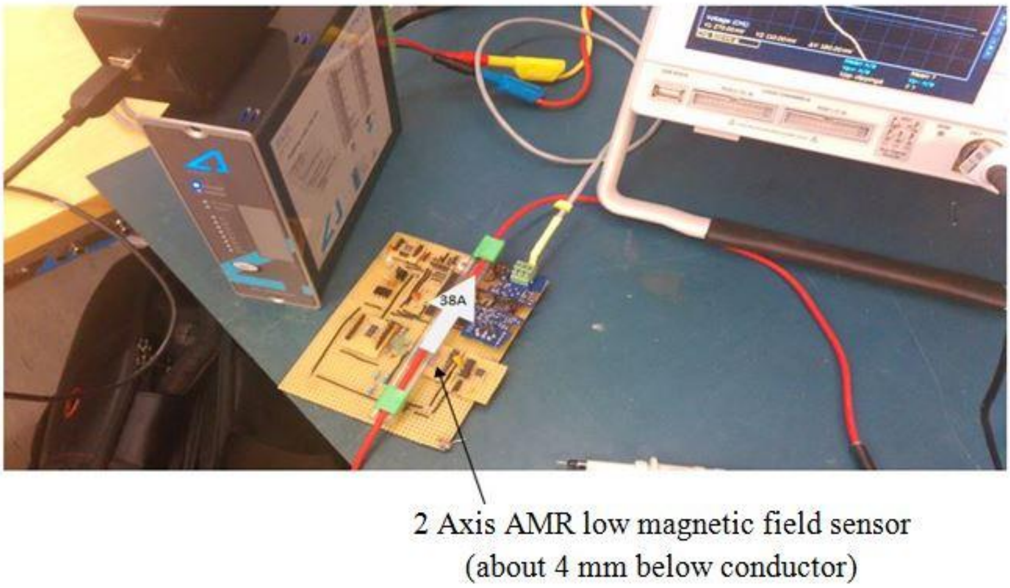

Figure 24. Test arrangement used when testing the sensor using camera flash and current source.

Figure 24 shows the arrangement used when testing the sensor module for high current fault condition. Here, 38A current is set to pass through the conductor (1) to create field strength of about ±5gauss across the magnetic sensor horizontal axis. This value is equivalent to the field strength created by 1200A current carryng conductor at 480mm away from the sensor (a curve to illustrate other current vs distance relations which creates the same field strength (±5gauss) is given in APPENDIX 3). The camera flash used for this purpose namely Mecablitz 20 B1 implements xenon gas. This type of light source has a wide spectrum distribution similar to an arc fault radiation pointed out in section 2.2. (A typical spectrum distribution curve for xenon gas discharge tube is provided in APPENDIX 4).

The resulting disturbance record curve from Magnetic field, IR and UV modules is shown in Figure 25,Figure 26 and Figure 27. Here, the horizontal axis shows a running index number for the sampled data, this value has to be multiplied by 100us to obtain the actual relative time value. In the given curve the first 200 samples represent the pre-activation record and the rest 800 samples shows the post activation data. At the time of testing the sensor was configured for rated current value of 1200A, live conductor minimum distance of 500mm, system frequency of 50Hz which corresponds to 1.37V or 43mV/100us magnetic field module activation threshold values. Also both light modules were configured for 620 ADC unit which corresponds to activation set-value 1.99V (i.e. equivalent IR intensity at λ365nm [8] (≈0.92mW/cm^2), UV intensity at λ365nm [9] (≈7.592mW/cm^2)) and or 62mV/100us rate of change activation level. The observation length set for all modules was four sampling periods of about 400us. Therefore, the total activation time under this condition was expected between 500us to 600us.

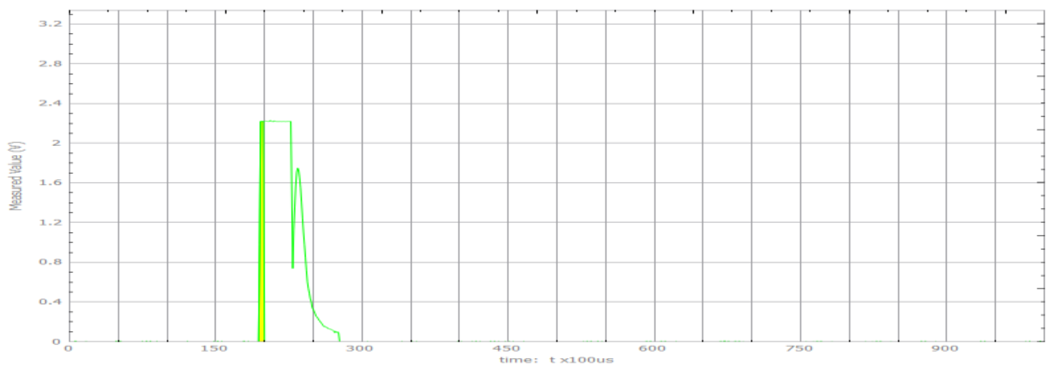

Figure 25. Disturbance record curve captured by IR module when the sensor is activated with a camera flash and current source. Here, the yellow background area of about 500uS is the time between when the event is detected by the IR module to the time when global activation is issued by the algorithm module.

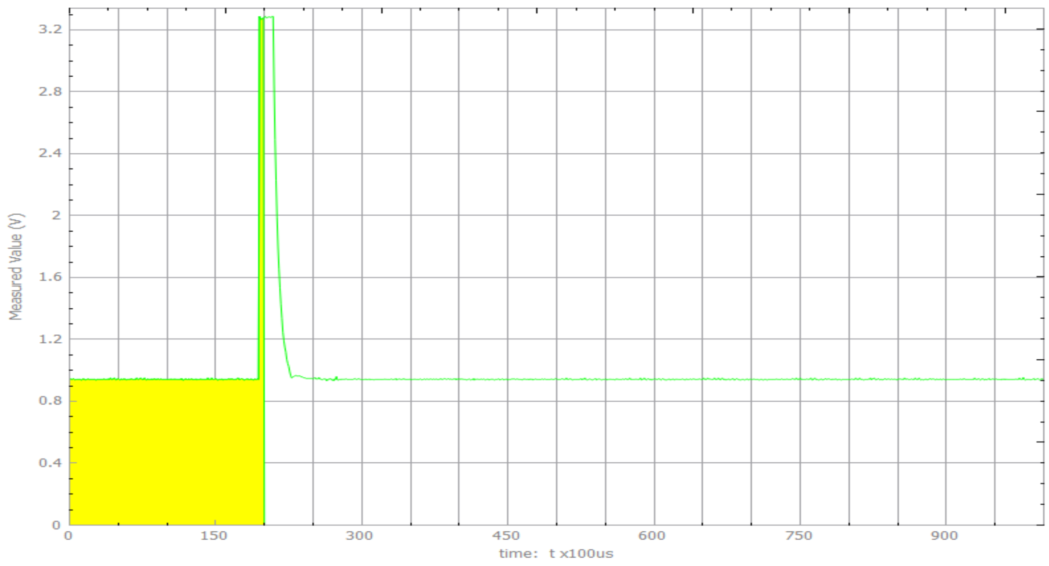

Figure 26. Disturbance record curve captured by UV module when the sensor is activated with a camera flash and current source. Here, a normal case output of the sensor element is about 1V (see section 4.1.2). Therefore, the pre activation record shows this value until the module detects the flash light.

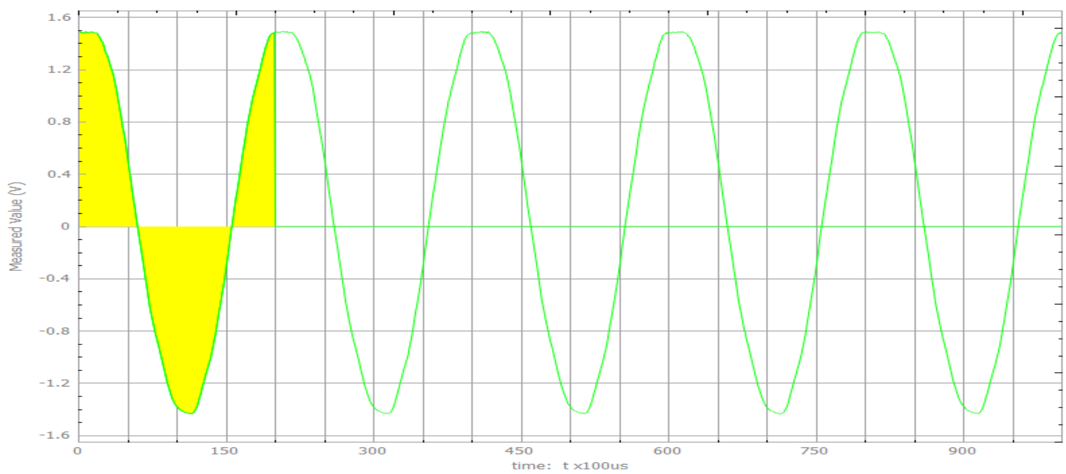

Figure 27. Disturbance record curve captured by the magnetic field module when the sensor is activated with a camera flash and current source. Here, because the magnetic field is applied before flashing, the module is already active for the entire pre-activation and post-activation period.

5.2 Firmware testing using emulated signal

Another test carried out to validate the prototype module operation with regard to high impedance fault condition was by supplying varies emulation data which overwrite real hardware reading, and see the response from the system. The emulation signal editor tool was developed in such a way that the user can easily edit and generate periodic signal data with a certain characteristic in time domain or frequency domain (Figure 28).

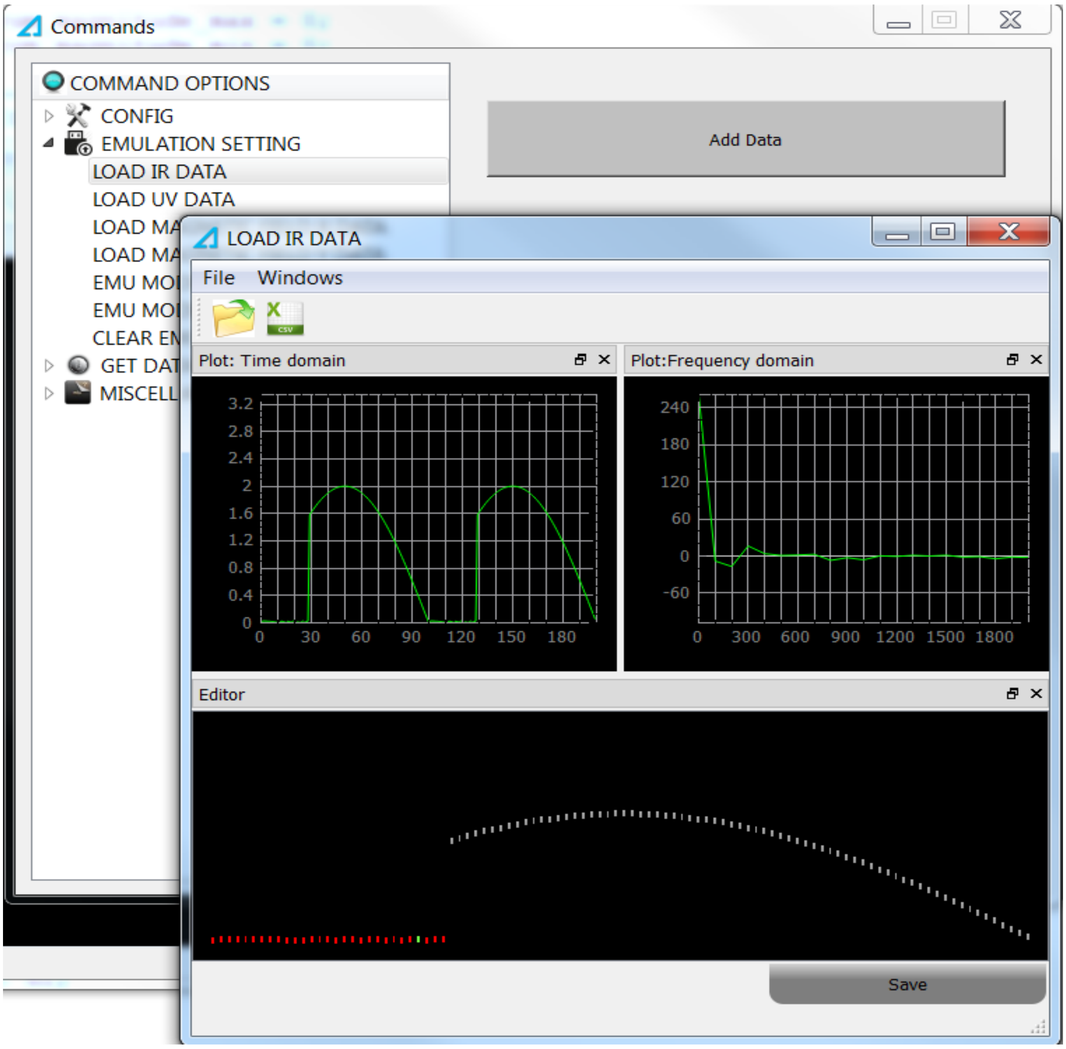

Figure 28. Emulation data editor tool screen capture. Here, the user can use the bottom side editor window to characterize a half cycle signal while monitoring the characteristics of the signal in time domain or frequency domain.

Figure 29, Figure 30 and Figure 31 show the resulting disturbance record curve for the emulated signal similar to the setup shown in Figure 28. In this case, only light modules were running in the emulation mode while the magnetic field module was reading the real hardware values. Thus, because the magnetic field module was not active during this time, the situation is similar to a high impedance fault condition. Here, the total activation time marked by timestamp value corresponding to the event is 22.5ms starting from the time when the first fast rising edge is detected. As explained in section 4.2.2.2, this is almost the time required to collect data for HIF assessment procedure. Thus, because the emulated data represents full sinusoidal 50Hz signal, it takes about 2.2ms from the first fast rising edge until the first peak is detected. Then following on, one cycle 20ms data (yellow background curve) is collected before HIF comparison is started.

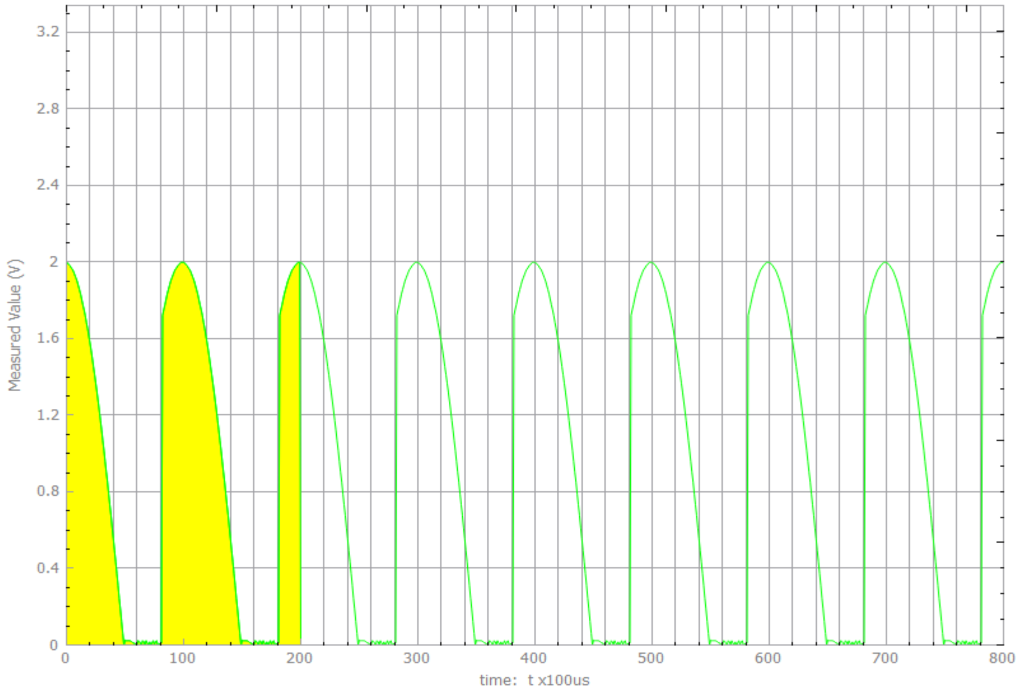

Figure 29. Disturbance record curve captured by IR module when the sensor is activated with an emulated HIF signal. The yellow background curve shows the data collected for HIF compression purpose.

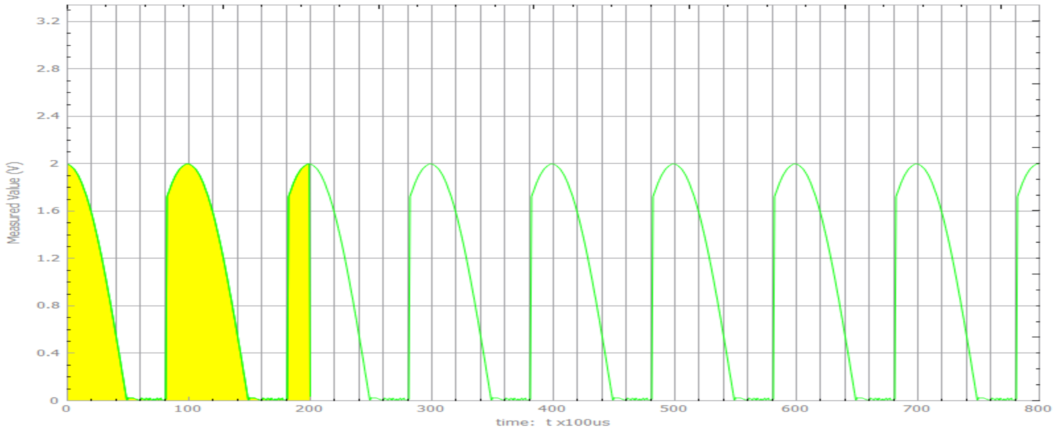

Figure 30. Disturbance record curve captured by UV module when the sensor is activatd with an emulated HIF signal.

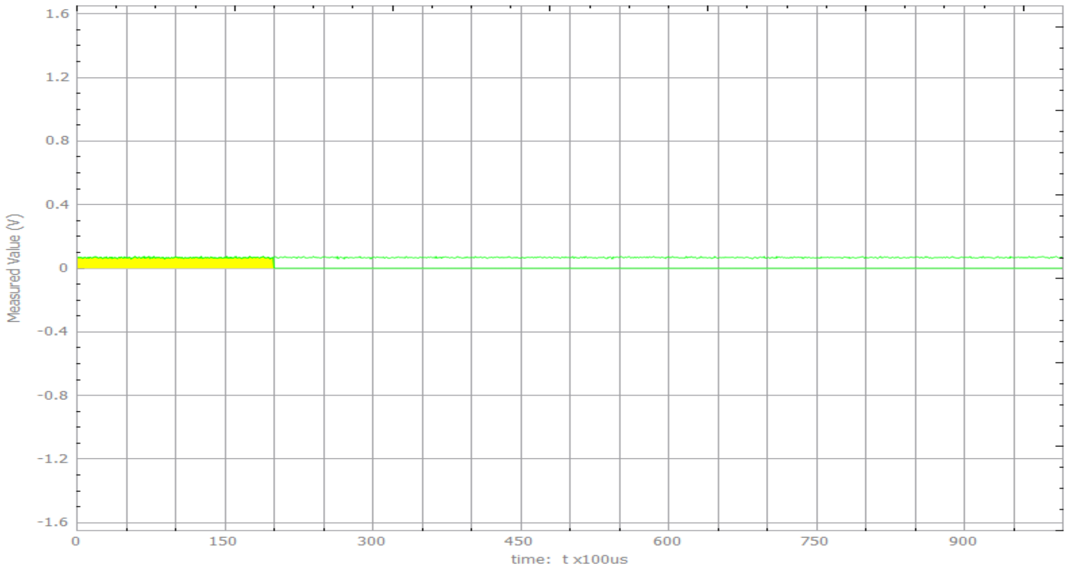

Figure 31. Disturbance record curve captured by magnetic field module when the sensor is activated with an emulated HIF signal.

6 CONCLUSSION

The thesis project was conducted with the intention of developing a complete standalone arc detection sensory module on the basis of previous researches and the current advancement made on sensing technologies. As a result, alternative approach is devised by adding low field linear magnetic sensor to the existing light point sensor system in order to improve trip security regarding low impedance arc fault detection. The added magnetic field sensor provides the system ability to observe both signals simultaneously. Therefore, a miner speed improvement is gained and also implementation of adaptive tuning for changing light level becomes easier and reliable. Furthermore, the sensor firmware was also developed to recognize high impedance faults by analyzing the presented light signal characteristic with a method adapted from widely accepted approaches, developed to detect such faults via a current signal. The use of light signal instead of current signal to recognize high impedance faults removes the uncertainties arising due to load condition or any other factors creating a risk of false positive. As a result, the approach makes it possible to detect such cases reliably with simplified and less time consuming algorithm. Moreover, since the devised method to detect high impedance faults is completely based on software algorism, it can directly be implemented on existing overcorrect plus light protection relays which uses fiber optics loop to transport the light signal.

In general, detecting both types of arc faults with adequate performance and price index implies additional advantage with respect to existing arc fault detection systems. In addition to this, since the methods introduced as an alternative approaches are basically a small shift from existing technologies, the system is very promising alternative to existing arc fault detection systems regarding switchgear protection. Further recommended development works include: Magnetic field distribution study within switchgear under low impedance arc fault or short circuit fault condition, System Optimization design including with final component selection, and certainly testing the system under actual scenario.

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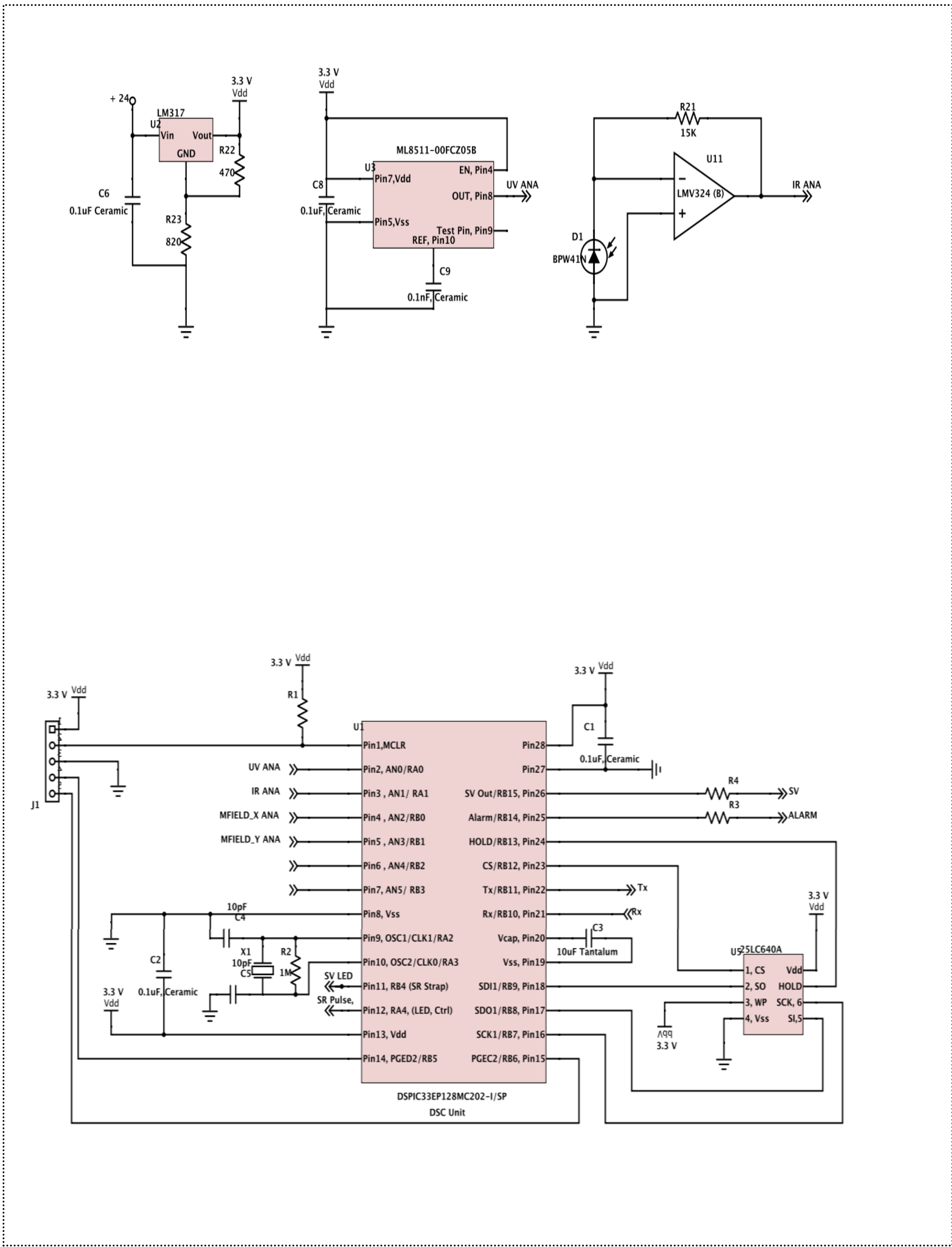
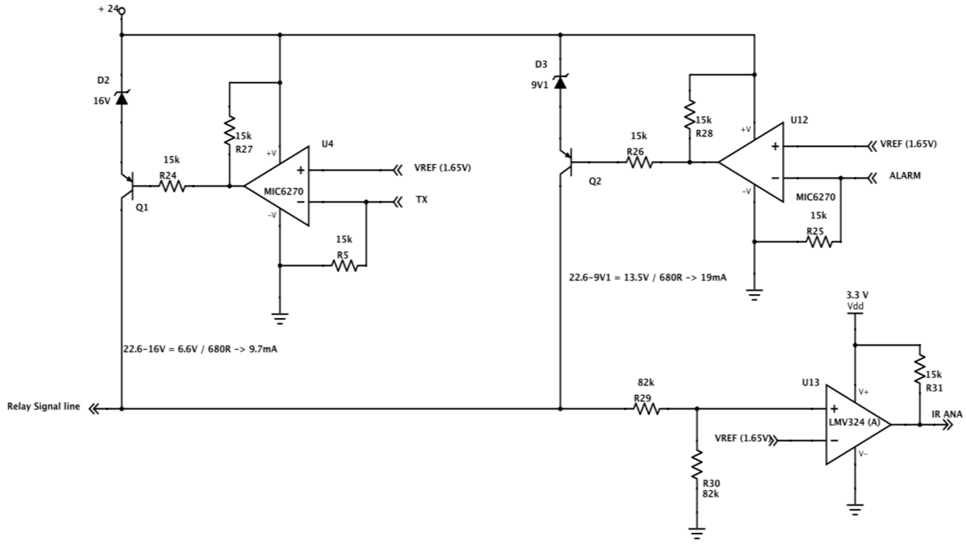
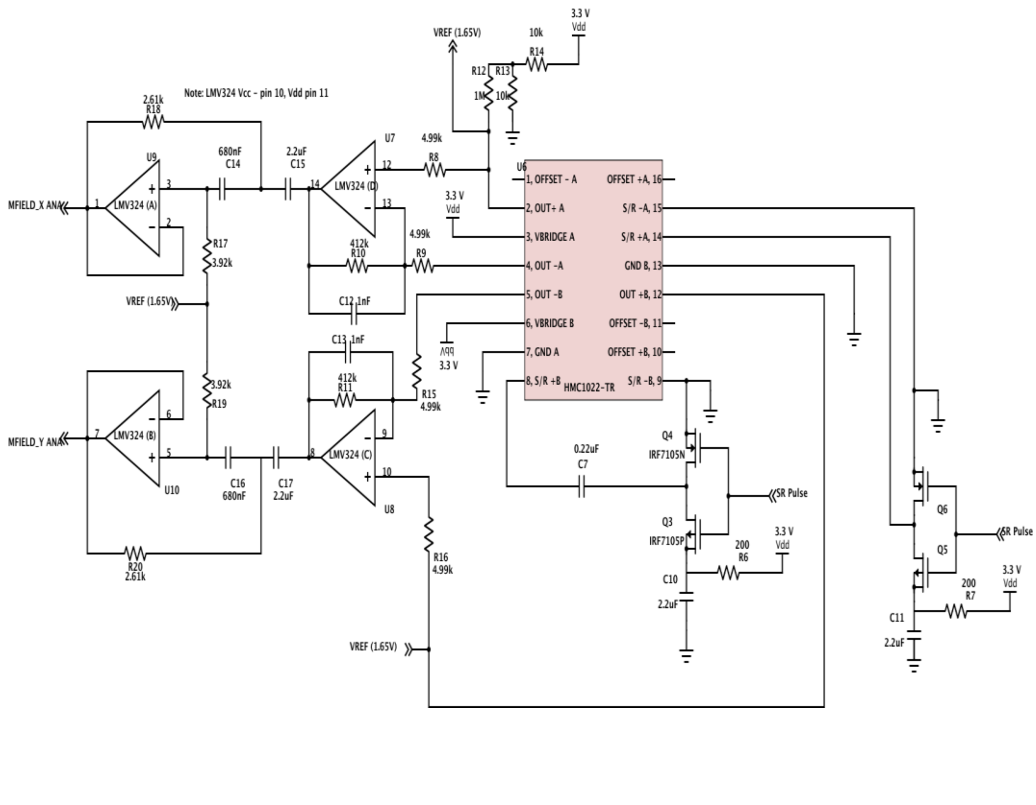
APPEARANCE

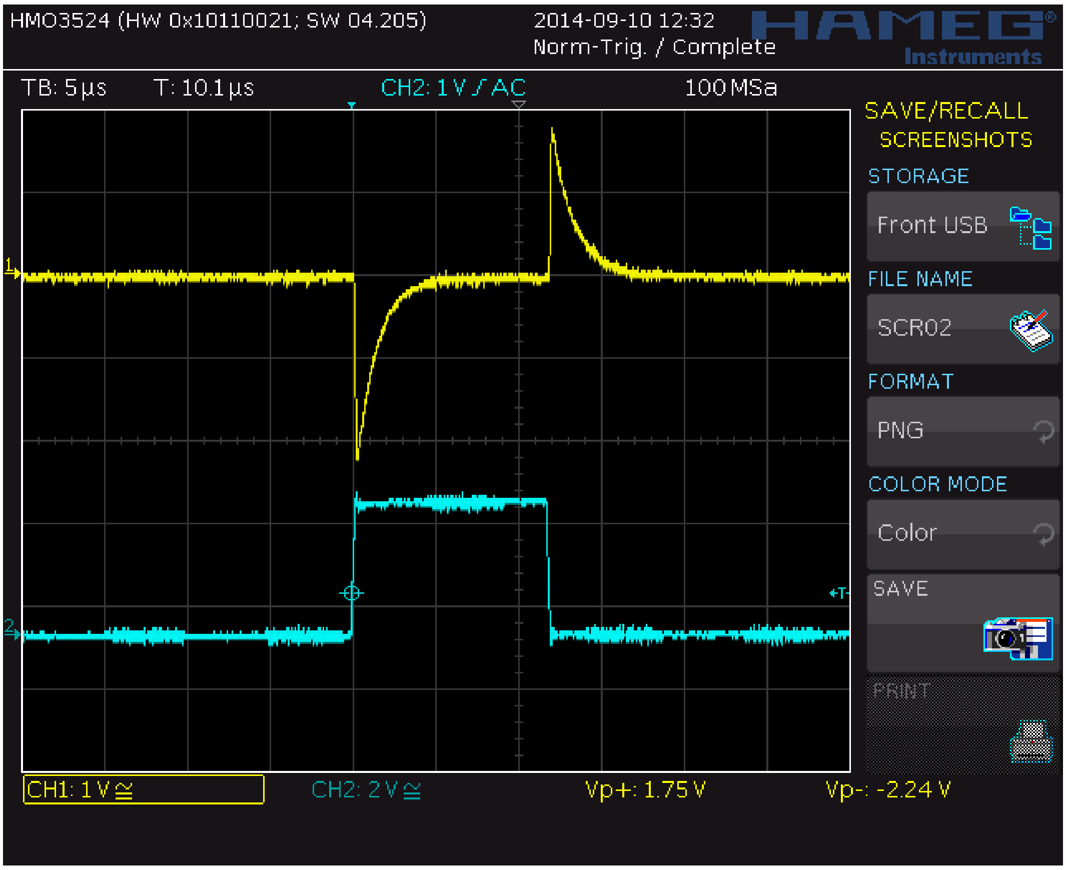
APPENDIX 1: Sensor Module hardware schematic



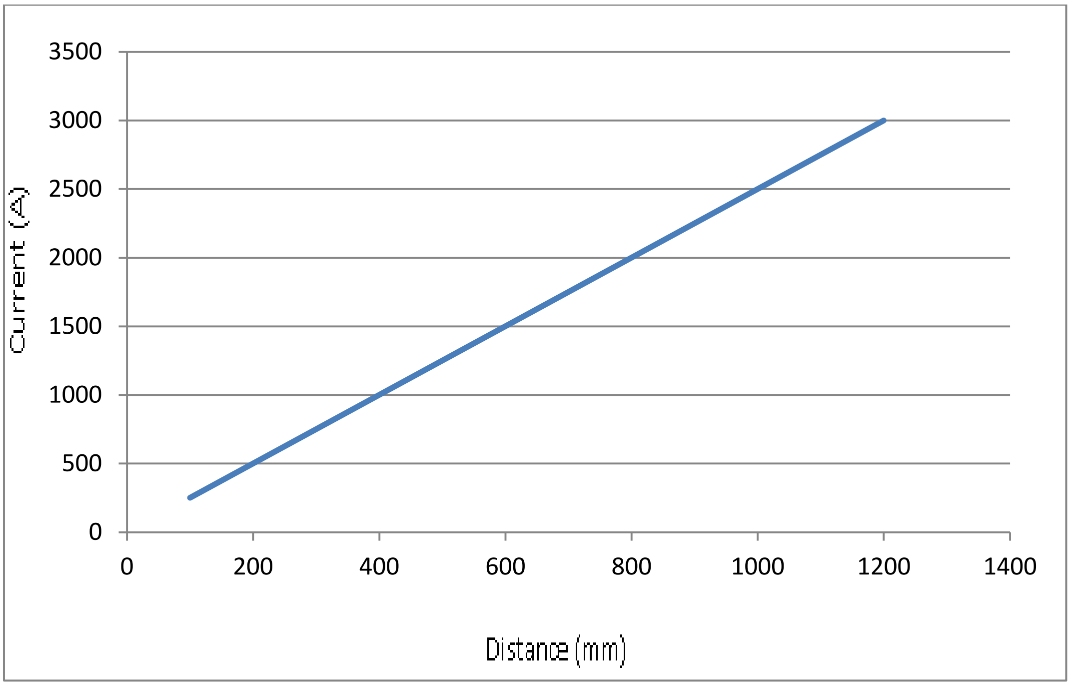

+ 24
D2
16V
Q1
15k
R24
15k
R27
U4
MIC6270
VREF (1.65V)
TX
15k
R5
22.6-16V = 6.6V / 680R -> 9.7mA
D3
9V1
Q2
15k
R26
15k
R28
U12
VREF (1.65V)
ALARM
MIC6270
15k
R25
22.6-9V1 = 13.5V / 680R -> 19mA
3.3 V
Vdd
15k
R31
82k
R29
U13
LMV324 (A)
IR ANA
VREF (1.65V)
R30
82k
Relay Signal line


VREF (1.65V)
10k
R14
3.3 V
Vdd
R12
1M
R13
10k
Note: LMV324 Vcc - pin 10, Vdd pin 11
2.61k
R18
U9
680nF
C14
2.2uF
C15
U7
4.99k
R8
MFIELD_X ANA
LMV324 (A)
R17
3.92k
LMV324 (D)
412k
R10
4.99k
R9
C12 1nF
VREF (1.65V)
C13 1nF
412k
R11
R15
4.99k
3.92k
R19
MFIELD_Y ANA
LMV324 (B)
C16
680nF
C17
2.2uF
U10
LMV324 (C)
U8
R20
2.61k
R16
4.99k
VREF (1.65V)
U6
1, OFFSET - A
2, OUT+ A
3, VBRIDGE A
4, OUT -A
5, OUT -B
6, VBRIDGE B
7, GND A
8, S/R +B
HMC1022-TR
OFFSET +A, 16
S/R -A, 15
S/R +A, 14
GND B, 13
OUT +B, 12
OFFSET -B, 11
OFFSET +B, 10
S/R -B, 9
3.3 V
Vdd
0.22uF
C7
Q4
IRF7105N
Q3
IRF7105P
SR Pulse
200
R6
3.3 V
Vdd
C10
2.2uF
Q6
Q5
SR Pulse
200
R7
3.3 V
Vdd
C11
2.2uF

APPENDIX 2: Set/reset driver circuit output oscilloscope capture



APPENDIX 3: Current Vs Distance relations with fixed ±5gauss field strength



APPENDIX 4: Typical spectrum distribution curve for xenon gas discharge tube