CONDITION MONITORING OF METAL OXIDE SURGE ARRESTERS AT POWER DITRIBUTION

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Degree of Master of Science

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science

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DECLARATION

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ABSTRACT

Metal Oxide Surge Arresters (MOSA) are proven to be reliable protective devices for power distribution and electrical transmission system. MOSA are subjected to electrical ageing or degradation due to constant AC conduction or transient voltages. Leakage current measured from surge arresters are used to observe its degradation and the resistive leakage component is extracted from the total to determine the health of the surge arresters. If resistive current increases, life of the surge arresters decreases. Generally leakage current is measured using current shunts or current transformers where it's necessary to measure the applied voltage which is very hard to measure in online condition. This proposed study develops a simple but accurate method to separate the resistive leakage current from the total leakage current without any voltage measurements by using a technique called Modified Phase Shifted Method (MPSM) which is totally based on manipulation of the total leakage current waveform and simulated in Matlab & Simulink. A prototype device is designed and developed to sense the leakage current from a surge arrester and transmit those data to Matlab & Simulink to perform the MPSM and determine the its resistive leakage current. This method enables remote and an online monitoring system which can alert the utility whenever the health of the installed surge arrester becomes low.

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LIST OF SYMBOLS & ABBREVIATIONS

MOSA – Metal Oxide Surge Arrester

MOV – Metal Oxide Varistor

ZnO – Zinc Oxide

SPD – Surge Protective Device

MPSM – Modified Phase Shifted Method

MCOV – Maximum Continues Operating Voltage

MCU – Micro Controller Unit

PIC – Peripheral Interface Controller

UART – Universal Asynchronous Receiver Transmitter

USB – Universal Serial Bus

MATLAB – Matrix Laboratory

PSCAD – Power System Computer Aided Design

RMS – Root Mean Square

Vc – Maximum Continues Operating Voltage

Vr – Rated Voltage

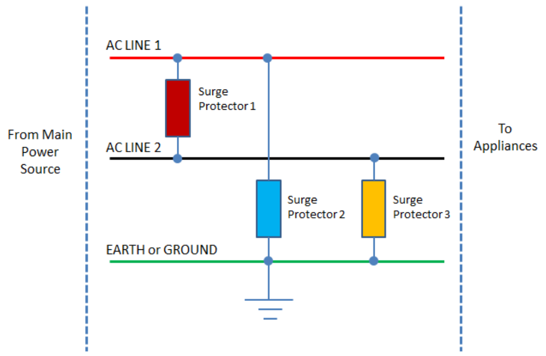
Vo – Operating Voltage

Vs – System Voltage

1. INTRODUCTION

1.1 Background

Surge arresters are installed in power transmission lines and in the substations between phase and earth to minimize the failure rates of the power system. Over voltages occurs due to lightning or switching operations. When a high surge strikes the power system due to a transient, the high voltage current travels through the arrester to the insulation or to the ground to avoid damaging the end equipment or the system.



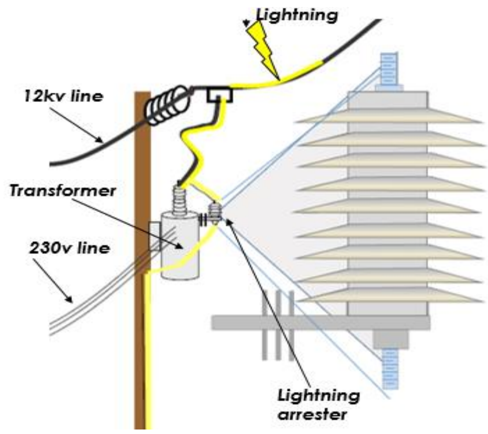


Figure 1: Surge arrester position in AC line

Generally the lightning arrester is for high Lightning currents that can occur with a direct lightning strike and are be simulated with the surge current of 10/350µs wave form which the amount of energy it can withstand is significantly bigger than the surge arresters. The surge arresters is for surges created by remote lightning strikes and switching operations and are simulated with the impulse of 8/20µs wave form. But commonly both types are called as surge arresters (SA).

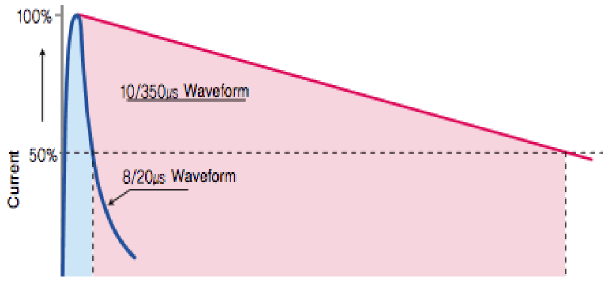


Figure 2: Lightning current waveforms

Surge arresters are used in domestic houses to power substation. So the arrester operating voltages differ for each application. Arresters can be designed to operate for high voltage system up to 1000kV. Also similar devices called as Surge Protective Device (SPD), Transient Voltage Surge Suppressors (TVSS), Surge Diverter, Surge Protector are generally for below 1000V

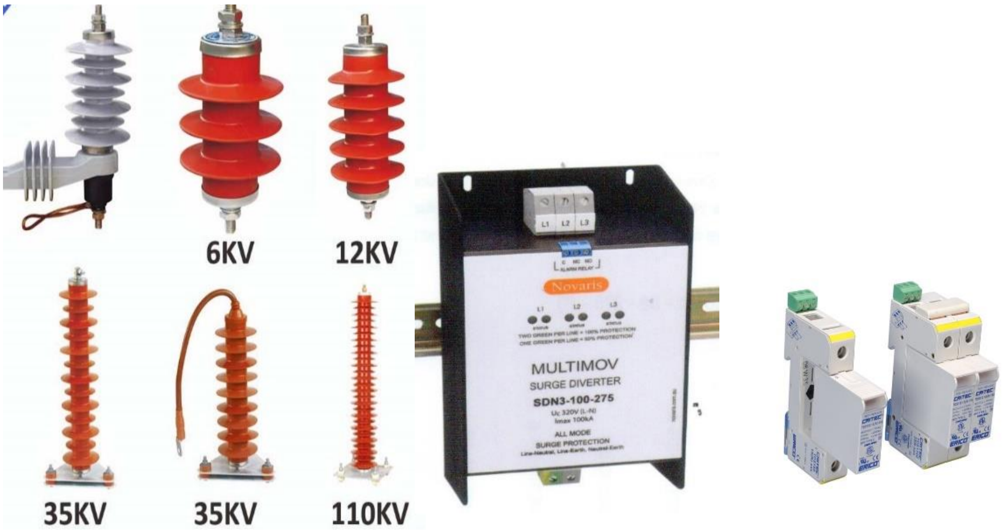


Figure 3: Diferent rated MOV arresters

Metal Oxide Varistor surge arresters are widely used in electrical systems due to its nonlinear high resistance to normal operating voltage and extremely low resistance to higher voltages. MOV arresters utilizes Zinc Oxide blocks exactly for this purpose. Thereby it conducts transients and protect the connected equipment or system such as a transformer. If this protection fails, the end equipment will be damaged causing loss.

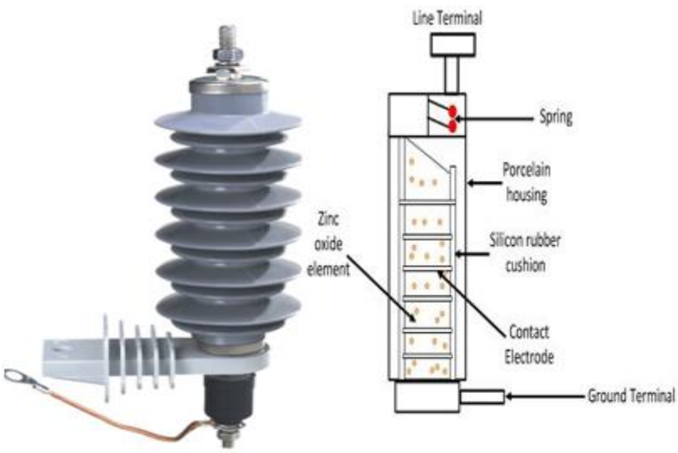


Figure 4: Inside of a MOV arrester

1.2 Motivation

The functionality or the capability of these MOV arresters decreases rapidly with the number of surges it has experienced and the life time of the SA. Once the SA are installed, the utilities seldom monitor the condition of these arresters due to lack of time and staff. If these arresters are damaged, the power system will be unprotected from high surge over voltages, thereby it can damage the connected electrical equipment causing massive loss. And the utilities may be not aware of it unless visually inspected.

In developed countries SA connected to power distribution systems are periodically monitored by using surge monitoring technologies, but currently there are no such technologies widely used in Sri Lanka. A surge arrester monitoring device may costs more than a surge arrester itself, so considering the cost, utilities do not purchase arrester monitoring devices. Therefore the need for a cost effective and online monitoring device which can accurately detect the status of the installed arresters is essential.

More than 20% of transformer failures in Sri Lanka are due to transients. An average of 150 surge arresters have been damaged and replaced last year. The increasing numbers of failures in power transmission and distribution system failures motivated the author to select this subject to research and propose a method and a prototype to monitor the health of the installed SA.

1.3 Objective

Objective of this research is to study the characteristics of the SA which can be used to monitor its condition and develop a relationship of those parameters to the lifetime of the arrester. Based on these relationships a device will be designed and developed to online monitor and evaluate the condition of the arrester and alert the utility to replace the arrester when their functioning capability becomes low.

1.4 Scope of work

The scope of works for this research are as follows;

i. Research on MOV surge arresters and identify the suitable technique which can be used to remotely sense the health of an installed arrester accurately.
ii. Study the techniques and develop a suitable method to extract the resistive leakage current from the total leakage current which indicates the ageing of the arresters.
iii. Test the arresters with transients and study the leakage current waveforms.
iv. Develop a prototype device which can sense the leakage current from the arrester and send those data to a remote computer via transceivers.
v. Identify a suitable software and develop a simulation to differentiate the resistive current component from the total leakage current.

2. LITERATURE REVIEW

2.1 Advantages of Metal Oxide Surge Arrester

Gapless Metal Oxide Surge Arresters are mostly used in power system protection. The voltage-current nonlinear characteristics of these arrester types are high efficient and have eliminated other types of surge arresters (SA) in the market.

Table below compares different arrester types.

Table 1: Types of surge arresters

Type of Surge Arrester	Working principle	High Energy/ High current	Low let- through voltage	No Follow- on Current
Gas Discharge	Inert gas	✗	✗	✗
Spark gaps	Air or gas	✓✓	✗	✗✗
Silicon Carbide	SiC blocks	✗✗	✓✓	✓
Metal Oxide	MO Varistor	✓	✓	✓

There are numerous benefits of Metal Oxide surge arresters compared to other types of arresters. These are discussed below

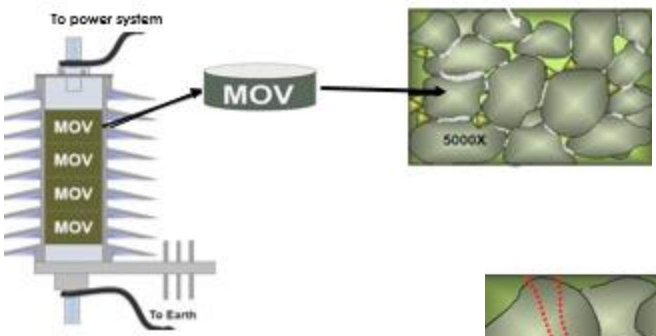
- The distinguishing feature of a zinc oxide is its exponential variation of current over a narrow range of applied voltage.
- The resistance of an MOV is nonlinear and decreases as voltage magnitude increases.
- At the normal operating condition, the leakage current in the ZnO is very low as compared to other diverters.
- In parallel-connected MOV circuits, the surge current is distributed through each of the MOVs, which results in an improved circuit with higher surge-current capability.

- There is no power follow current in ZnO diverter where as in other cases even after the transient there will be still some power discharges.
- MOVs has relatively large surge-current and energy ratings.
- It has high energy absorbing capability and a very low let through voltage to the load.
- ZnO diverters possess high stability during and after prolonged discharge.
- MOV have a maximum continuous operating voltage rating, which indicates the maximum voltage the device is expected.

Thus it is proved that MOVs are much efficient arrester types for protection in power system.

2.2 Construction and operation of MO Surge Arrester

MO arresters consists of varistor disks which are semiconductor that is sensitive to voltage. At normal Voltages the MOV disk is an insulator and will not conduct current. But at higher voltages caused by a transient, it becomes a conductor. Metal Oxide Varistor consist of billions of Zinc Oxide grains. These grains acts as electronic switches that turn On and Off in microseconds to form a current path from the top terminal to the ground terminal of the arrester. There by it divert the surge current and protect the electrical devices.



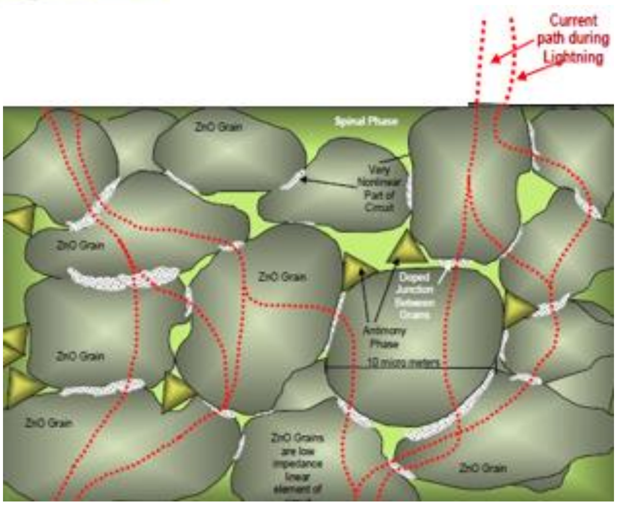


Figure 5: Operation of a MOV arrester

An equivalent electric circuit of a Zinc oxide blockis shown below. The diverted current to the earth would consist mostly of capacitive component as well as resistive component.

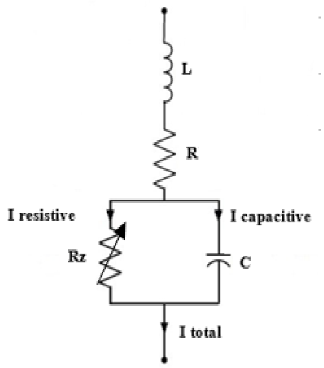


Figure 6: Equivalent circuit of ZnO block

Where,

L is the Inductance which is determined by the geometry of the current flow path

R is the resistance of the ZnO grains with a resistivity of about 0.01 Ωm

Rz is the non-linear resistance of the granular layers where the resistivity ρ changes from 10^8 Ωm for low electric field stress to just below 0.01 Ωm for high stress

C is the capacitance between the granular layers with relative dielectric constant between 500 and 1200 depending on manufacturing process

2.3 Characteristics of the MOSA

2.3.1 Voltage-Current

MO Surge arrester have an extremely high resistance during normal system operation and a relatively low resistance during transient over voltages. That is, it must have non-linear voltage versus current (V-I) characteristic. Figure below shows the V-I characteristics of ZnO element which are divided into three regions.

1. **Low current region;**

In this region the characteristics vary considerably with the temperature T. This region is located at a point where the line-frequency voltage is applied in applications for metal oxide arresters and it becomes important to pay attention particularly to the characteristic change with energized time and the temperature dependence

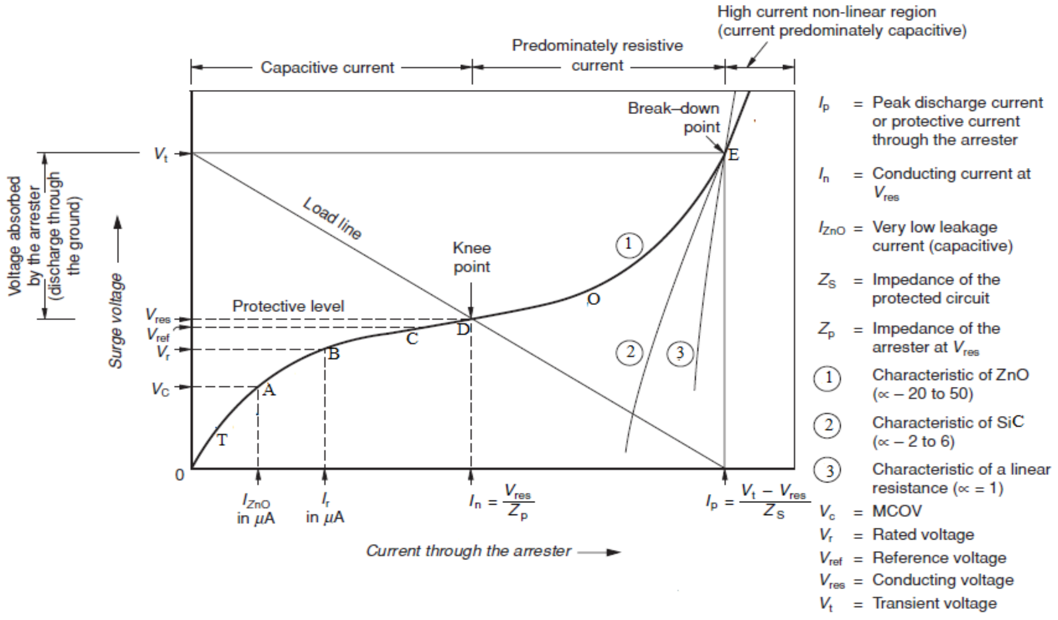


Figure 7: Current - Voltage graph

Temperature Co efficient (point T on graph): Initial temperature of the arrester

Maximum Continuous operating voltage (MCOV), Vc (point A on graph): Designated r.m.s value of power frequency voltage that may be applied continuously between the terminals of the arrester without a discharge. The continuous operating voltage of the arrester must be higher than the maximum continuous operating voltage of the system. The current is in the range of a few µA. Therefore Maximum continuous operating voltage is given as,

$$V_c = \frac{V_m}{\sqrt{3}}$$ (Phase to neutral)

Voltages above Vc (MCOV) may be temporary over voltages (TOVs)

2. **Operating region;**

In applications of ZnO surge arrester this second region relates to protective characteristics when a lightning impulse current has flowed through the arrester. The nonlinearity is generally given by the following experimental expression:

I=CV α

where α = nonlinear exponent and C is a constant. The greater the value of α, the better is the protective characteristics.

Rated voltage, Vr (point B on graph):

Maximum permissible r.m.s value of power frequency voltage between arrester terminals at which is designed to operate correctly under temporary over voltages.

The arrester can withstand this voltage without a discharge for minimum 10s under continuously rated conditions. Now it also draws a current resistive in nature, in the range of a few m A.
The lower this current, lower will be the loss and the heat generated during an over voltage and hence better energy absorption capability. Below the knee point the graph sharply drooping with the temperature rise causing a higher leakage current.

Reference voltage, Vref (point C on graph):
This is an r.m.s. voltage close to the knee-point where it commences conduction and draws a current that is resistive in nature, in the range of a few mA. Typical values are 0.4–10 mA. This voltage is applied to the arrester to determine the peak value of the resistive component of the reference current which constitutes an important parameter to define the characteristics of an arrester.

3. **High current region;**

In high current region , the resistivity of ZnO grain is dominant and the characteristic is given by:

$V \approx KI$ (4)

Where K is the resistivity of the ZnO grain.

Residual voltage, Vres (Point D on graph): Peak value of the voltage that appears between arrester terminals when a discharge current or surge is injected.

Transient voltage,Vt (Point E on graph): Maximum permissible energy that an arrester may be subjected to without being damaged and without loss of its thermal stability.

2.3.2 Current-Time

In case of a lightning or switching surge, the current from the surge is diverted through the arrester, in most cases to earth. Most commonly used surge arrester for power distribution has a rating of 8/20 µs at a discharge current. When a surge occurs the current through the arrester rises from 10% of peak to 90% of peak in 8 microseconds and falls to 50% of peak in 20 microseconds.

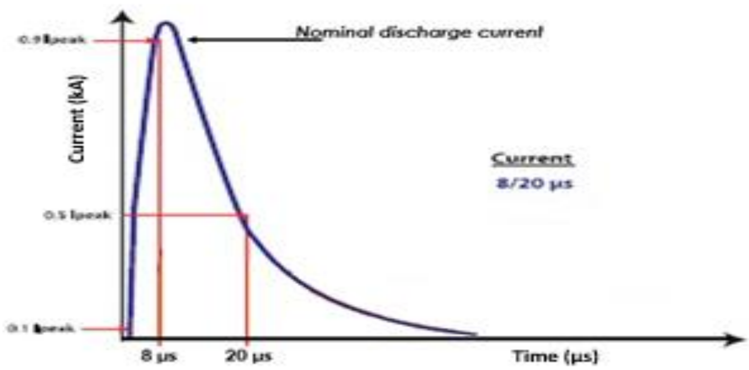


Figure 8: Current - Time graph

In the graph;

Discharge current: Impulse current that flows through the arrester.

Nominal discharge current: Peak value of lightning current impulse, which is used to classify an arrester.

Lightning impulse protective level: Voltage that drops across the arrester when the rated discharge current flows through the arrester.

2.3.3 Voltage-Time

Typical voltage wave form of an arrester at transient is specified by 1.2/50 µs. When a surge occurs, the voltage through arrester rises from 10% of peak to 90% of peak in 1.2 microseconds and falls to 50% of peak in 50 microseconds

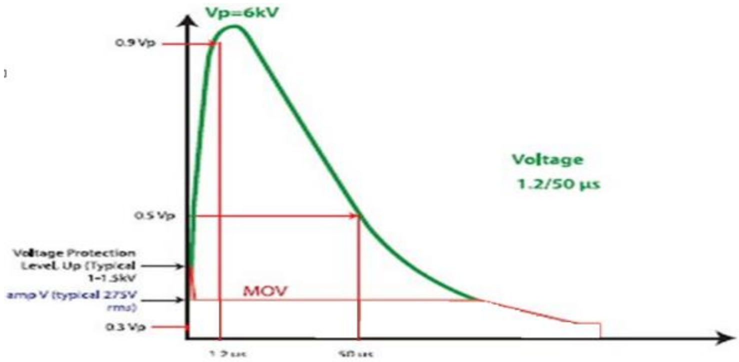


Figure 9: Voltage - Time graph

2.4 Factors affecting the life time of MOSA

MOV arresters are subjected to various electrical and mechanical stresses during its life time. These stresses will affect the characteristics of the MOV arresters and eventually its performance degrades on continues operation. Therefore the arresters should be able to withstand these stresses as well as protect the power distribution system throughout its life time. Also arresters should be designed to stay thermally stable after a transient event.

Sun heats the arrester such that the internal pressure increases relative to ambient and outward gas leakage occurs. When the arrester cools at night, this process reverses, with internal pressure dropping below ambient and external air being drawn into the arrester. Such a cycle can repeat itself over many days, months or even years before the moisture inside builds to the point where there is a problem with reduced dielectric integrity

Figure 10: MOV arrester failure

Main factors affecting the lifetime of MOSA are:

- Entry of moisture: Due to bad sealing which increases thermal heating, leakage current and causes discharges and degradation of Zinc Oxide Blocks.
- Manufacturing defects: Localized losses and discharging caused by poor inter-disc contact
- Electrical aging of MOV disk:
  - Housing deterioration or pollution changing the voltage distribution along the .stack
  - Mechanical fractures in the MO material due to thermal runaway after a high-.current surge.
  - Damage of sealing due to thermal heating produced inside varistor.
  - Damage due to surge current concentration at the edge of the electrode resulting in failure.
  - Resultant damage to the disc created by previous multiple-stroke lightning surges.

Almost 86% of Surge arrester failures are due to moisture ingress. Only 5% is due to surges. These factors could cause problems for the surge arrester in service. As a result, it is very important to measure the condition of arresters in service. The moisture absorption in an arrester results in slightly increased leakage current

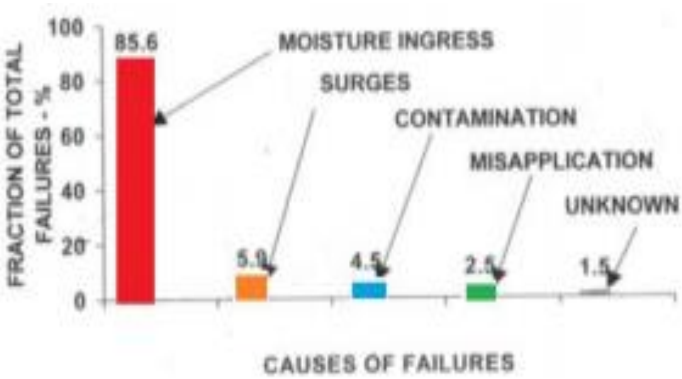


Figure 11: Causes of MOV arrester failurs

MOV surge arresters go through several stages before the dielectric breakdown of the MOV blocks;

- Degradation Failure Mode:
  When a MOV block's nominal voltage drops by 90% of its initial Value.
- Linearization Failure mode: (Short circuit mode)
  When a grain boundary chain between the two opposite electrodes of a MOV block is lost.
- High clamping voltage failure mode:
  When a MOV block's clamping voltage increases by 110% of its initial value.
- Leakage current instability failure mode:
  When leakage current of a MOV block increases firmly with time when maximum continues operating voltage (MCOV) is applied.
- Catastrophic failure mode:
  When a MOV block meets with a sudden or complete failure.

It can be observed that surge arrester experiences several modes before the complete dielectric breakdown process. Therefore a suitable method should be considered for arrester monitoring purpose

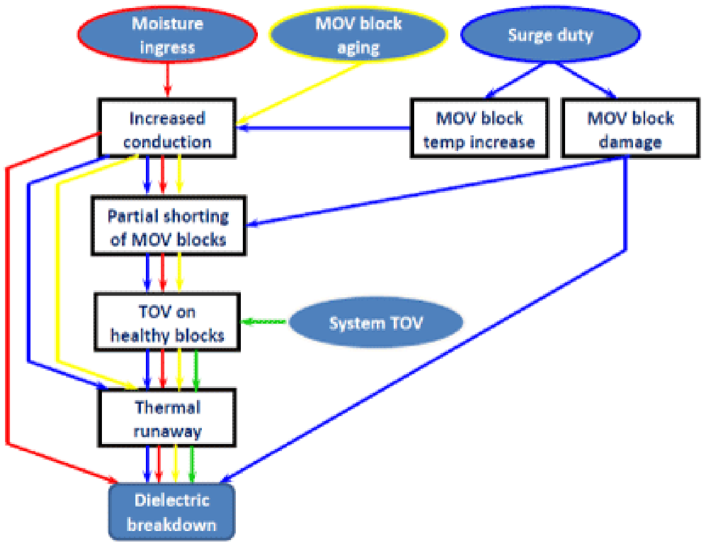


Figure 12: Dielectric breakdown of MOV arrester

2.5 Importance of monitoring of Surge Arresters

In the lightning overvoltage and switching overvoltage range, the magnitude of overvoltage can reach several per unit if the system is without arrester protection. Arrester could limit overvoltage below withstand voltage of equipment.

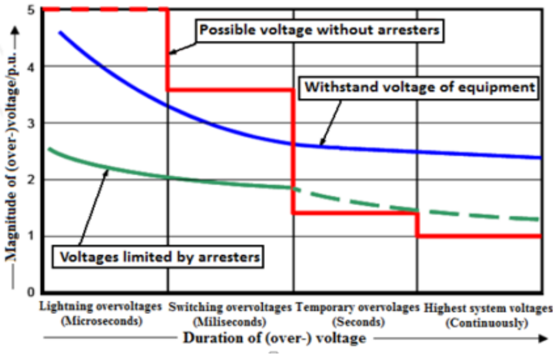


Figure 13: Voltage protection by MOV arrester

However the functionality of the installed surge arresters changes with high transient impulse which affect thermal stability, external insulation, energy withstand capability and causes aging. If the SA is damaged, the surge may travel to connected equipment such as transformer and thereby damage it causing massive loss since there is no protection.

Many of these devices are not inspected once they are installed and the user is not aware of their operating status and the failure of the SPD does not necessarily cause any immediately noticeable symptoms for the user. Utilities are facing a problem of detecting surge arrester status due to lack of time and staff for visual inspection. If a surge monitoring device is connected along with the arrester, it can monitor the health of SA and send those information to the utilities automatically. This can reduce damages to the equipment due to transient over voltages and also this can reduce labor hours as well. Therefore arrester monitoring is very significant.

3. SURGE ARRESTER MONITORING METHODS

3.1 Different types of arrester monitoring techniques

Functionality of the installed surge arresters changes with high transient impulse which affect thermal stability, external insulation, energy withstand capability and causes aging. There are few methods to monitor the health of SA. Table below compares the different techniques and contrasts the benefits of each test type based on the situation is presented

Table 2: Arrester monitoring methods

Arrester monitoring methods/ Definition of terms	**Sensitivity to arrester health**	**Informative**	**Reliable**	**Ease of use**	**Speed of use**	**Cost**	**Remote monitoring**
Infra-red/Thermal imaging	High	High	High	Easy	Fat	Medium	No
Surge counter/spark gaps	Very low	Low	Very low	Easy	Slow	Low	No
Total leakage current	Low	Low	Low	Easy	Fast	Low	Yes
Watt loss	High	High	High	Hard	Slow	High	Yes
Resistive current	**Very high**	**High**	**Very high**	**Hard**	**Medium**	**High**	**Yes**
IR measurement	Low	Medium	Medium	Hard	Slow	High	No
Partial discharge test	Low	Low	Low	Hard	Medium	High	No

Extraction of resistive leakage current is the most suitable method since it is the most Informative, reliable and sensitive to arrester health. The existing methods may be cost high and hard to use but cost effective and simple device can be developed without the need of complex hardware or online voltage measurements.

3.2 Suitability of resistive leakage current for arrester monitoring

The total leakage current from an arrester is combined with capacitive component and resistive components through the MOV disks and over the external housing of the arrester. Capacitive current is caused by the permittivity of the ZnO elements such as grading capacitors which are dielectric constant and unwanted stray capacitance which do not gives any indication of the aging of MOV disks. Resistive current is purely caused by the electrical ageing of the ZnO elements and the porcelain surface current

Nearly 90% of leakage current is capacitive therefore a large increase in the resistive leakage current is needed before a noticeable change occurs in the total leakage current level. Therefore, the total leakage current is not suitable for arrester health diagnostic purposes

The resistive leakage current is defined as the Instantaneous value of the total current when the voltage across the arrester is at its maximum. Resistive current measurement is the reliable method of monitoring the health of surge arrester. Factors which lead to high resistive current are as follows;

- Ingress of Moisture
- Electrical aging of ZnO blocks
- Increase in arrester temperature
- Housing surface pollution

That explains why the extraction of resistive leakage current is the most reliable method for condition monitoring of MOV surge arresters.

The higher resistive leakage current may ultimately bring in the SA to thermal instability and may result in complete failure/breakdown of the arrester. Hence, the resistive leakage current is the true indicator of health of an SA in service.

3.3 Comparison of various resistive current measurement methods

Table below compares different techniques used to extract resistive current. It can be seen that Shifted current method is the most accurate method to extract the resistive component from the total leakage current. The most important is that this method doesn't require the applied voltage. Also an online monitoring device can be developed using this technique to remotely sense the leakage current and separate the resistive from the user end.

Table 3: Resistive current monitoring methods

Definition of terms / Methods	Principle	Ease of use	Accuracy	Voltage measurement	Online monitoring	Cost
Compensation Method	Analyse applied voltage and leakage current	Medium	Low	Needed	No	Medium
Harmonics analysis	Analysing the harmonics in the leakage current waveform	Medium	Medium	Not needed	No	High
Point of Wave Technique	Analyse applied voltage and leakage current waveform	Medium	Medium	Needed	Yes	Medium
Modified Phase Shifted Method algorithm	Manipulation of leakage current waveform	Medium	High	Not needed	Yes	medium

Modified Phase shifted Method gives an accurate measurement and can be implemented in a signal processing computer software. This algorithm is explained in Chapter 8.

4. SIMULATION RESULTS FOR LEAKAGE CURRENT BEHAVIOUR OF MOV ARRESTERS

The proposed method focuses on the ZnO arrester characteristic in low current region. In the low current region, Resistance of ZnO grains which is much lesser than the nonlinear resistance and the inductance L can be neglected. Therefore, in the continuous operating voltage region, the ZnO surge arrester is modelled as a non-linear resistor with a linear capacitive element in parallel as shown in the figure.

The simplified equivalent circuit is modelled in PSCAD and simulated with transients. When an over voltage is applied to the 30kV rated surge arrester, it can be observed that the output leakage current through the arrester is distorted. The leakage current graph varies significantly when applied voltage is increased by gap of 5kV.

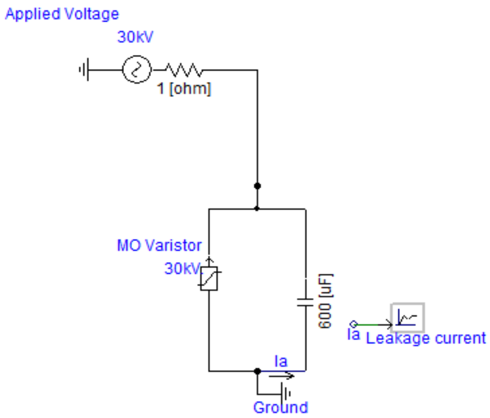


Figure 14: Equivalent MOV circuit Modelled in PSCAD

When a 20 kV supply is passed through a 30 kV rated arrester, it can be observed that the leakage current is sinusoidal wave and therefore no discharge from the surge arrester. 25kV is the MCOV of a 30kV rated surge arrester.

When a 30 kV supply is passed through the same system, it can be observed that the leakage current is still a pure sine wave. This is the rated point at which arrester is operated correctly under temporary over voltages.

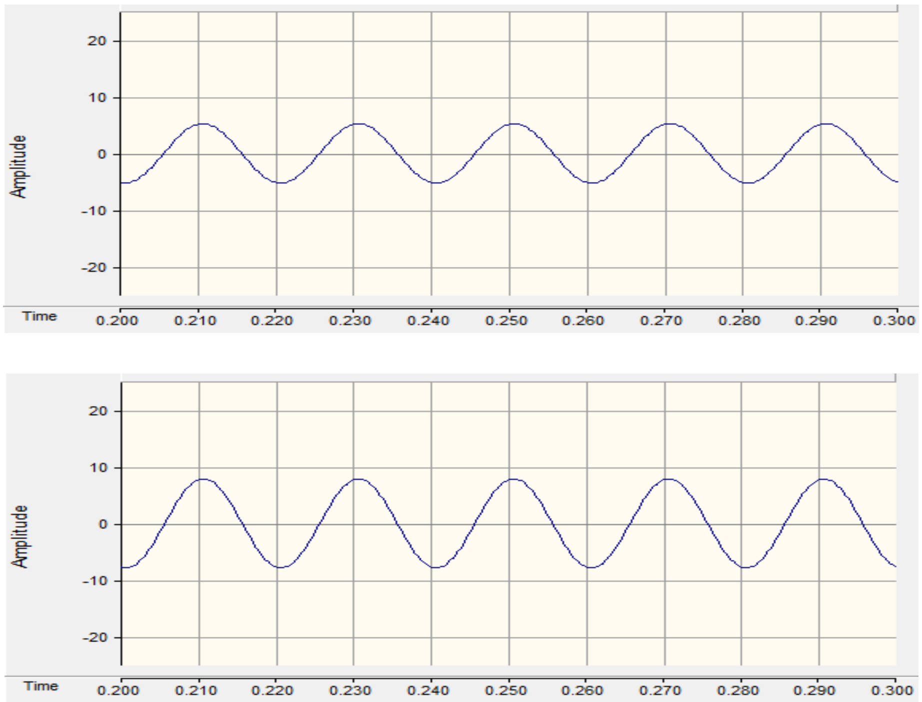


Figure 15: Simulation results for 25kV & 30kV

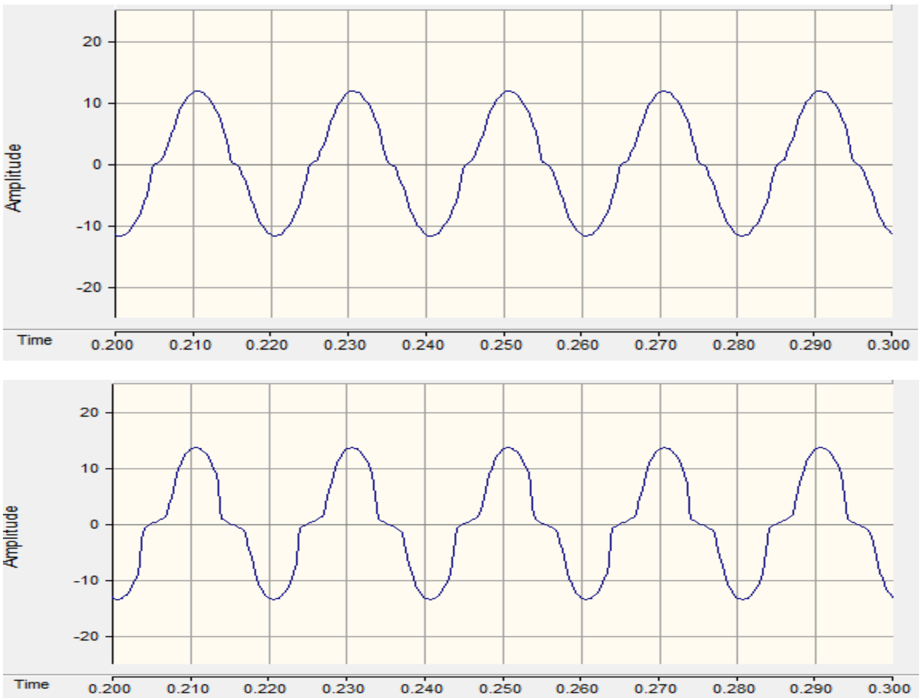


Figure 16: Simulation results for 45kV & 60kV

At 45kV leakage current slightly distorted and there onwards distortion increases when the applied voltage is increased. At 60kV it can be observed that leakage current is strongly distorted.

The continuous conduction of MOSA under distorted AC voltage stress is simulated and subsequently analysed in this study. It can be observed that the higher the MOSA devices subjected to AC voltage, higher the increased rate of leakage current.

When a supply of 90kV or more is passed through a 30 kV rated arrester, s strong distorted leakage current can be observed since a strong discharge has occurred in the surge arrester.

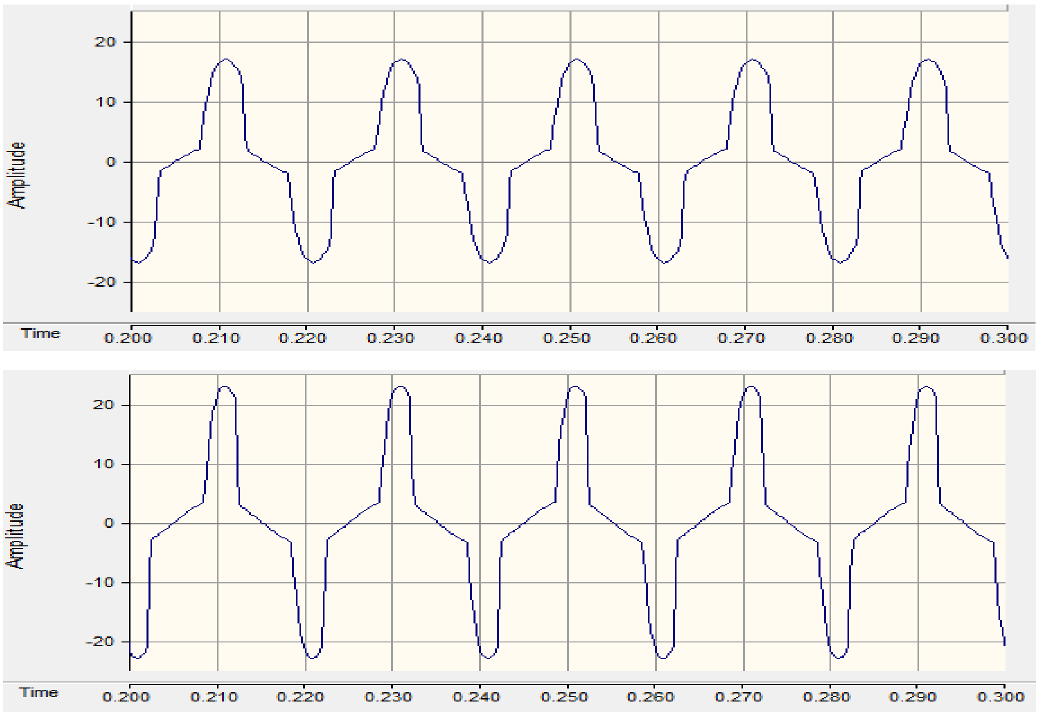


Figure 17: Simulation results fro 75kV & 90kV

A perfect arrester which has no degradation has a leakage current similar to a sinusoidal wave. A functioning arrester which has low degradation and operated under its rated voltage, the leakage current can be considered almost capacitive as shown in figure. When the surge arrester is subjected to some kind of degradation the resistive component becomes sufficient enough to distort the flawless waveform of the leakage current as seen in the figure

5. EXPERIMENT SETUP TO MEASURE LEAKAGE CURRENT OF MOV ARRESTERS

High voltage metal oxide surge arrester manufacturers provides 250 µA as the maximum leakage current in normal environmental conditions. The following measurements were taken from a logbook of 30kV surge arrester.

Table 4: MOV arrester log book of an arrester at a site

Date of measurement	Actual measurement	Condition of the arrester
1st year	70	Good
3rd year	90	Good
5th year	115	Good
7th year	160	Sign of deterioration
7.5 year	220	Sign of rapid deterioration
8th year	300	Required servicing or replacement

MOV surge arresters are available from 275V up to 1000kV. High voltage lab facilities needed to test the HV rated surge arresters where the SA are connected by HV AC charged capacitors. The SA should be earthed via an Ammeter to measure the leakage current. A current probe oscilloscope can be clipped on the earth wire to observe the leakage current waveforms. Impulse Generator needed for transient experiments.

Arresters are supplied with a voltage of its rated value for a specific time, then increase the voltage step by step for a specific time and observe the leakage current. Then connect it to the impulse generator to supply with a transient voltage and observe the leakage current. Then repeat with the previous experiment with the HV test

Experiment setup to test HV rated surge arresters are shown below.

Figure 18: Manual impulse generator

Figure 19: AC High voltage tester

For an experiment 30kV (Vr) surge arrester was removed from a power distribution line, was cleaned and tested with transients. Test results show that the arrester is starting to deterioration.

Table 5: Test results of 30kV MOV arrester

kV	20	25	30	35	40	45	50	55	60
μA	0	10	17	49	92	142	166	185	210

For another experiment a partially damaged 475V (Vc) surge arrester which was removed from a low voltage transmission line was used for testing and leakage current measurements were recorded. Leakage current waveforms were also observed in the oscilloscope. Test results shows its better to replace the arrester.

Figure 20: 475V MOV arrester testing

Table 6: Test results of 475V MOV arrester

V	300	350	375	400	425	450	475	500
μA	15	24	51	80	120	155	180	222

When an over voltage is supplied to the surge arrester above its rated voltage, increasing leakage current were observed and the amplitude of the leakage current were seen varying. If the arrester is in a good state he corresponding leakage current waveform should be pure sine wave as shown in the figure 21 below

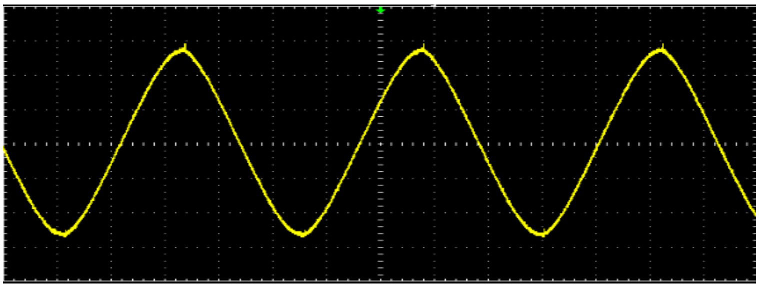


Figure 21: Leakage current when arresetr is in good state

Leakage current of 17µA measured when a constant voltage of 30kV is continuously applied to 30kV arrester which is considered as highly capacitive leakage current.

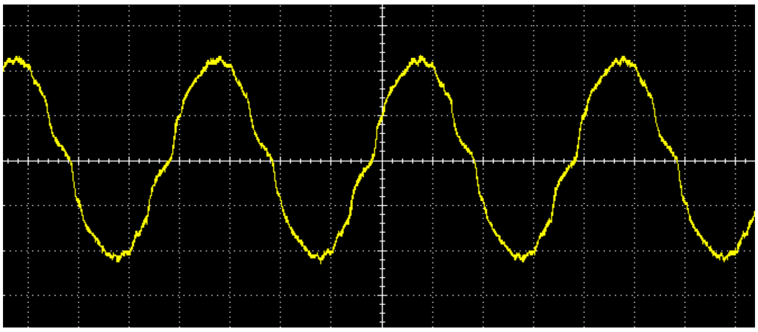


Figure 22: Leakage curretn of 65µA

Leakage current of 180µA measured when a constant voltage of 475V is continuously applied to 475V arrester which is considered as highly resistive leakage current.

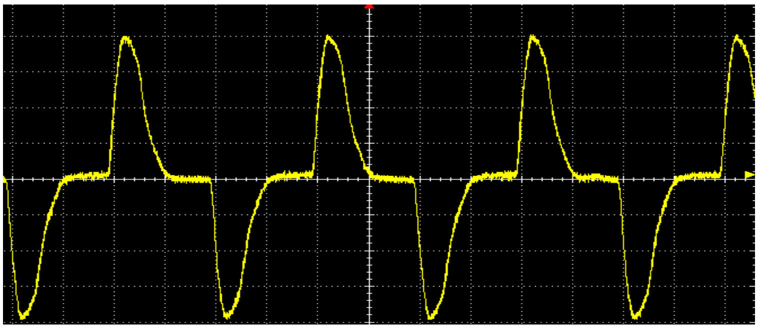


Figure 23: Leakage currnet of 460µA

The experiment and measurements were carried out on a functional MO arresters at a room temperature. The total leakage current from the arrester and the input voltage were measured simultaneously.

PSCAD Simulation leakage current results were exactly same as the practically tested arrester leakage current waveforms.

Health of this surge arrester cannot be determined by theses measured leakage current since these inclusive of capacitive current from the arrester. Therefore resistive part should be differentiated from these values to determine the health of this arrester. The total leakage current (I_X) of the arrester is given by a vector sum of capacitive current (I_C) and the resistive leakage current (I_R). I_C does not vary with degradation of the MO arrester but I_R varies with the degradation of the MOV arrester, below is a typical phasor relationship of all three currents.

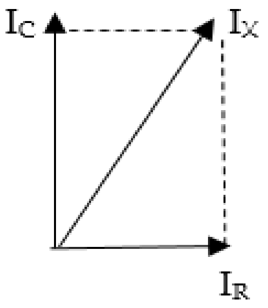


Figure 24: Phasor diagam of leakage current components

6. MODIFIED PHASE SHIFTING METHOD

Modified Phase Shifted Method of separating the resistive part from the total leakage current is the most suitable for the condition monitoring of SA. The method is totally based on manipulation of the total leakage current waveform. The algorithm and the implementation of this method are discussed below.

6.1 Algorithm of MPSM

Leakage current components are time dependent, therefore the components I_X (Total), I_C (Capacitive) and I_R (Resistive) can be written as follows

$$I_X(t) = I_R(t) + I_C(t) \quad (1)$$

The resistive leakage current component could obtain with cancelled capacitor leakage current component from the total leakage current.

$$I_R(t) = I_X(t) - I_C(t) \quad (2)$$

$$I_X(t) = I_C\cos\omega t + [I_R] \quad (3)$$

Where, $[I_R]$ is the resistive component with harmonics. The cancellation of capacitive leakage current component from total leakage current done by adding another capacitive current Ic with different phase angle π, so

Substituting equation (3) in equation (2)

$$I_R(t) = I_C\cos\omega t + [I_R] + I_C\cos(\omega t - \pi) \quad (4)$$

$$I_R(t) = I_C\cos\omega t + I_C\cos(\omega t - \pi) + [I_R] \quad (5)$$

Equation 5 can be written as,

$$I_R(t) = 2I_C\cos\frac{\pi}{2}.I_C\cos(\omega t - \frac{\pi}{2}) + [I_R] \quad (6)$$

Where as

$$2I_C\cos\frac{\pi}{2}.I_C\cos\left(\omega t - \frac{\pi}{2}\right) = 0 \quad (7)$$

In Modified Shifted Method, the original leakage current is shifted by quarter period of time,

$$Ishifted(t) = \quad I_C \cos{(\omega t - 1/4f)} \qquad (8)$$

$$Isum(t) = I_C \cos(\omega t) + [I_R] + I_C \cos{(\omega t - 1/4f)} \qquad (9)$$

Ishifted is the shifted total leakage current (by a quarter of period of waveform), and Isum is the summation of the total leakage current and the shifted current wave form. By signal manipulation technique, from this summation current, the capacitive component of total leakage current can be determined, and thereafter the resistive component of the leakage current can also be obtained by subtracting the capacitive component from the total leakage current.

MPSM technique is explained step by step below:

1. First the original total leakage current wave form is obtained.
2. Frequency of the total leakage current is determined.
3. A new waveform is formed by introducing a quarter period delay to the original leakage waveform. That is shifting it by 90^0. The sifted current has the same magnitude with phase difference of 90^0.
4. Then both the waveforms are summed together and their peak time is detected. That peak time is the peak time of the resistive component.
5. Then the peak time of the capacitive component is determined which is equal to quarter period before or after peak time of the resistive component.
6. Then the peak value of the capacitive component can be determined from the original leakage waveform by reading the corresponding value at that time.
7. Then the capacitive leakage current is generated from the peak time, peak value and the frequency detected.
8. Thereby the resistive current is obtained by subtracting the capacitive current from the total leakage current.

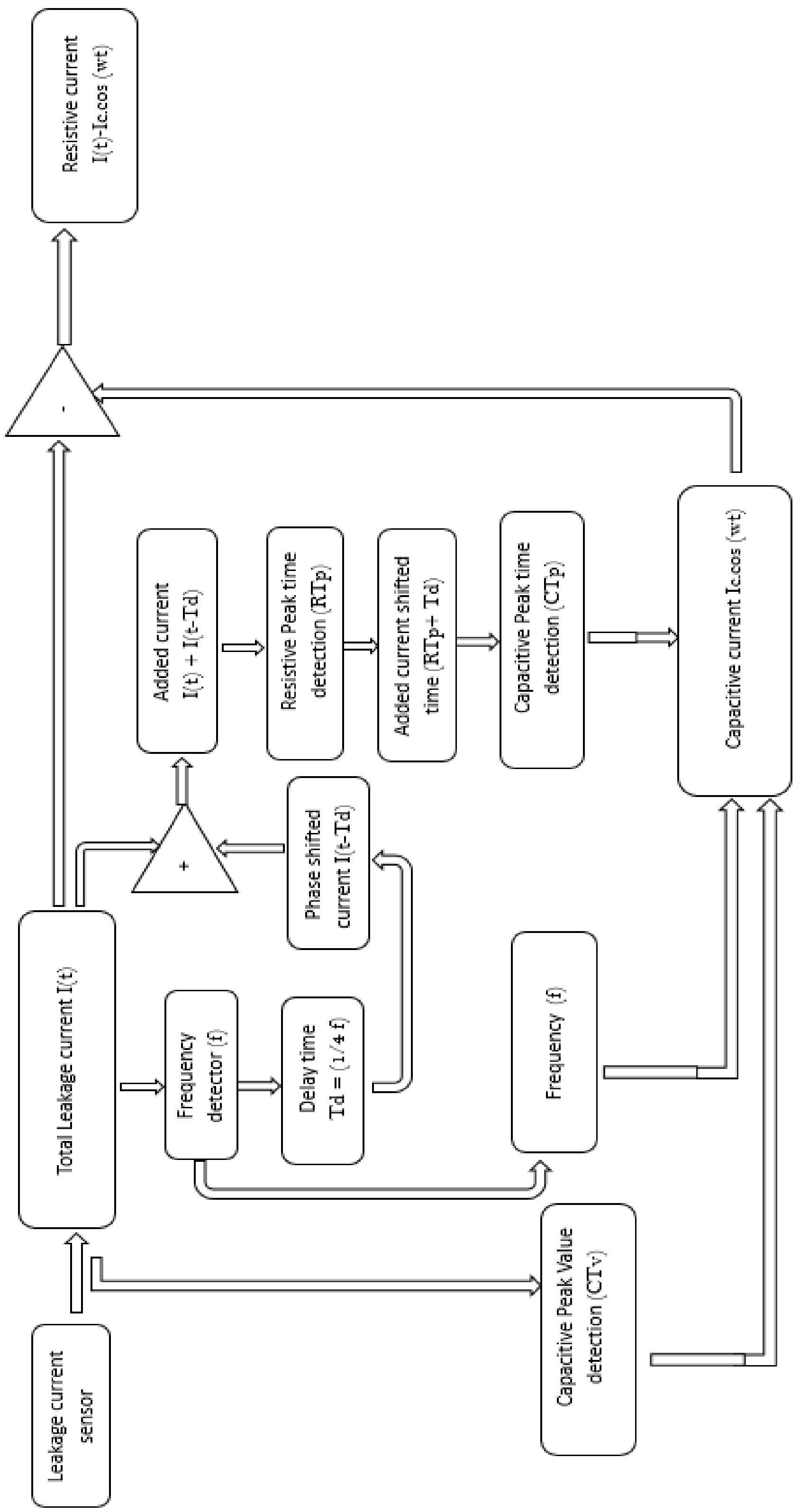


Figure 25: Flowchart of the MPSM

6.2 Implementation of MPSM in MATLAB & SIMULINK

MPSM algorithm implemented in Matlab and Simulink version 9.0. It is a graphical programming environment for modelling, simulating and analysing dynamical systems as well as for signal processing.

The main reason for selecting this software for this algorithm is that MPSM can be easily implemented in Simulink blocks to analyse signals and Matlab can read the leakage current data and compute RMS values. Moreover this enables online monitoring system.

Figure 26: Matlab & Simulink

Overall model of the MPSM is shown in figure 27 below. The model is divided into parts and explained for easy understanding.

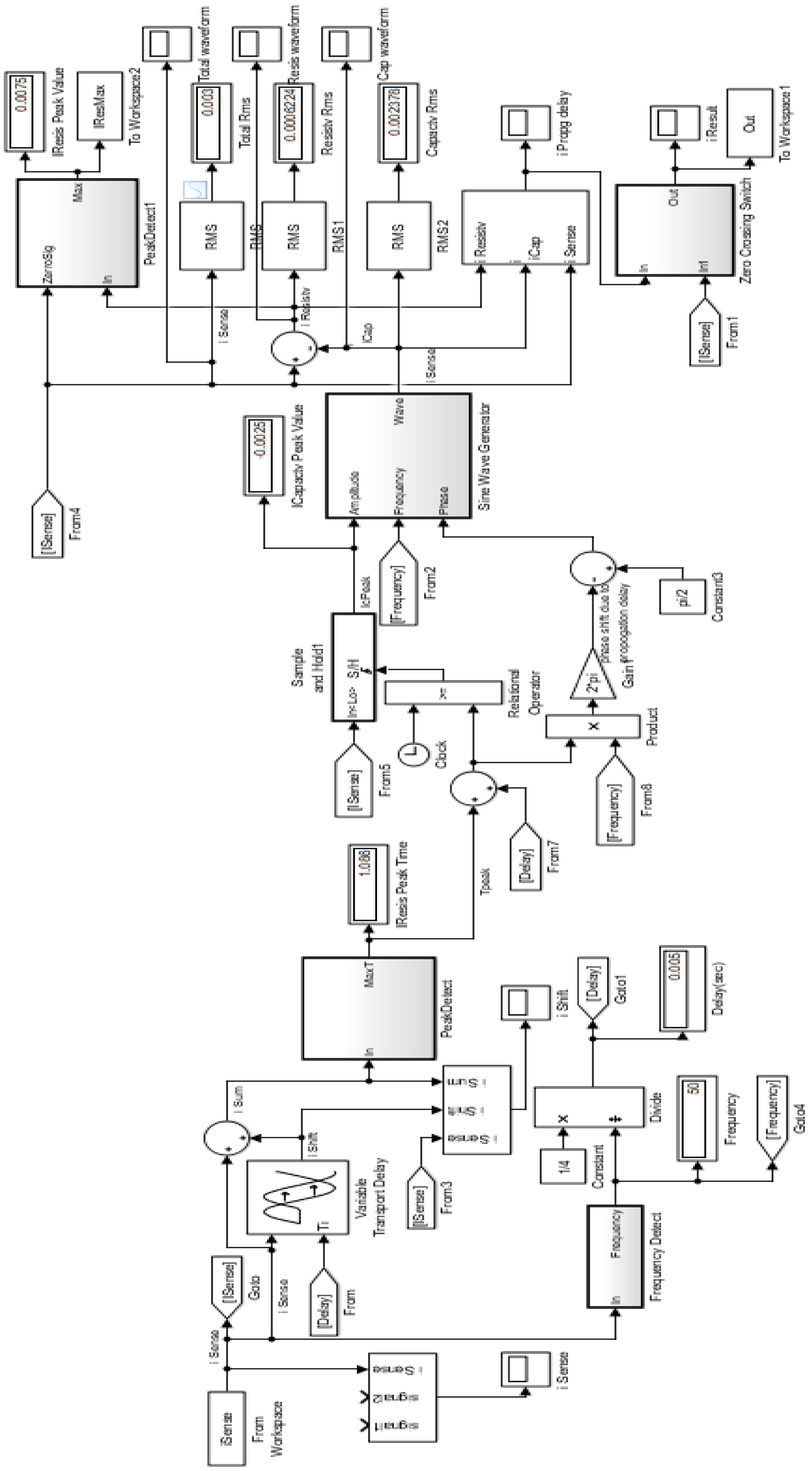


Figure 27: Overall MPSM model in Simulink

6.2.1 Acquire signal and Phase shifting Process

First the total leakage current is acquired and its frequency is detected. And then the signal is delayed by a quarter period of time where the variable transport delay block will process the phase shifting process. 'i sense' is the total leakage current acquired.

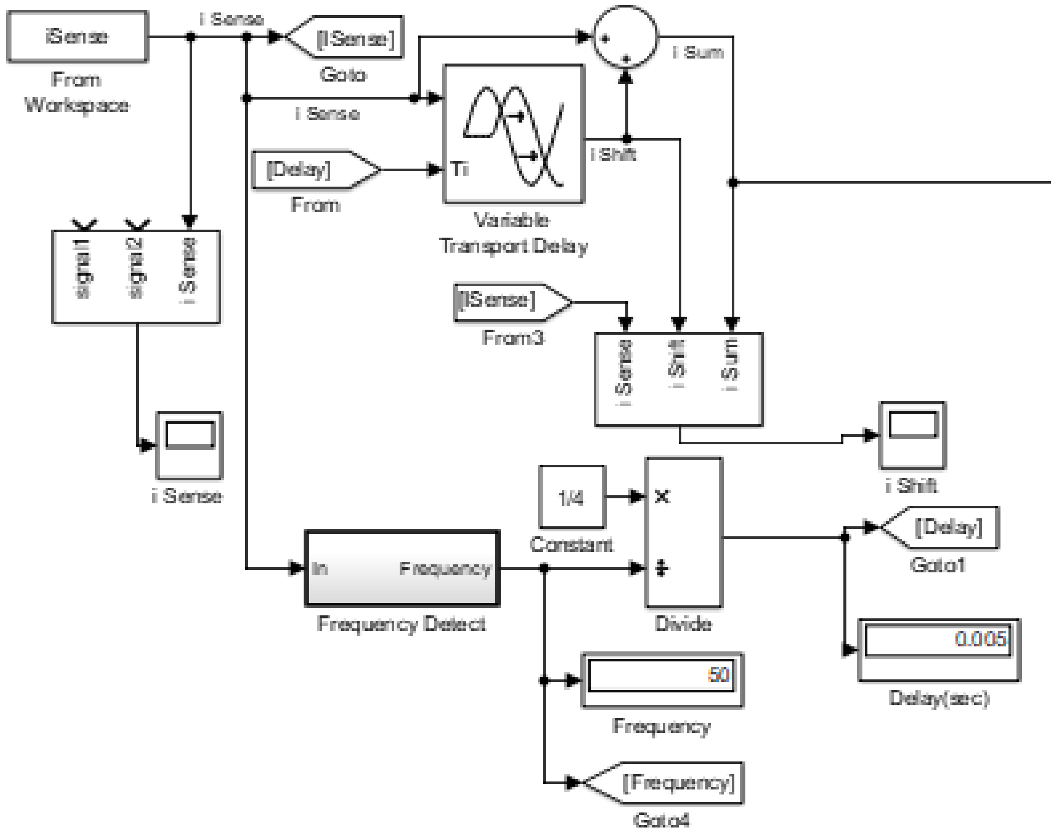


Figure 28: Acquire & phase shifting process

Frequency detection block

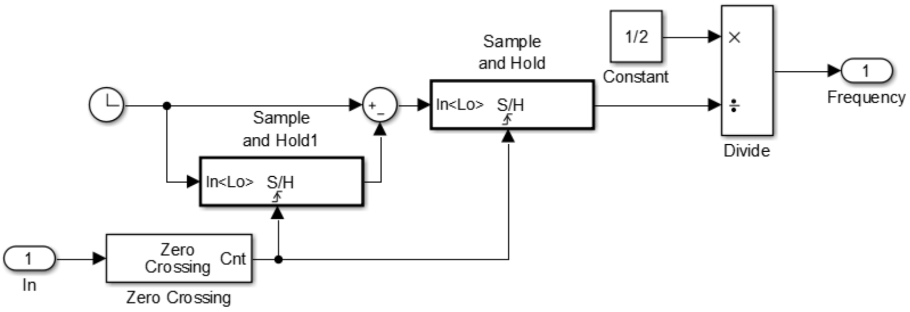


Figure 29: Frequency detection process

- Determine the phase of the signal since f=1/T
- Counts time taken for one full cycle. And divide by two gives frequency.

6.2.2 Generation of Capacitive component

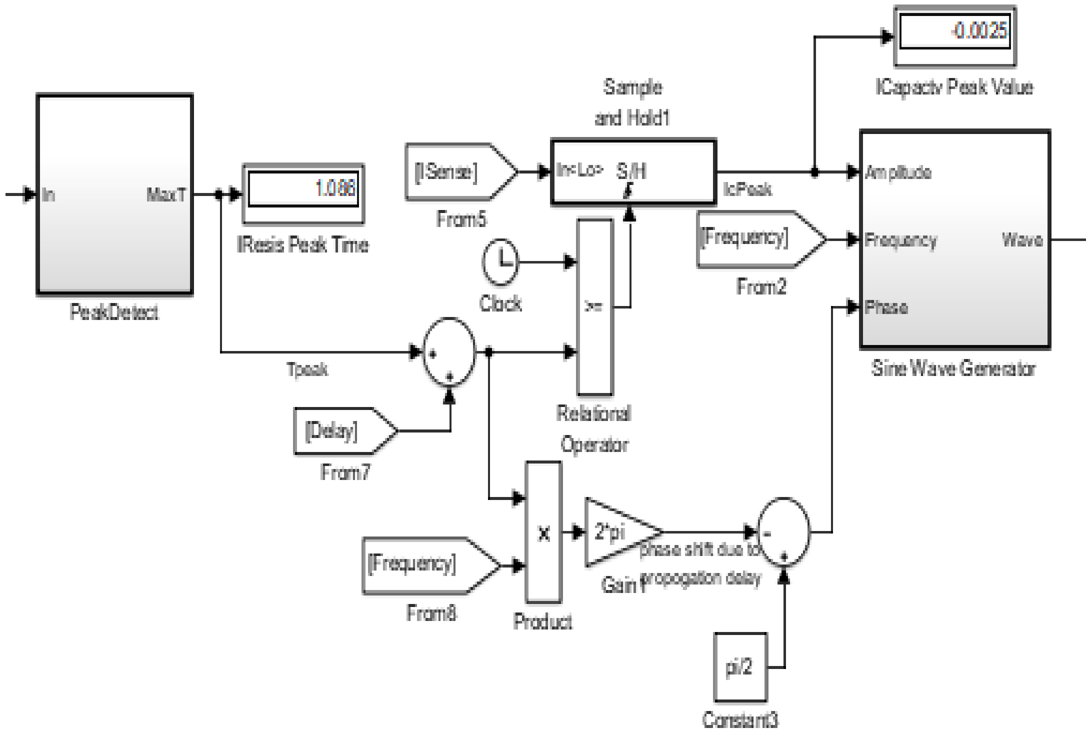


Figure 30: Capacititve current generatiob process

Then the peak time of the resistive component is detected, then the peak time of the capacitive component is detected by adding a delay to the shifted signal and thereby phase of the capacitive is found. Amplitude is found by using a sample and hold block the where the highest value is detected by the relational operator. Frequency detected is fed to the sine wave generator along with phase and amplitude. The output is the capacitive wave.

Peak detection block

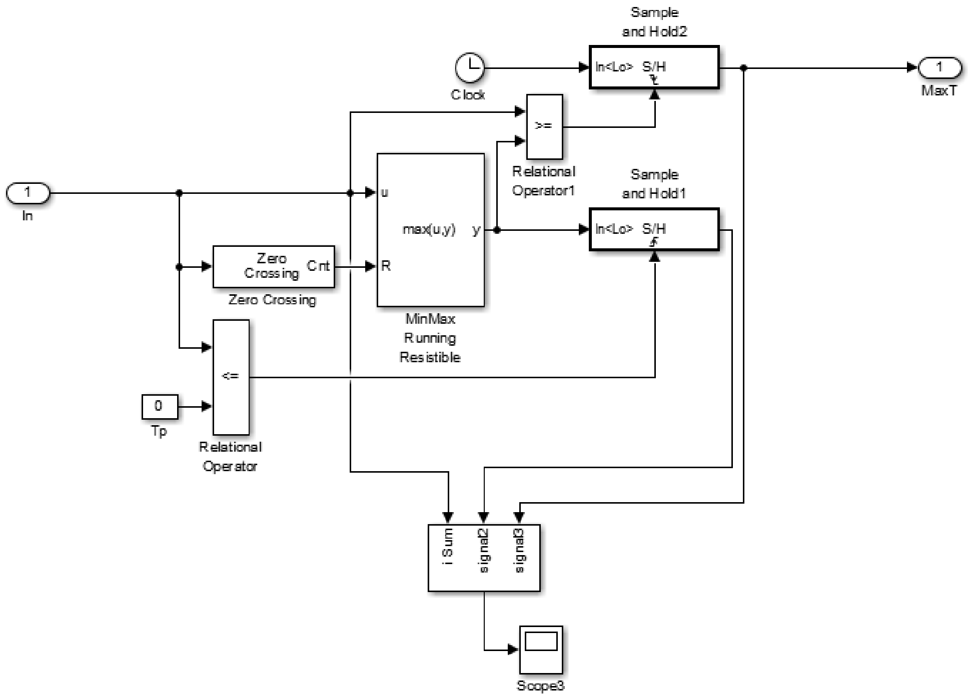


Figure 31: Peak detection process

- Zero crossing will detect waveform transition from positive and negative.
- Relational operator calculates on which is greater on its two inputs and produces max output.
- Sample and Hold will acquires the input and then holds the output at the acquired input value until the next triggering event occurs.
- Clock will output the current simulation time

Sine wave generator block

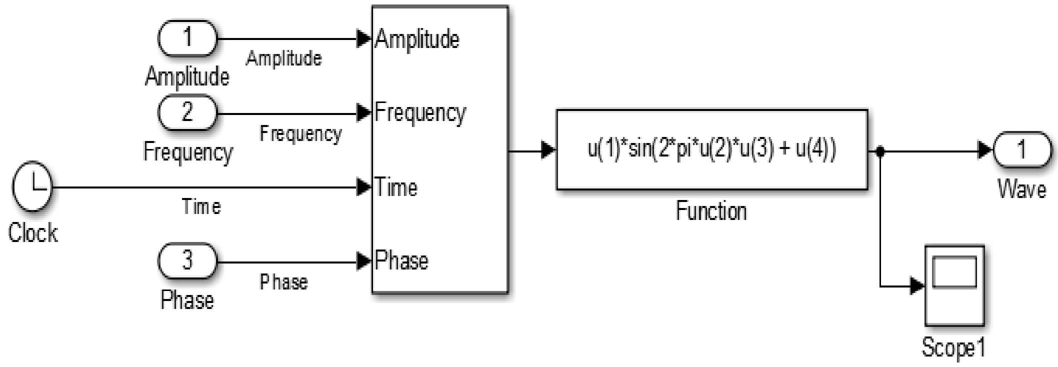


Figure 32: Sine wave generator

- Sine wave =amplitude× sin (2π*frequency ×time + phase)

6.2.3 Extraction of Resistive current

Then the generated capacitive is deducted from the total and the resultant is the resistive waveform. Finally Peak value and RMS values are calculated. Zero crossing switch is used to remove the initial wave cycles which has a propagation delay due to phase shift.

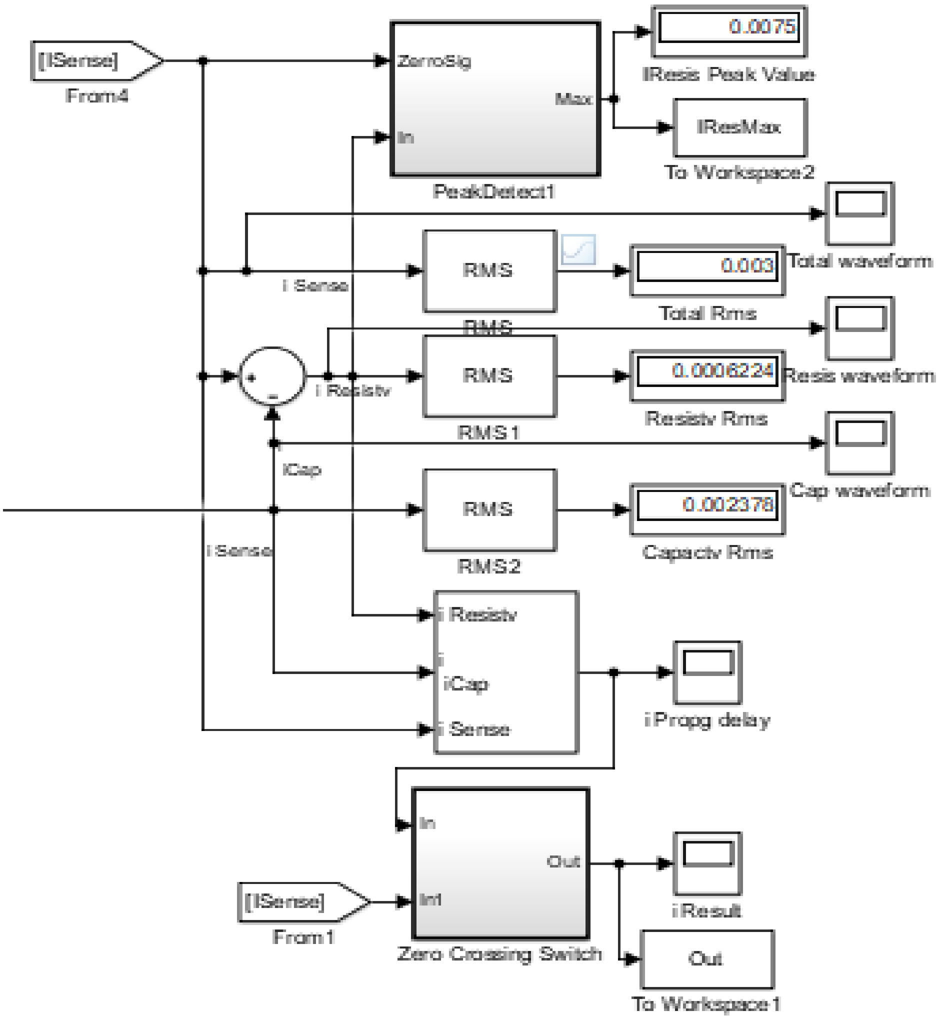


Figure 33: Extraction of resistive leakage current

Zero crossing block

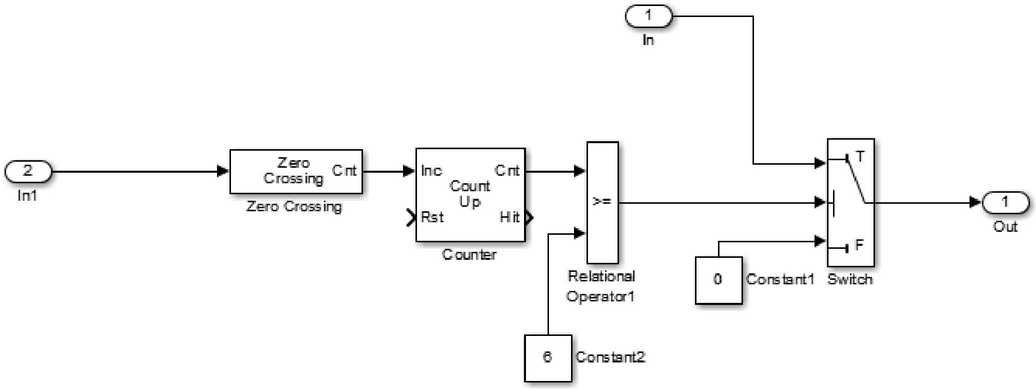


Figure 34: Zero crossing block

- First 3 cycles were out of phase due to the propagation delay. Therefore 6 pulses were skipped

7. CONDITION MONITORING DEVICE DEVELOPMENT

Leakage current signals is to be transmitted to a computer via a leakage current sensor. The leakage current is sent to earth via this sensor. Protection circuit prevents the sensor from transients.

The output of the sensor is AC signal which is fed to a Micro controller unit. This signal is transferred to computer via transceivers. Matlab can acquire these signals without any translators.

A block diagram of the proposed prototype device is given below

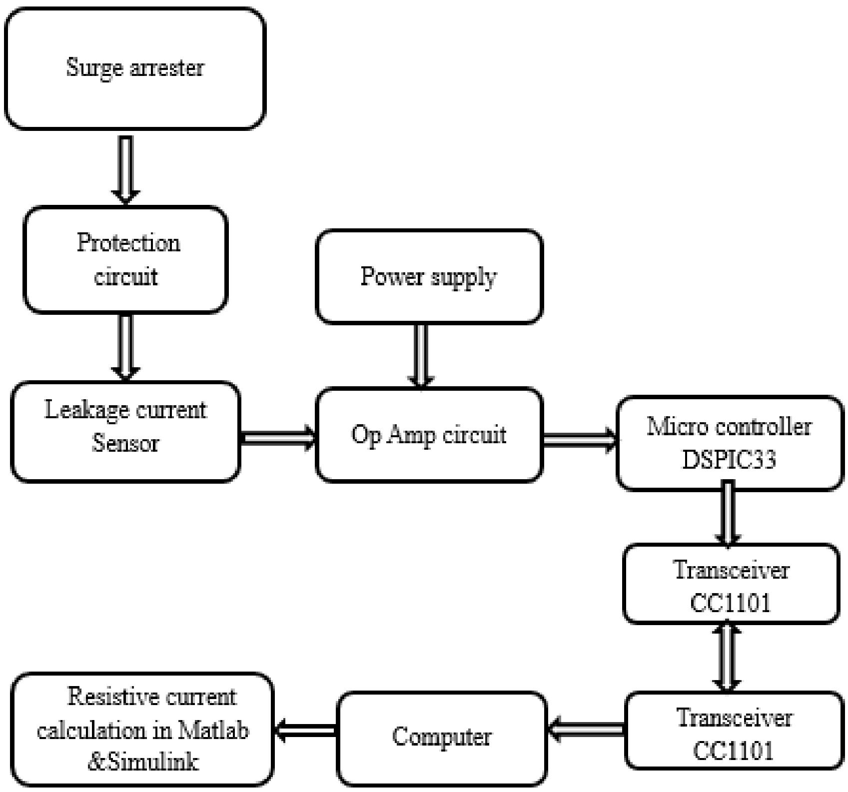


Figure 35: block diagram of the prposed decvice

Each component is briefly explained below

1. **Leakage current sensor**

Figure 36: Leakage current sensor

Extra low current cannot be accurately measured by common current sensors due to amplification errors. Specially tuned leakage current sensors is used for this purpose. This custom made sensor is a hall effect type current sensor which can sense a low current of 1uA. Leakage current sensor can be tuned to measure small currents. The output of the sensor is a replica of the input current. An input of 1µA AC will give an output of 1mV AC. Sensing resolution can be tuned and changed to a desired input output range

Technical Specifications are given below

Sensing input currentn range : 0 – 5mA

Corresponding output : 0- 5V

Power supply to power the sensor : +-12

2. Protection circuit

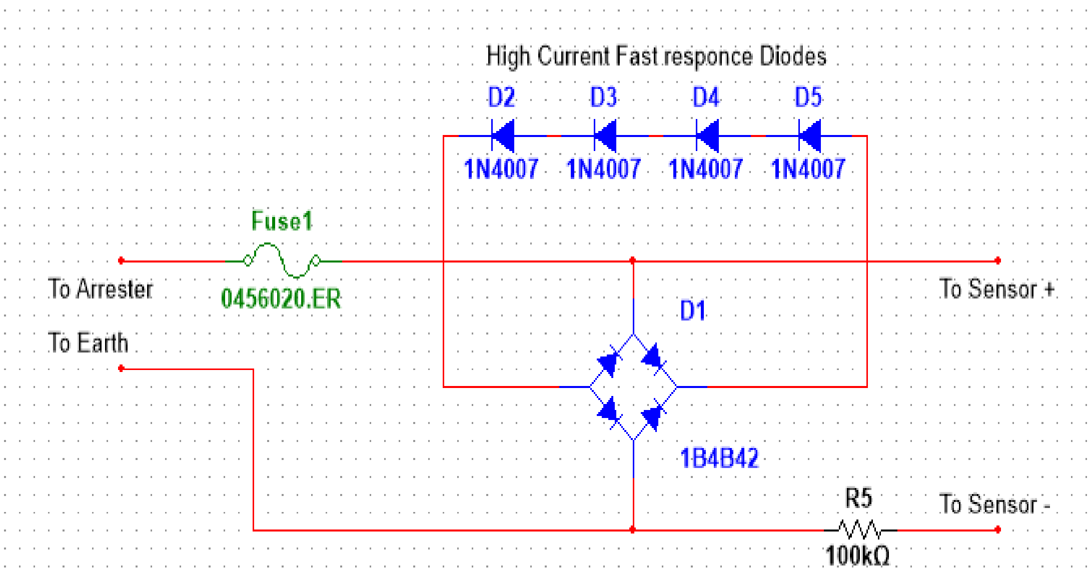


Figure 37: protection circuit

- The leakage current from a surge arrester have to pass through semi conductor diode bridge and high current diodes,
- The diode bridge protects the sensor from over voltage.
- The high curretn fast response diodes will protects the circuit from impulse.
- If the diodes burn and protection fails the fuse will burn and stop the current flowing to the sensor by diverting to earth.

3. Opearational amplifier circuit

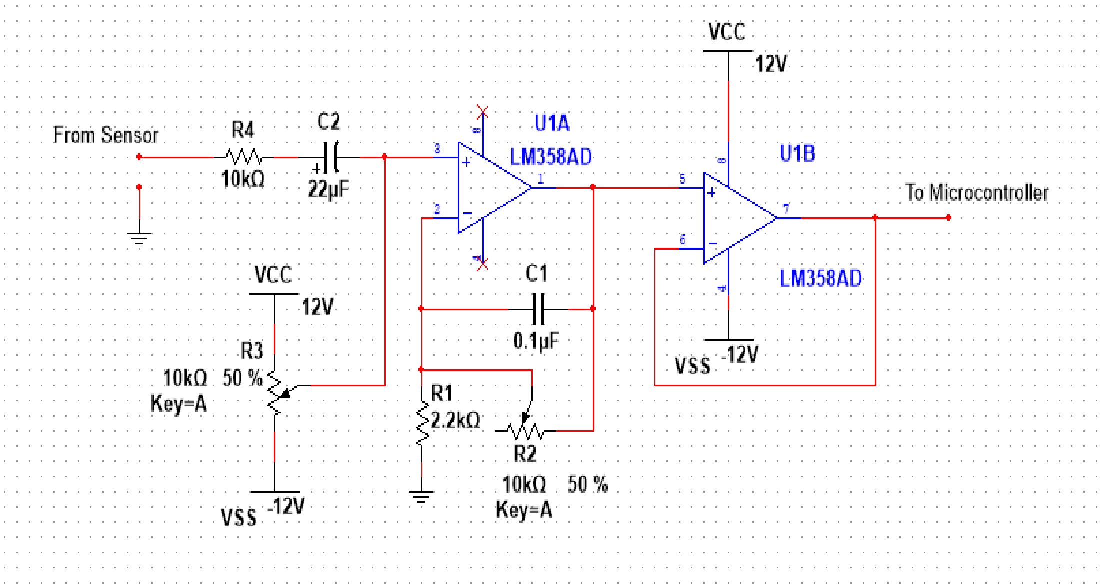


Figure 38: Operational amplifier circuit

- The amplifier 1 is used to adjust the gain of the sigmal while the amplifier 2 is used to level shift the voltage to 3.3V to power the micro controller unit.
- The current signal is first passeed through capacitor C2 which allows AC current only. The capacitor C1 is used for noise filtering.

4. **Micro controller unit**

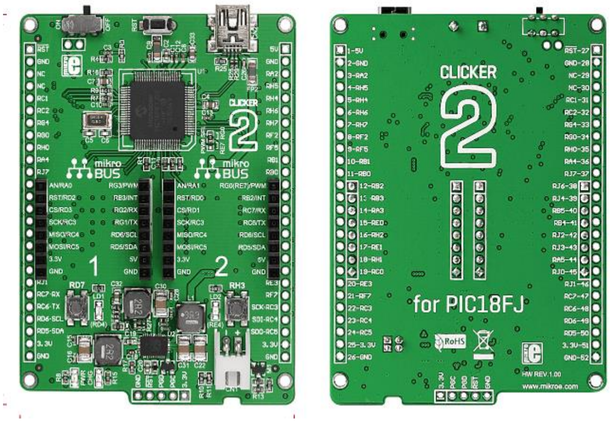


Figure 39: MCU development board

Development board of consisting of dsPIC33 is a 16-bit low power high-performance microcontroller is rich with on-chip peripherals and features 512 KB of program memory and 53,248 bytes of RAM. It has integrated full speed USB 2.0. support is programed with Micro Pascal software with a USB UART boot loader. It can accommodate two additional RAM port for extra data. The signal from the sensor is fed to a analog input of the board and ready to transmit via the UART port.

5. Transciever

Figure 40: Transcievers

CC1101 type transciever module is used for communication betweeen the sensor and the computer. Transmitter part is connected to the UART port of the MCU board and the reciever is attached to the computer USB port. Received signal is straight away read by Matlab without any translators. This transceiver module can communicate about 1000m apart and operates in frequency range of 434-439 MHz. This can easily sample in a rate of 5 kHz.

Over all arrester monitoring device

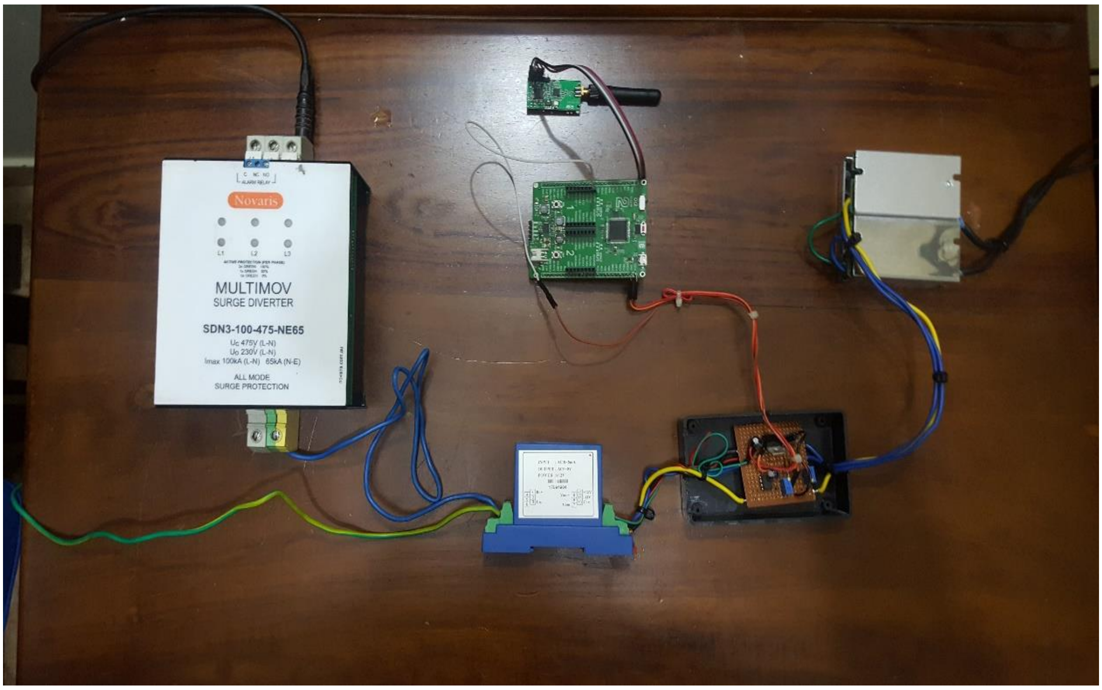


Figure 41: Overall arrester monitoring device

- On site devices are leakage current sensor, an amplifier, MCU, transmitter and a power supply module to power all these devices.
- Sensed current by the sensor is amplified and fed to MCU, the MCU reads the data and transmits to the receiver via the transmitter.

User end devices

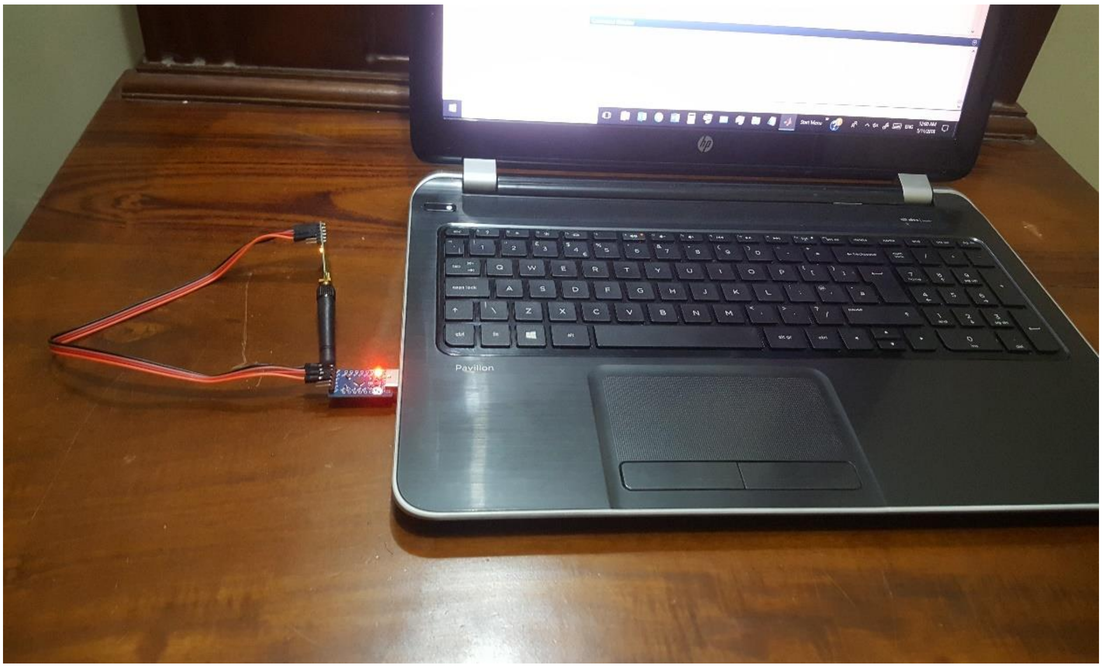


Figure 42: User end device

- User end devices are a computer with Matlab & Simulink and a receiver
- When the simulation is run, the software reads the serial port of the computer where the transceiver pair is connected.
- This will trigger the transceivers to communicate. The transmitter transmits the leakage current data and the receiver connected to a computer will receive it and store it in Matlab workspace.
- The Simulink will acquire those data from workspace and process the MPSM algorithm and compute the waveforms and the current values.

8. RESULTS AND DISCUSSIONS

The leakage current sensed via the sensor is successfully transmitted to Matlab. The MPSM was implemented and the leakage current was successfully separated to capacitive and resistive current components. Figure 43 below shows the separated total leakage current, capacitive and resistive current waveforms of a 275V surge arrester.

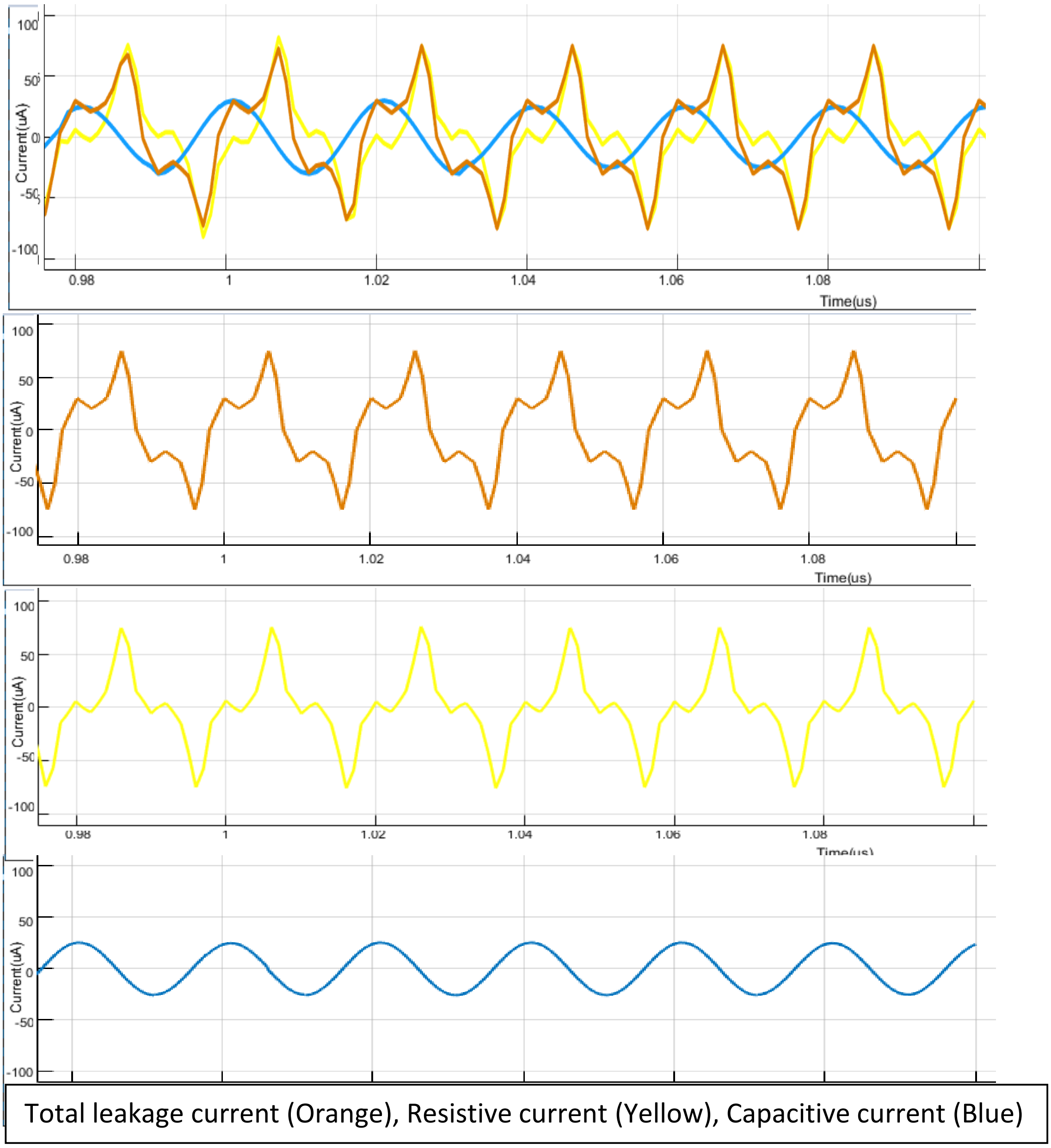
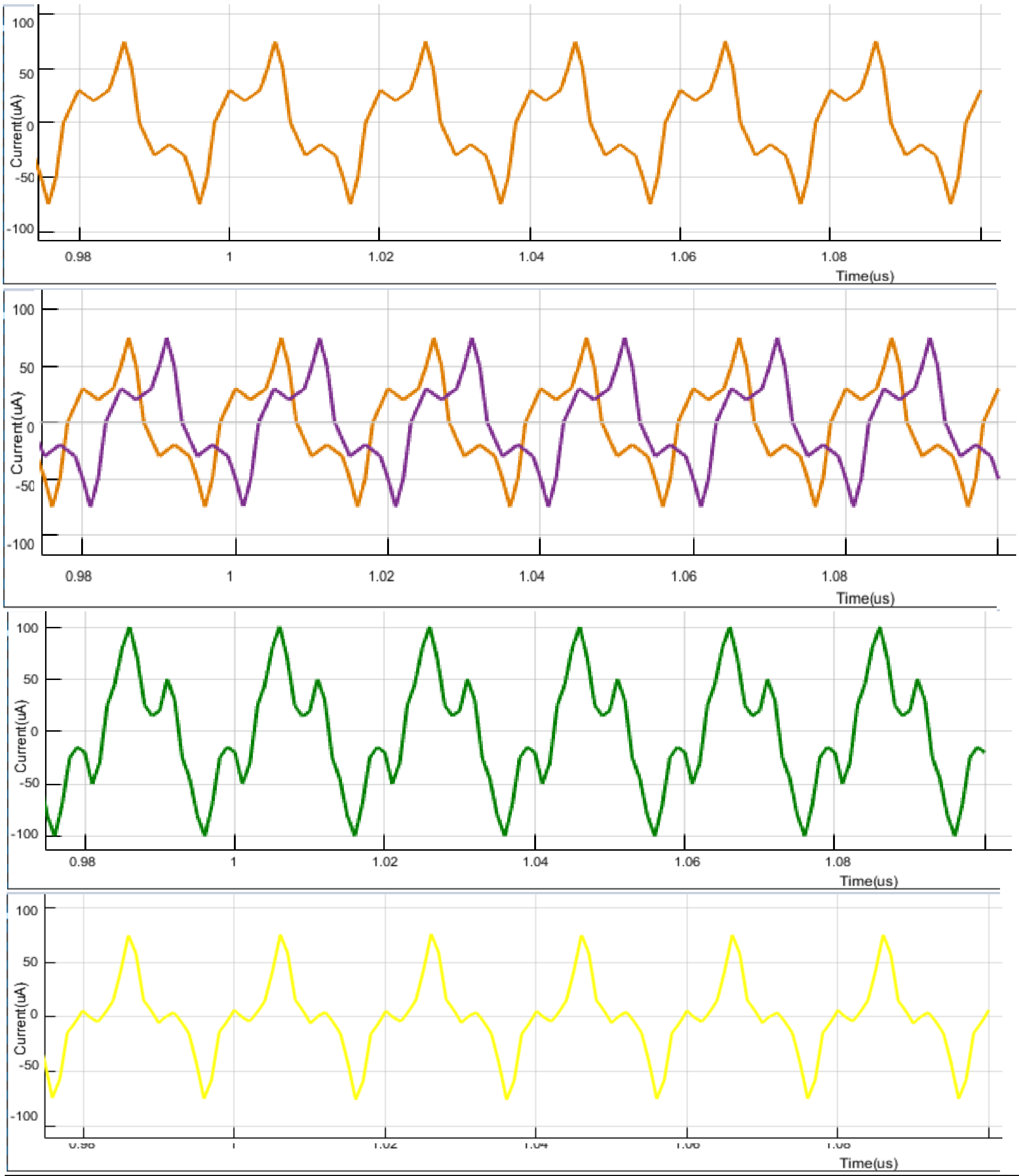


Figure 43: Leakage current waveforms of 275V surge arrester

From the figure 43, it is shown that the total leakage current waveform is the summation of capacitive and resistive current waveform

It is observed form figure 44 that summation current peak time is the resistive current's peak time.

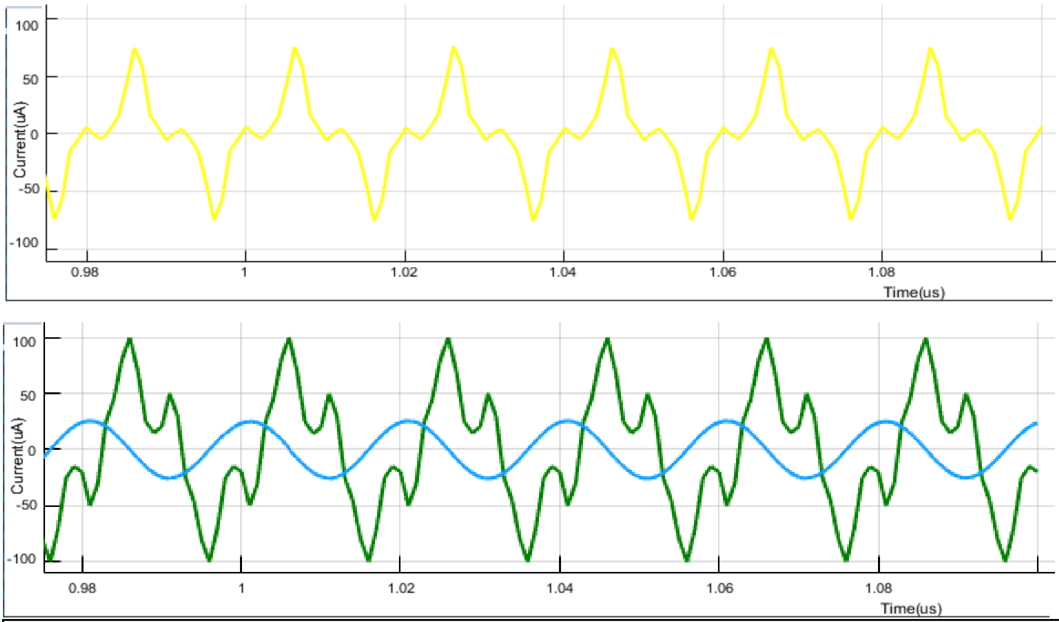


Total leakage current (Orange), Shifted current (Purple), Summation current (Blue)

Resistive current (Yellow),

Figure 44: Resistive peak waveform

It is observed in figure 45 that the peak time of the capacitive component occur at quarter period before and after the resistive peak times or the summation waveform



Total leakage current (Orange), Shifted current (Purple), Summation current (Blue)

Resistive current (Yellow),

Figure 45: Capacitive peak waveform

Above waveforms justifies the accuracy of the results obtained from the developed device and the MPSM technique. Hence the results are satisfactory

.

RMS blocks computes the corresponding resistive and capacitive current values. It is seen that the leakage current from a 275V surge arrester has a resistive current of 6.2µA.

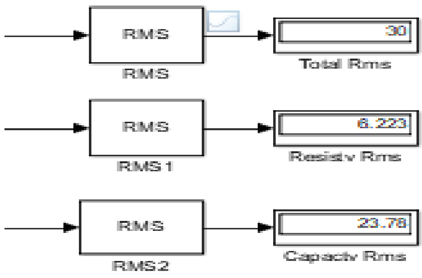


Figure 46: RMS values of current componenets for 275v arrester

Peak value of the resisitive current is found using a peak detector block. An alarm file is inserted to sound an alarm when the resistive peak value is more than the recommended value of 250µA.

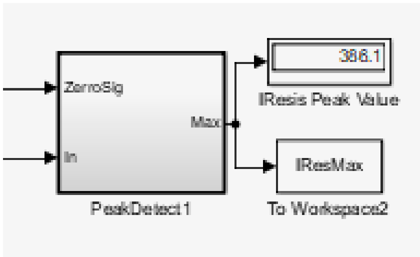


Figure 47: Resisitive peak value

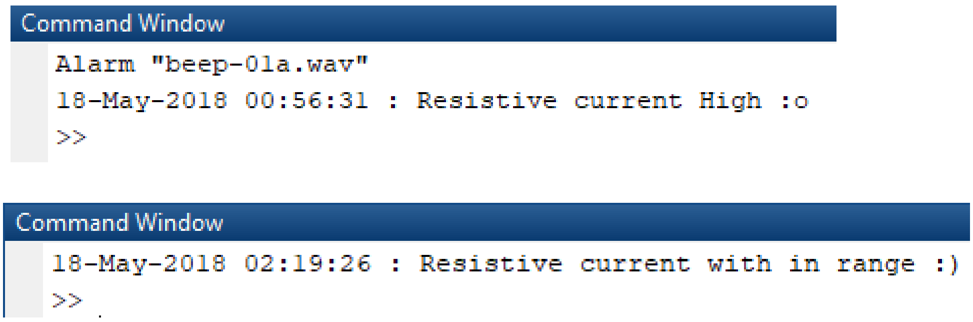


Figure 48: Resistive High/Low alarm

Current waveforms from a 30kV surge arrester. Results shows a high capacitive component in the total leakage current

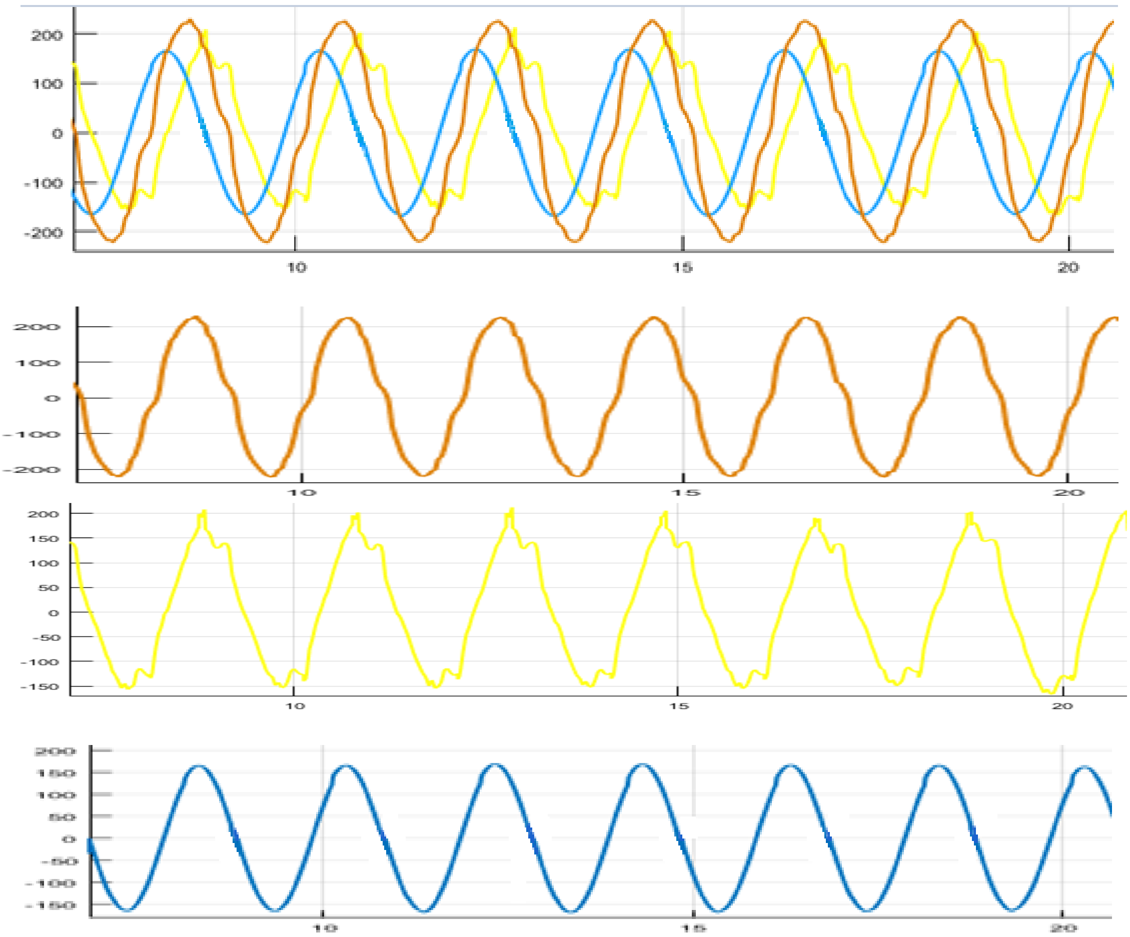


Figure 49: Leakage current waveforms of 30kV surge arrester

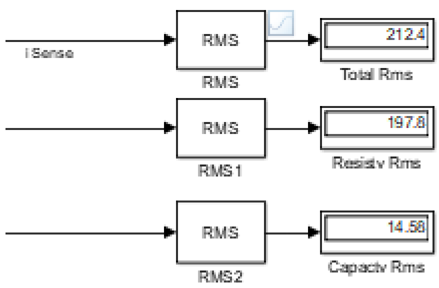


Figure 50: High resistive RMS results for 475V arrester

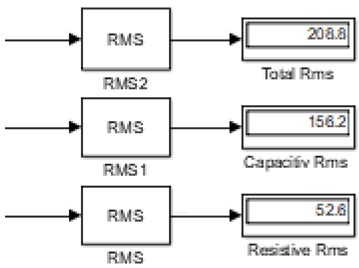


Figure 51: High Capacitive RMS results for 30kV

Current waveforms from a 475V surge arrester. Results shows a high resistive component in the total leakage current.

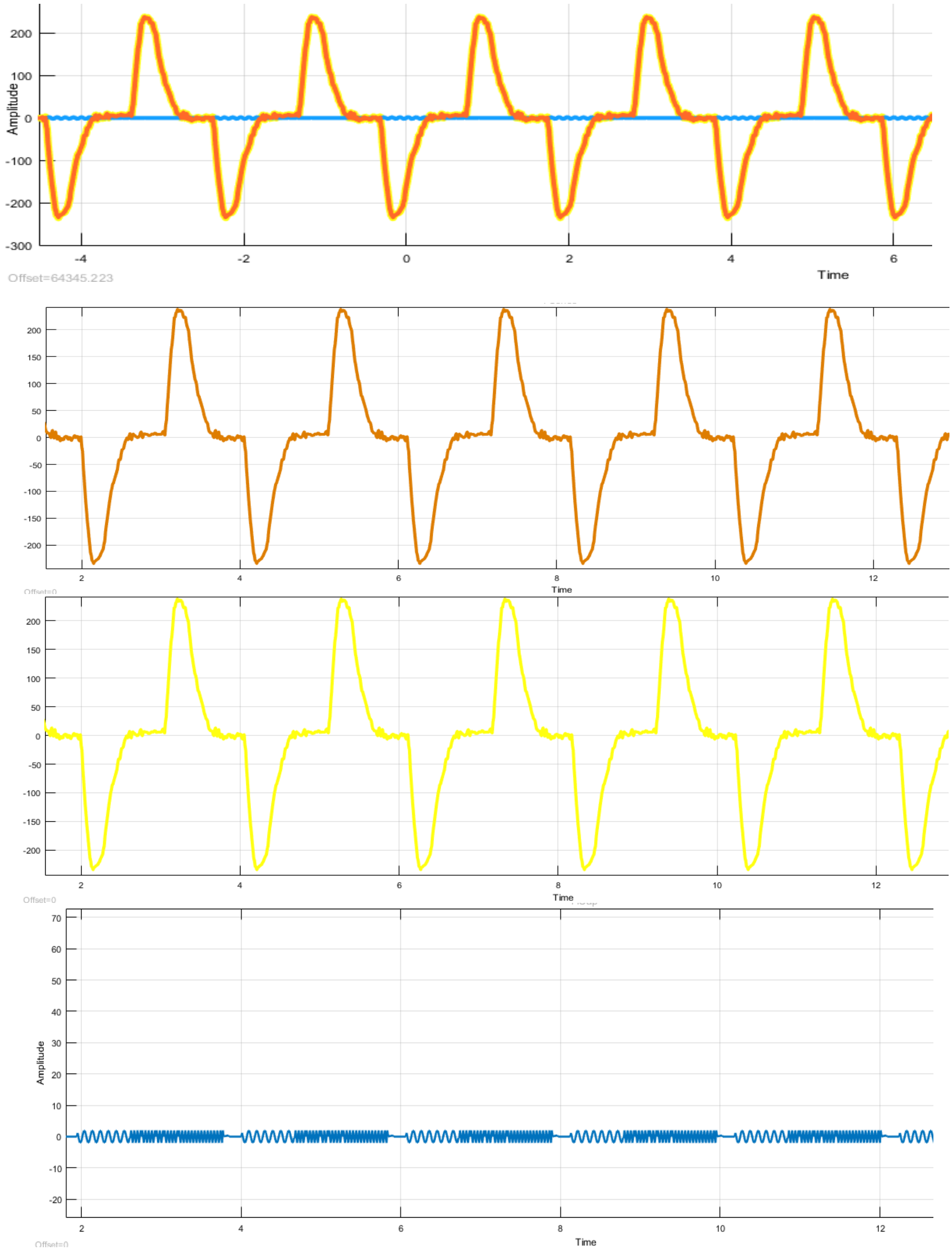


Figure 52: Leakage current results of 475V arrester

9. CONCLUSION AND RECOMENDATIONS

From above discussions it is studied that Metal oxide surge arresters are the most efficient type of arrester to protect power systems. Measuring the resistive leakage current is the reliable method to monitor the condition of the MOSA and it can be done in an online condition.

MPSM is accurate method to extract the resistive component from the total leakage current. This technique can be easily implemented in Matlab & Simulink. Using a current sensors to acquire leakage current signals to Matlab & Simulink, an online monitoring system is developed to remotely monitor the health of the installed surge arresters at power distribution.

Finally author conclude that by implementing the above we can have the following benefits:

- Prevent arrester failures by replacing aged arresters before breakdown.
- Reduce the Utility labour hours and increase the safety of the staff.
- Avoid disturbances in the electric power supply.
- Reduce the risk for damages to other equipment due to arrester failure.

LIST OF REFERENCES

Bibliography

Appendix

1. Make : Novaris Multi MOV Surge Diverter
   Model: SDN3-100-475-NE65
   Rating: Vc-475V, Vo-230V

2. Make : Oblum Electrical Industries
   Model: PBW
   Rating: Vc-25kV, Vr-30kV

Save Time: 2018-01-13 14:59:12		
Status:	Trigd	
Frequency:	50.000 Hz	
Period:	20.000 mS	
SP:	200.000 µS	
PK-PK:	476.000 µA	
	µS	µA
1	0	-170
2	200	-198
3	400	-220
4	600	-226
5	800	-230
6	1000	-222
7	1200	-228
8	1400	-226
9	1600	-212
10	1800	-208
11	2000	-190
12	2200	-174
13	2400	-150
14	2600	-126
15	2800	-110
16	3000	-92
17	3200	-84
18	3400	-72
19	3600	-60
20	3800	-52
21	4000	-46
22	4200	-30
23	4400	-16
24	4600	-12
25	4800	-4
26	5000	-2
27	5200	2
28	5400	6
29	5600	2
30	5800	6
31	6000	2
32	6200	8
33	6400	4
34	6600	4
35	6800	0
36	7000	4
37	7200	6
38	7400	6
39	7600	6
40	7800	6
41	8000	6
42	8200	8
43	8400	4
44	8600	8
45	8800	6
46	9000	4
47	9200	20
48	9400	56
49	9600	100
50	9800	142
51	10000	178
52	10200	202
53	10400	224
54	10600	230
55	10800	234
56	11000	236
57	11200	236
58	11400	234
59	11600	220
60	11800	214
61	12000	202
62	12200	178
63	12400	156
64	12600	130
65	12800	120
66	13000	100
67	13200	86
68	13400	70
69	13600	64
70	13800	60
71	14000	44
72	14200	40
73	14400	22

74	14600	18
75	14800	8
76	15000	8
77	15200	6
78	15400	2
79	15600	4
80	15800	2
81	16000	0
82	16200	0
83	16400	-2
84	16600	4
85	16800	-2
86	17000	0
87	17200	0
88	17400	0
89	17600	0
90	17800	-4
91	18000	-2
92	18200	0
93	18400	2
94	18600	-4
95	18800	0
96	19000	-4
97	19200	-18
98	19400	-52
99	19600	-96
100	19800	-136
101	20000	-172
102	20200	-200
103	20400	-216
104	20600	-228
105	20800	-226
106	21000	-232
107	21200	-230
108	21400	-226
109	21600	-216
110	21800	-212
111	22000	-196
112	22200	-172
113	22400	-152
114	22600	-128
115	22800	-110

116	23000	-98
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118	23400	-74
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121	24000	-42
122	24200	-34
123	24400	-20
124	24600	-12
125	24800	-10
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127	25200	-4
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129	25600	4
130	25800	2
131	26000	8
132	26200	2
133	26400	6
134	26600	6
135	26800	6
136	27000	4
137	27200	4
138	27400	6
139	27600	6
140	27800	8
141	28000	6
142	28200	6
143	28400	6
144	28600	6
145	28800	10
146	29000	6
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148	29400	60
149	29600	102
150	29800	144
151	30000	174
152	30200	208
153	30400	224
154	30600	234
155	30800	234
156	31000	236
157	31200	234

158	31400	226
159	31600	224
160	31800	212
161	32000	202
162	32200	180
163	32400	154
164	32600	134
165	32800	116
166	33000	104
167	33200	86
168	33400	76
169	33600	66
170	33800	56
171	34000	44
172	34200	34
173	34400	28
174	34600	16
175	34800	10
176	35000	8
177	35200	2
178	35400	10
179	35600	2
180	35800	8
181	36000	0
182	36200	2
183	36400	-4
184	36600	-2
185	36800	-4
186	37000	0
187	37200	2
188	37400	-2
189	37600	0
190	37800	-4
191	38000	-2
192	38200	2
193	38400	0
194	38600	2
195	38800	-4
196	39000	0
197	39200	-18
198	39400	-58
199	39600	-100

200	39800	-138
201	40000	-170
202	40200	-200
203	40400	-220
204	40600	-230
205	40800	-230
206	41000	-228
207	41200	-226
208	41400	-222
209	41600	-216
210	41800	-210
211	42000	-198
212	42200	-174
213	42400	-152
214	42600	-130
215	42800	-110
216	43000	-94
217	43200	-84
218	43400	-74
219	43600	-64
220	43800	-48
221	44000	-42
222	44200	-28
223	44400	-22
224	44600	-12
225	44800	-4
226	45000	-4
227	45200	4
228	45400	-2
229	45600	4
230	45800	4
231	46000	2
232	46200	0
233	46400	4
234	46600	6
235	46800	4
236	47000	8
237	47200	4
238	47400	4
239	47600	8
240	47800	4
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243	48400	6
244	48600	4
245	48800	4
246	49000	0
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248	49400	66
249	49600	104
250	49800	142
251	50000	178
252	50200	206
253	50400	228
254	50600	234
255	50800	238
256	51000	236
257	51200	234
258	51400	228
259	51600	218
260	51800	210
261	52000	196
262	52200	180
263	52400	154
264	52600	134
265	52800	112
266	53000	98
267	53200	90
268	53400	74
269	53600	70
270	53800	54
271	54000	46
272	54200	36
273	54400	22
274	54600	16
275	54800	10
276	55000	8
277	55200	4
278	55400	6
279	55600	2
280	55800	0
281	56000	4
282	56200	0
283	56400	2

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285	56800	0
286	57000	-2
287	57200	0
288	57400	0
289	57600	0
290	57800	-2
291	58000	-2
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294	58600	0
295	58800	0
296	59000	0
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298	59400	-60
299	59600	-102
300	59800	-140
301	60000	-174
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303	60400	-224
304	60600	-228
305	60800	-230
306	61000	-230
307	61200	-234
308	61400	-222
309	61600	-212
310	61800	-208
311	62000	-190
312	62200	-170
313	62400	-148
314	62600	-122
315	62800	-110
316	63000	-90
317	63200	-86
318	63400	-70
319	63600	-62
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6	2400	68
7	2800	112
8	3200	132
9	3600	164
10	4000	176
11	4400	184
12	4800	204
13	5200	208
14	5600	220
15	6000	220
16	6400	228
17	6800	228
18	7200	220
19	7600	212
20	8000	208
21	8400	184
22	8800	172
23	9200	148
24	9600	116
25	10000	76
26	10400	52
27	10800	40
28	11200	28
29	11600	16
30	12000	-4
31	12400	-60
32	12800	-112
33	13200	-124
34	13600	-156
35	14000	-168
36	14400	-176
37	14800	-188
38	15200	-200
39	15600	-208
40	16000	-216
41	16400	-216
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44	17600	-208
45	18000	-200
46	18400	-172
47	18800	-168
48	19200	-140
49	19600	-108
50	20000	-68
51	20400	-40
52	20800	-28
53	21200	-16
54	21600	-8
55	22000	16
56	22400	72
57	22800	116
58	23200	140
59	23600	164
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62	24800	196
63	25200	208
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65	26000	220
66	26400	228
67	26800	228
68	27200	220
69	27600	212
70	28000	212
71	28400	176
72	28800	172
73	29200	156
74	29600	116
75	30000	76
76	30400	52
77	30800	40

78	31200	28
79	31600	16
80	32000	-8
81	32400	-64
82	32800	-100
83	33200	-128
84	33600	-152
85	34000	-168
86	34400	-176
87	34800	-188
88	35200	-204
89	35600	-212
90	36000	-216
91	36400	-216
92	36800	-220
93	37200	-212
94	37600	-200
95	38000	-204
96	38400	-172
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107	42800	108
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158	63200	132
159	63600	160
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166	66400	224
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173	69200	148
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176	70400	52
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265	106000	224
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268	107200	224
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271	108400	172
272	108800	172
273	109200	156
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