# A NEW HIGH VOLTAGE PARTIAL DISCHARGE INDICATOR SYSTEM

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

İBRAHİM OĞUZ GÜL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

JUNE 2006

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. İsmet Erkmen
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Mirzahan Hızal
Supervisor

**Examining Committee Members**

| | | |
|---|---|---|
| Prof. Dr. Ahmet Rumeli | (METU, EE) | |
| Prof. Dr. Mirzahan Hızal | (METU, EE) | |
| Prof. Dr. Arif Ertaş | (METU, EE) | |
| Prof. Dr. Nevzat Özay | (METU, EE) | |
| Prof. Dr. Cengiz Taplamacıoğlu | (Gazi Unv., EE) | |

**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

Name, Last name :İbrahim Oğuz Gül

Signature :

# ABSTRACT

A NEW HIGH VOLTAGE PARTIAL DISCHARGE INDICATOR SYSTEM

Gül, İbrahim Oğuz
MSc., Department of Electrical and Electronics Engineering
Supervisor : Prof. Dr. Mirzahan Hızal

June 2006, 105 pages

In this thesis work, a new digital partial discharge magnitude indicator with LCD display was designed. This system was implemented in high voltage partial discharge detection and measurement systems. AVRISP In-System Programmer is used to program the microprocessors used inside the display unit. The time resolution of the system (one pixel of the display unit) is 4 microseconds. The unit is capable of counting the number of impulses of the input voltage that is coming from the high voltage system within user selectable time intervals. The changeable values of the time intervals are 2, 4, 6, 8 and 10 seconds. It is also capable of showing the maximum value of the impulses in a given time interval. This maximum value is a number changing between 0 and 256. By calibration of the system, it was possible to indicate the discharge magnitudes in picocoulombs.

Keywords : HV discharge, microprocessor, impulse, time interval, time resolution

# ÖZ

YENİ BİR YÜKSEK VOLTAJ KISMİ DEŞARJ GÖSTERGE SİSTEMİ

Gül, İbrahim Oğuz
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. Mirzahan Hızal

Haziran 2006, 105 sayfa

Bu tez çalışmasında LCD göstergeli yeni bir kısmi deşarj büyüklük ölçer dizayn edilmiştir. Bu sistem yüksek voltaj kısmi deşarj araştırma ve ölçme sistemlerinde denenmiştir. AVRISP In-System Programmer; gösterge sisteminin içerisinde kullanılan mikroişlemcileri programlamak için kullanılmıştır. Sistemin çözünürlüğü (gösterge ünitesindeki bir piksel) 4 mikrosaniyedir. Ünite; yüksek voltaj sisteminden gelen input voltajındaki anlık voltaj atlamalarının sayısını kullanıcının seçebileceği zaman aralıkları içerisinde sayabilmektedir. Zaman aralıklarının değişen değerleri 2, 4, 6, 8 ve 10 saniyedir. Ünite ayrıca verilen zaman aralığındaki anlık voltaj atlamalarının maksimum değerini gösterebilmektedir. Bu maksimum değer 0 ile 256 arasında değişen bir sayıdır. Sistemin kalibrasyonu sayesinde deşarj büyüklüklerini picocoulomb cinsinden göstermek mümkün olmuştur.

Anahtar Kelimeler : Yüksek voltaj deşarjı, mikroişlemci, anlık voltaj atlaması, zaman aralığı, zaman çözünürlüğü

To My Parents

# ACKNOWLEDGMENTS

I would like to express my gratitude to Prof. Dr. Mirzahan Hızal for their valuable supervision, understanding.

I am grateful to my family, especially to my mother, for their endless trust.

# TABLE OF CONTENTS

## LIST OF FIGURES

FIGURES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| ADC | Analog-to-Digital Converter |
| ISP | In-System Programmer |
| P.D.M | Partial Discharge Meter |
| GIS | Geographic Information System |
| HV | High Voltage |
| IEEE | Institute of Electrical and Electronics Engineers |
| PD | Partial Discharge |
| CIV | Corona Inception Voltage |

# CHAPTER 1

# INTRODUCTION

## 1.1 Gas Discharges

Although discharges, either within insulation or from adjacent conductors, have been known for more than fifty years to cause progressive deterioration and ultimate breakdown, this subject has received little attention in textbooks on high voltage techniques at the beginning. Much of what was known about discharges and their detection was scattered over a great number of articles and reports.

This neglect of knowledge of discharges has occurred mainly because the rate of deterioration of traditional insulating materials stressed at the usual field strengths was quite slow. Moreover, in cases where discharges may really be deleterious (e.g. mass-impregnated paper cables) they occurred simultaneously in such great numbers that they considerably increased the dielectric losses. A Schering bridge measurement in which the increase in loss-angle was measured with increasing voltage was then able to detect the occurrence of discharges. Special methods for the detection of discharges were introduced later. Particularly the introduction of plastic dielectrics rendered this necessary. Plastic insulation was applied in such a way (e.g. by extrusion or casting) that small numbers of voids could easily occur. Discharges in occasional voids did not appreciably increase dielectric losses; therefore special discharge detection methods were needed. [1]

In other cases discharge detection was introduced where the field strength in a traditional dielectric was increased. For instance, in oil-impregnated transformers and capacitors discharges may arise in the oil at places with a strongly divergent field, and they should be detected in order to be controlled.

The development of sensitive discharge detectors has permitted more detailed investigations of the behaviour of discharges. Such knowledge is essential for the understanding and interpretation of the results of discharge detection. It is thus appropriate first to consider the various types of discharges which can occur. [1]

## 1.2 Types and Behaviours of Discharges

Electric discharges which do not bridge electrodes are called partial discharges. Between the discharge and one or both electrodes, a sound dielectric is present in the shape of a solid, liquid or gaseous insulator. Examples of this type of discharge are discharges in a cavity in a solid dielectric (both electrodes are shielded from the discharges by the solid), discharges on a surface (at least one electrode is shielded by a solid dielectric), and discharges around a sharp point at high voltage (the discharge is shielded from one electrode by a column of non-ionized gas). Although the magnitude of such discharges is usually small, they can cause progressive deterioration and ultimate failure, so that it is essential to detect their presence as a non-destructive control test.

Partial discharges belong to a far greater group of gas discharges. In all these discharges gas molecules are ionized by the impact of electrons. The newly formed electrons gain speed in an electric field, ionizing more molecules by impact, so that an avalanche of electrons is formed. The electrons in the avalanche and the ions left behind move towards the electrodes, thereby forming a passage of current through the gas. [2]

The term ionization is often used for partial or internal discharges. This is incorrect because the scope of this term is far broader according to its definition: a process by which an atom becomes electrically charged due to losing or gaining one or more of its extra nuclear electrons. Figure 1.1 shows the correlation between the various terms.

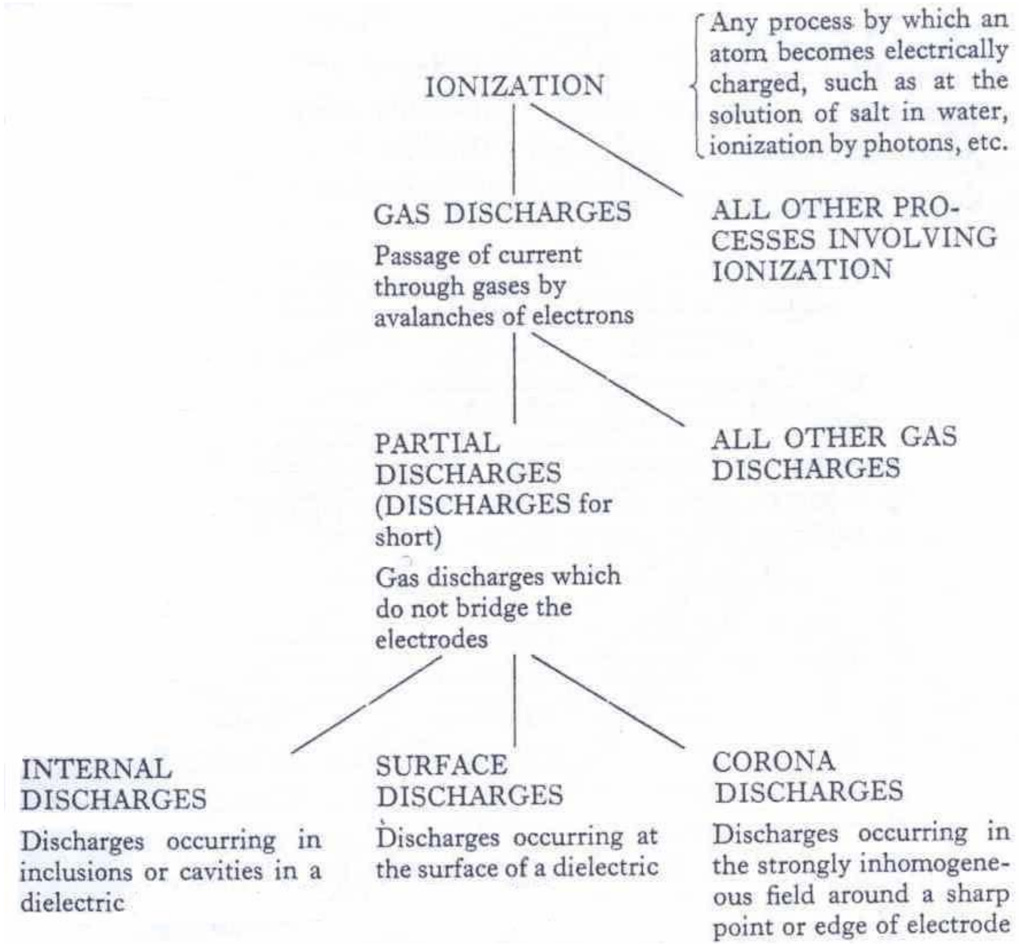


Figure 1-1 Ionization Tree

### 1.2.1 Internal Discharges

Internal discharges in a dielectric occur in inclusions of low dielectric strength. The material in the inclusion breaks down at a stress which is low compared with the breakdown strength of the surrounding dielectric. Moreover, the dielectric constant of the material in the inclusion is often lower than that of the dielectric, so that the electric stress in the inclusion is higher than in the dielectric and the inclusion breaks down even earlier.

A frequently occurring inclusion is the gas-filled cavity. It can occur in extruded plastics, cast resins, and so on.

The behaviour of internal discharges at a.c. voltage can be described conveniently with the analogue circuit of Figure 1.2. [3, 4, 5, 6] The capacity of the cavity is represented by capacitor ***c***, the capacity of the dielectric in series with ***c*** by ***b***. The rest of the sample is represented by ***a***.

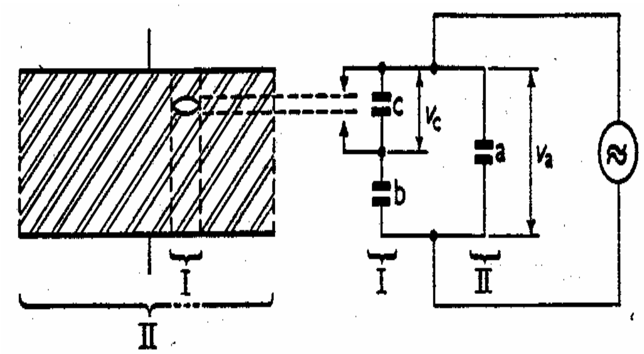


Figure 1-2 Representation of a cavity in a dielectric

In Figure 1.3 the high voltage across the dielectric is denoted Va, the voltage across the cavity is Vc. When this voltage Vc reaches the breakdown voltage $U^+$ a discharge occurs in the cavity; $U^+$ is specific to the material in the cavity. The voltage then drops to $V^+$ (usually less than 100 V) when the discharge extinguishes. This voltage drop takes place in less than $10^{-7}$ seconds; [3, 7] this is extremely short compared with the duration of a 50 Hz sine-wave so that the voltage drop may be regarded as a step function.

After the discharge has been extinguished, the voltage over the cavity increases again. This voltage is determined by the superposition of the main electric field and the field of the surface charges at the cavity walls left behind after the last discharge.

These fields counteract one another. When the voltage over the void reaches $U^+$, a new discharge occurs. This happens several times, after which the high voltage Va over the sample decreases and the voltage Vc drops to $U^-$ before a new discharge occurs.

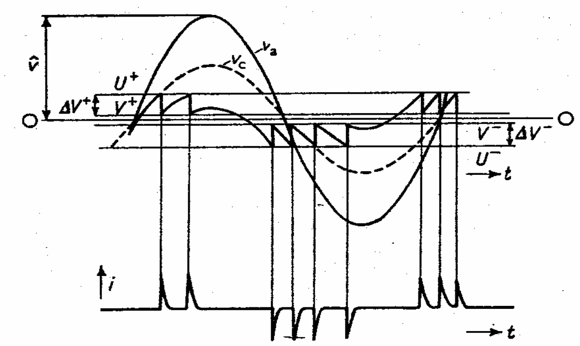

Figure 1-3 Recurrence of internal discharges

The a.c. voltage across the sample at which discharges start to occur when the voltage is increased is called the inception voltage, the corresponding stress in the surrounding dielectric the inception stress. If the voltage is decreased after discharges have been started, the voltage at which the discharges extinguish is usually lower than the inception voltage. This voltage is called the extinction voltage and the corresponding stress is called the extinction stress. The breakdown strength of the cavity, $U^+$ or $U^-$, is sometimes called the ignition voltage of the cavity. The residual voltage, $V^+$ or $V^-$, is sometimes called the remanent voltage.

When the d.c. voltage is applied, discharges occur during the rise of the voltage, as in the case of a.c. voltage. After the voltage has become constant, discharges occur only infrequently. [1]

### 1.2.2 Surface Discharges

Surface discharges may occur if there exists a stress component parallel to a dielectric surface. This applies to bushings, ends of cables, the overhang of generator windings, and the condition in which a discharge from outside hits the surface. The discharge affects the electric field, so that in general the discharges extend beyond the region where the original surface component of the electric field was high enough to cause discharges.

The behaviour of surface discharges at a.c. voltage can be deduced from the diagram shown in Figure 1.2. The capacity between the electrode and the region of the surface covered by the discharge corresponds to ***c*** (see Figure 1.4), ***b*** corresponds to the capacity of the dielectric in series with ***c***, and ***a*** corresponds to the sample.

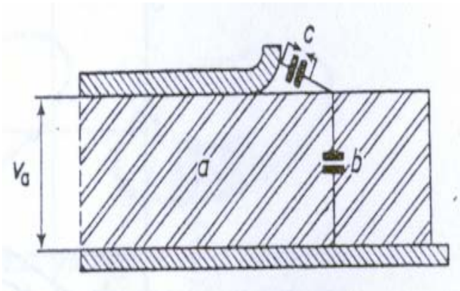


Figure 1-4 abc Diagram for surface discharges

This circuit leads to similar discharge patterns as with internal discharges. However, as the electrode arrangement is asymmetric and the discharge is at one side bounded by metal, asymmetric patterns will occur as in the case of metal-bounded discharges in cavities. A frequently occurring discharge pattern is one in which many small discharges occur when the upper electrode is negative, and fewer larger discharges when this electrode is positive. The ratio between negative and positive discharges can be anything between 1:1 and 10:1. The difference is attributed to the difference in mobility of positive and negative surface charges. [1]

Surface discharges may occur when d.c. voltage is switched on. After that discharges will occur very infrequently, such as internal discharges. With impulse voltages surface discharges may also occur.

### 1.2.3 Corona Discharges

A corona is a process by which a current, perhaps sustained, develops from an electrode with a high potential in a neutral fluid, usually air, by ionizing that fluid so as to create a plasma around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules.

When the potential gradient is large enough at a point in the fluid, the fluid at that point ionizes and it becomes conductive. If a charged object has a sharp point, the air around that point will be at a much higher gradient than elsewhere, and can become conductive while other points in the air do not. When the air becomes conductive, it effectively increases the size of the conductor. If the new conductive region is less sharp, the ionization may not extend past this local region. Outside of this region of ionization and conductivity, the charged particles slowly find their way to an oppositely charged object and are neutralized.

If the geometry and gradient are such that the ionized region continues to grow instead of stopping at a certain radius, a completely conductive path may be formed, resulting in a momentary spark or a continuous arc. [8]

Corona discharge usually involves two asymmetric electrodes; one highly curved (such as the tip of a needle, or a narrow wire) and one of low curvature (such as a plate, or the ground). The high curvature ensures a high potential gradient around one electrode, for the generation of a plasma.

Coronas may be positive or negative. This is determined by the polarity of the voltage on the highly-curved electrode. If the curved electrode is positive with respect to the flat electrode we say we have a positive corona, if negative we say we have a negative corona. The physics of positive and negative coronas are strikingly different. This asymmetry is a result of the great difference in mass between electrons and positively charged ions, with only the electron having the ability to undergo a significant degree of ionizing inelastic collision at common temperatures and pressures. [8]

Corona discharge of both the positive and negative variety have certain mechanisms in common.

**a)** A neutral atom or molecule of the medium, in a region of strong field (high potential gradient, near the curved electrode) is ionized by an exogenous environmental event (for example, as the result of a photon interaction), to create a positive ion and a free electron.

**b)** The strong field then operates on these charged particles, separating them, and preventing their recombination, and also accelerating them, imparting each of them with kinetic energy.

**c)** As a result of the energisation of the electrons (which have a much higher charge/mass ratio and so are accelerated to a higher velocity), further electron/positive-ion pairs may be created by collision with neutral atoms. These then undergo the same separating process creating an electron avalanche. Both positive and negative coronas rely on electron avalanches.

**d)** In processes which differ between positive and negative coronas, the energy of these plasma processes is converted into further initial electron dissociations to seed further avalanches.

**e)** An ion species created in this series of avalanches (which differs between positive and negative coronas) is attracted to the uncurved electrode, completing the circuit, and sustaining the current flow.

The onset voltage of corona or Corona Inception Voltage (CIV) can be found with Peek's law (1929), [9] formulated from empirical observations. Later papers derived more accurate formulas. The current carried by the corona is determined by integrating the current density over the surface of the conductor. The power loss is determined by multiplying the current and the voltage.

#### 1.2.3.1 Negative Corona

A negative corona is manifested in a non-uniform corona, varying according to the surface features and irregularities of the curved conductor. It often appears as tufts of corona at sharp edges, the number of tufts altering with the strength of the field. The form of negative coronas is a result of its source of secondary avalanche electrons. It appears a little larger than the corresponding positive corona, as electrons are allowed to drift out of the ionizing region, and so the plasma continues some distance beyond it. The total number of electrons, and electron density is much greater than in the corresponding positive corona. However, they are of a predominantly lower energy, owing to being in a region of lower potential-gradient. Therefore, whilst for many reactions the increased electron density will increase the reaction rate, the lower energy of the electrons will mean that reactions which require a higher electron energy may take place at a lower rate. [10]

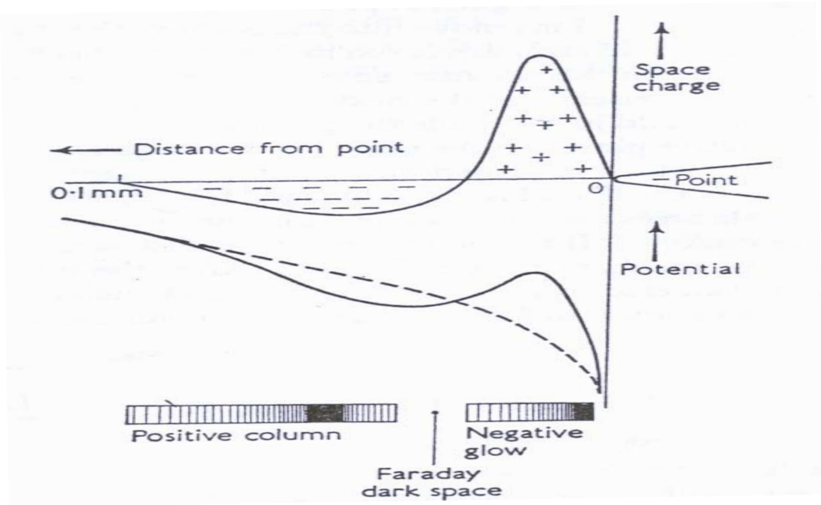


Figure 1-5 Negative corona; space charge and potential distribution

Negative coronas are more complex than positive coronas in construction. As with positive coronas, the establishing of a corona begins with an exogenous ionization event generating a primary electron, followed by an electron avalanche. [10]

Electrons ionized from the neutral gas are not useful in sustaining the negative corona process by generating secondary electrons for further avalanches, as the general movement of electrons in a negative corona is outward from the curved electrode. For negative corona, instead, the dominant process generating secondary electrons is the photoelectric effect, from the surface of the electrode itself. The work-function of the electrons (the energy required to liberate the electrons from the surface) is considerably lower than the ionization energy of air at standard temperatures and pressures, making it a more liberal source of secondary electrons under these conditions. Again, the source of energy for the electron-liberation is a high-energy photon from an atom within the plasma body relaxing after excitation from an earlier collision. The use of ionized neutral gas as a source of ionization is further diminished in a negative corona by the high-concentration of positive ions clustering around the curved electrode. [10]

Under other conditions, the collision of the positive species with the curved electrode can also cause electron liberation. [10]

The difference, then, between positive and negative coronas, in the matter of the generation of secondary electron avalanches, is that in a positive corona they are generated by the gas surrounding the plasma region, the new secondary electrons travelling inward, whereas in a negative corona they are generated by the curved electrode itself, the new secondary electrons travelling outward.

A further feature of the structure of negative coronas is that as the electrons drift outwards, they encounter neutral molecules and, with electronegative molecules (such as oxygen and water vapour), combine to produce negative ions. These negative ions are then attracted to the positive uncurved electrode, completing the 'circuit'. [8, 10]

A negative corona can be divided into three radial areas, around the sharp electrode. In the inner area, high-energy electrons inelastically collide with neutral atoms and cause avalanches, whilst outer electrons (usually of a lower energy) combine with neutral atoms to produce negative ions. In the intermediate region, electrons combine to form negative ions, but typically have insufficient energy to cause avalanche ionization, but remain part of a plasma owing to the different polarities of the species present, and the ability to partake in characteristic plasma reactions. In the outer region, only a flow of negative ions and, to a lesser and radially-decreasing extent, free electrons toward the positive electrode takes place. The inner two regions are known as the corona plasma. The inner region is an ionizing plasma, the middle a non-ionizing plasma. The outer region is known as the unipolar region. [8, 10]

#### 1.2.3.2 Positive Corona

A positive corona is manifested as a uniform plasma across the length of a conductor. It can often be seen glowing blue/white, though much of the emissions are in the ultraviolet. The uniformity of the plasma owes itself to the homogeneous source of secondary avalanche electrons. With the same geometry and voltages, it appears a little smaller than the corresponding negative corona, owing to the lack of a non-ionizing plasma region between the inner and outer regions. There are many fewer free electrons in a positive corona, when compared to a negative corona, except very close to the curved electrode: perhaps a thousandth of the electron density, and a hundredth of the total number of electrons.

However, the electrons in a positive corona are concentrated close to the surface of the curved conductor, in a region of high-potential gradient (and therefore the electrons have a high energy), whereas in a negative corona many of the electrons are in the outer, lower-field areas. Therefore, if electrons are to be used in an application which requires a high activation energy, positive coronas may support a greater reaction constants than corresponding negative coronas; though the total number of electrons may be lower, the number of a very high energy electrons may be higher. [11]

Beyond the plasma, in the unipolar region, the flow is of low-energy positive ions toward the flat electrode.

As with a negative corona, a positive corona is initiated by an exogenous ionization event in a region of high potential gradient. The electrons resulting from the ionization are attracted toward the curved electrode, and the positive ions repelled from it. By undergoing inelastic collisions closer and closer to the curved electrode, further molecules are ionized in an electron avalanche. [10, 11]

In a positive corona, secondary electrons, for further avalanches, are generated predominantly in the fluid itself, in the region outside the *plasma* or avalanche region. They are created by ionization caused by the photons emitted from that plasma in the various de-excitation processes occurring within the plasma after electron collisions, the thermal energy liberated in those collisions creating photons which are radiated into the gas.

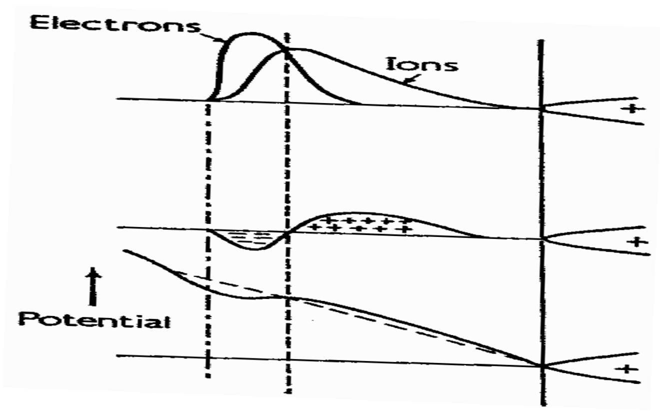


Figure 1-6 Positive corona; space charge and potential distribution

The electrons resulting from the ionization of a neutral gas molecule are then electrically attracted back toward the curved electrode, attracted into the plasma, and so begins the process of creating further avalanches inside the plasma. [10, 11]

As can be seen, the positive corona is divided into two regions, concentric around the sharp electrode. The inner region contains ionizing electrons, and positive ions, acting as a plasma, the electrons avalanche in this region, creating many further ion/electron pairs. The outer region consists almost entirely of the slowly migrating massive positive ions, moving toward the uncurved electrode along with, close to the interface of this region, secondary electrons, liberated by photons leaving the plasma, being re-accelerated into the plasma. The inner region is known as the plasma region, the outer as the unipolar region. [10, 11]

# CHAPTER 2

# DETECTION & CLASSIFICATION OF PARTIAL DISCHARGES

In the literature, there are lots of information about partial discharge detection and measuremet methods.

Discharges give rise to many phenomena which may be used for detection. These phenomena are illustrated as follows:

Partial discharges →
- Electric phenomena →
  - Electric impulses
  - Dielectric losses
- Electromagnetic radiation
- Light
- Heat
- Noise
- Gas pressure
- Chemical transformations

The detection of electric phenomena is most frequently performed with measurement of dielectric losses and detection of electric impulses. The non-electric detection methods are not used so often because they are in many cases less sensitive than the electric ones. Any of these phenomena might be used for detection of discharges at a.c. voltage, d.c. voltage, or voltage surges. This research will be limited to detection at a.c. voltage only. In all cases attention must be paid to the following aspects. [1]

**Detection:** Detection comprises the determination of the absence or presence of discharges. The voltage at which the discharges appear is determined. All sorts of methods may be used.

**Measurement:** The magnitude of the discharges may be measured by means of several electrical methods.

**Location:** Location comprises the establishment of the place of the discharges. The choice of the method depends strongly on the nature of the investigated object. Noise or light produced by discharges may sometimes be used. With cable cores electrical scanning methods are available.

**Evaluation:** Evaluation comprises the assessment of damage involved by discharges. This is a difficult task; even if the magnitude and location of the discharges and characteristics such as field strength and frequency are known, it is difficult to predict the voltage life of the dielectric.

## 2.1. Electrical Detection Methods

As has been indicated in Figure 1.2, discharges in a sample cause current impulses in the leads of the sample. A great variety of circuits is in use to detect these impulses, but all these circuits can be reduced to one basic diagram. In Figure 2.1, this diagram is shown. [1] The elements are:

**a)** High voltage source

**b)** Sample ***a*** affected by discharges

**c)** Impedance ***Z***, across which voltage impulses occur caused by the current impulses in the sample

**d)** Coupling capacitor ***k***, which facilitates the passage of the high frequency current impulses

**e)** Amplifier '***A***'

**f)** Observation unit '***O***', which may be, for instance, a loudspeaker, a voltmeter, or an oscilloscope

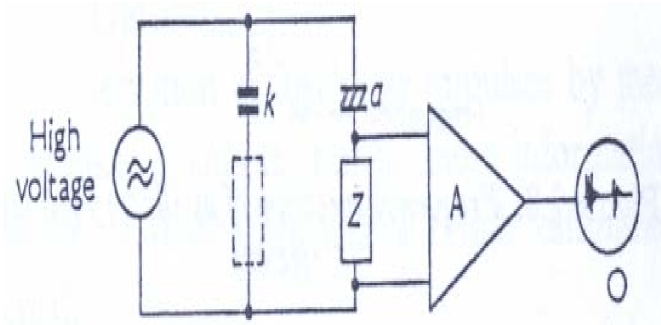


Figure 2-1 Basic diagram for electrical discharge detection

The impedance Z may be connected to the sample in two ways: either Z is placed in series with the sample (see Figure 2.1) or Z is placed in series with the coupling capacitor which is indicated in Figure 2.1 by a dotted line. Both ways are electrically equal: the same voltage occurs across the impedance Z. In practice, the connection of Z may be of importance. For instance, if the sample is large, Z is often placed in series with k so that the large charging current of ***a*** does not pass through the impedance Z. Two impedances commonly used are a resistor R shunted by a capacity C, or an oscillatory circuit, RLC. The voltage impulses which occur across these impedances may be calculated with the aid of Laplace transformations. [1]

In the RC circuit, the impulse appears to be unidirectional and is given by:

$$V = \frac{q}{(1+C/k)a+C}.\exp(-t/Rm) \qquad \text{(Equation 2.1) [1]}$$

where q is the magnitude of the discharge causing the impulse, q=b.ΔV. Furthermore,

$$m = \frac{ak}{a+k} + C \qquad \text{(Equation 2.2) [1]}$$

In the RLC circuit the impulse is an attenuated oscillation with the same voltage as an RC circuit.

$$V = \frac{q}{(1+C/k)a+C}.\exp(-t/2Rm).\cos wt \qquad \text{(Equation 2.3) [1]}$$

$$\text{where } w = \sqrt{\left\{ \frac{1}{Lm} - \frac{1}{4R^2m^2} \right\}} \qquad \text{(Equation 2.4) [1]}$$

It follows from equations (2.1) and (2.3) that the height of the impulse is proportional to the magnitude q of the discharge.

It follows further that the height of the impulse is independent of R. However, if R is small, the time constant Rm is small and thus the impulse is sharp. In most amplifiers this sharp impulse will not fully be amplified and the resulting impulse becomes smaller if R is decreased.

If *a* is large the height of the impulse is determined by *a* only, as

$$V' \approx \frac{q}{a'} \quad \text{for } a \gg C \text{ and } k$$

It also follows from equation (2.1) that a coupling capacitor *k* is necessary, as otherwise *C/k* in the denominator is large and the impulse becomes small. In some circuits, a separate capacitor for *k* is not provided and *k* is equal to the capacitance of the high voltage source. It is clear from the above considerations that this may lead to uncertain results. [1]

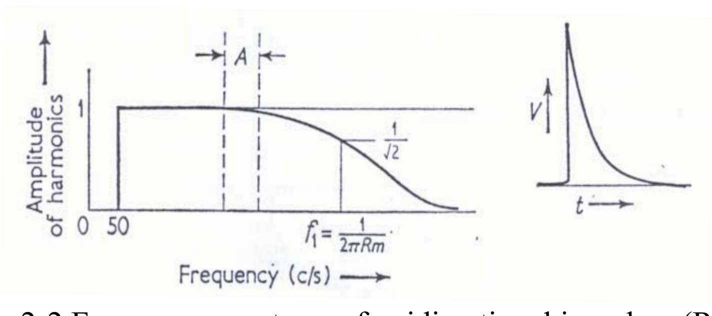


Figure 2-2 Frequency spectrum of unidirectional impulses (RC circuit)

For the RC circuit, the unipolar impulses produced over the RC detection impedance have a frequency spectrum which is nearly constant in height up to a frequency $f_1 = 1/(2\pi Rm)$, as shown in Figure 2.2. [1]

As *m* depends on circuit constants, the extension of the frequency spectrum depends on the circuit and the magnitude of the resistor R.

The amplifier used for the amplification of these impulses should obviously have a bandwidth which extends to or beyond $f_1$. In some cases a narrow-band amplifier with a midband frequency below $f_1$ is used, as shown under A in Figure 2.2. The height of the signal obtained is proportional to that of the original signal. [1]

For the RLC circuit, the oscillatory impulses which occur over an RLC network have a frequency spectrum as shown in Figure 2.3. The midband frequency *w* is given by Formula 2.4. It follows from this formula that *w* is determined both by the RLC impedance and the circuit constants.

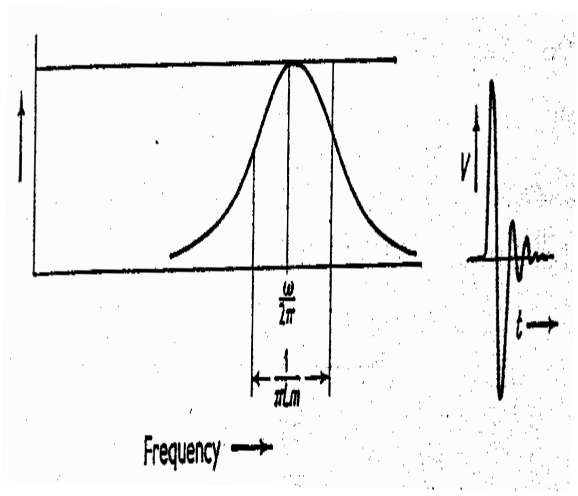


Figure 2-3 Frequency spectrum of oscillatory impulses (RLC circuit)

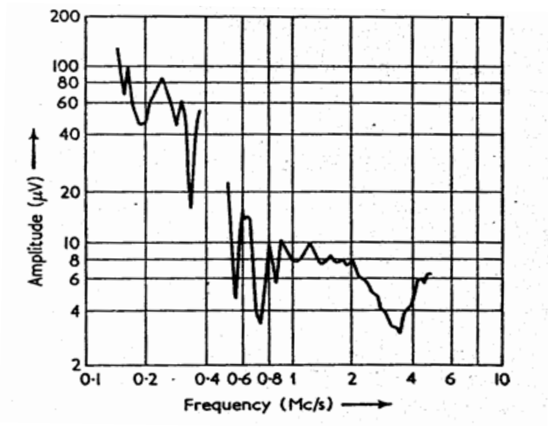


Figure 2-4 Frequency spectrum of an impulse in a transformer

The amplifier behind an RLC network should have a bandwidth which is equal to or broader than that of the signal. According to Mole [12], sufficient sensitivity is obtained if this bandwidth is more than thirty times the bandwidth of the signal. If the sample comprises self-induction, as is the case, for instance, in a transformer, the frequency spectrum is not as smooth as in Figures 2.2 or 2.3. Widman [13] has shown that the frequency spectrum of discharge impulses from a high voltage transformer may follow a complicated pattern. In such a case RC detection with a broad-band amplifier is preferred.

With the elements of the preceding section, different detection circuits can be built up. Three groups of detection methods may be distinguished.

**a)** The current impulses in the leads of the sample are transformed into voltage impulses, which are amplified and observed. These methods are called straight detection methods.

**b)** The impulses are observed as in straight detection methods, but special measures are taken in order to reject disturbances caused by discharges in the high voltage source, the leads, bushings, terminals, etc. These methods are called balanced detection methods.

**c)** The power which is dissipated by the current impulses is measured. These methods belong to the loss detection methods.

All these systems are characterized by two important qualities: the sensitivity and the resolution. The sensitivity is defined by the smallest discharge (stated in picocoulombs) which can just be detected. With electrical methods the sensitivity depends on the capacitance of the object.

If the discharge impulses are observed separately, either with an oscilloscope or with an impulse counter, the resolution of the detection circuit is of interest. By resolution the number of impulses per unit of time which can be separated is meant. According to Mole [14], the resolution is defined by the number of impulses which may be distinguished in one quadrant of the 50 Hz sine wave. If more impulses per quadrant are present, an indistinct and hazy picture results.

### 2.1.1 Straight Detection Methods

In 1952 Blanchardie and Aftalion [15] published a circuit which they used for testing transformers. The coupling capacitor *k* is formed by a sphere-gap, the detection resistor is placed in series with *k* and forms part of a high pass filter which rejects the 50 Hz mains frequency.

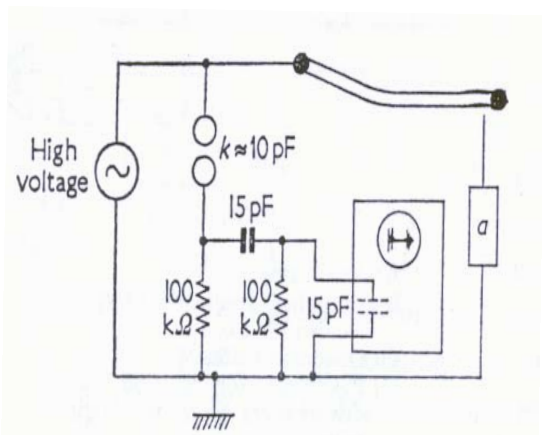


Figure 2-5 RC circuit of Blanchardie and Aftalion

This circuit was used for discharge detection in transformers. Bandwidth of oscilloscope ≈ 1 Hz to 5 MHz.

The amplifier is a broad-band amplifier and the impulses are observed by means of an oscilloscope. In Figure 2.5 this circuit is shown. The sample, usually a transformer, is connected to the circuit by means of a corona-free high voltage bar. The detection by means of a resistor yields an equal response to all oscillations which might be generated by discharges in the inductive transformer windings. The minimum detectable discharge magnitude, i.e. the sensitivity, of the set-up is not stated. An estimation made from the data given leads to 20-50 pC in a sample with a capacity of 1 nF.

Renaudin [16] published in the CIGRE of 1954 a straight detection circuit, also devised for routine tests on transformers (see Figure 2.6). The detection resistor is stepped down by means of an input transformer. As Renaudin supposes that the frequency spectrum of the discharge impulses is straight from 100 kHz to 1 MHz, he considers it sufficient to amplify a small band of 4 kHz in this region. This has the advantage that a high gain can be reached, but has the disadvantage that some oscillations in a transformer are better detected than others. The height of the impulses is recorded on a quadratic voltmeter- an electronic device which integrates the second power of the voltage so that large impulses affect the reading more than smaller ones.

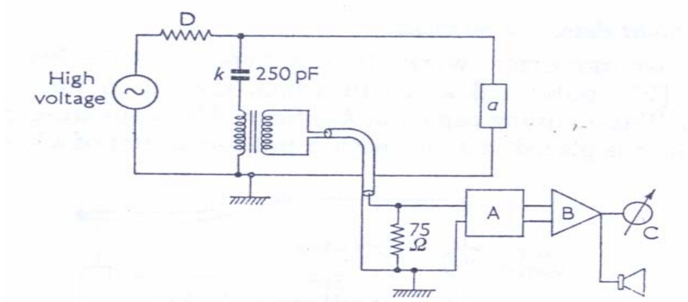


Figure 2-6 RC circuit of Renaudin

***A***: Attenuator

***B***: Amplifier, midband 130 kHz, bandwidth 4kHz

***C***: Quadratic voltmeter

***D***: Resistance for filtering out disturbances from the high voltage source

A loudspeaker is provided for aural observation of the impulses. The sensitivity of the device is not stated, but it is likely to be low.

Knosp [17] has further developed this detector. In 1962 he described an instrument with a midband frequency of 10 kHz only. The bandwidth is a few hundred cycles per second. With this detector he obtains a more uniform response to discharges at different locations in a high voltage machine. Furthermore, the sensitivity is 10 to 100 times better than with the former instrument.

The circuit of Laverlochere (Figure 2.7) has been devised for measurements on experimental test cells of small capacity [18]. The detection resistor is placed in series with the sample '***a***'. Full advantage is taken of the abilities of resistance detection by using a broad-band amplifier. The bandwidth is 800 kHz, which corresponds to a resolution of 3000 impulses per quadrant. The impulses are observed by means of impulse counters. The sensitivity is not stated, but it is estimated that it is of the order of 1pC in a sample of 1000 pF.

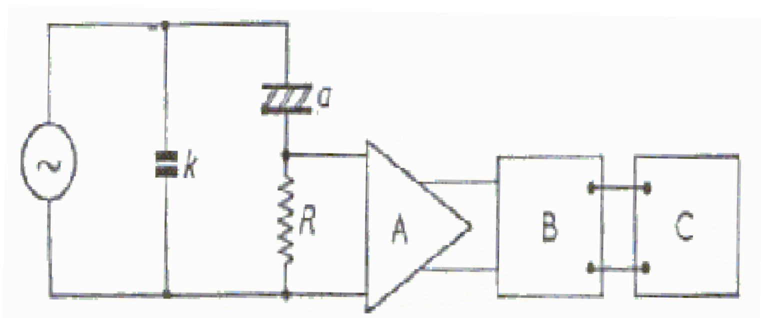


Figure 2-7 RC circuit of Laverlochere for discharge detection on test cells

***A***: Amplifier, bandwidth 800 kHz

***B***: Electronic device which classifies impulses according to their height

***C***: Impulse counter

Up to this point the given example circuits are of type RC. There are also RLC circuits with straight detection method.

A circuit whis has often been mentioned is that of Quinn [19], published in 1940. A small coil is placed in series with the sample (see Figure 2.8). The frequency of the attenuated oscillations which occur over L is determined by the values of L, *a*, and *k*; consequently this frequency varies with varying samples. The oscillatory impulses are broad-band amplified and observed with an oscilloscope. The small self-induction L is mainly chosen because of the elimination of the 50 Hz test frequency.

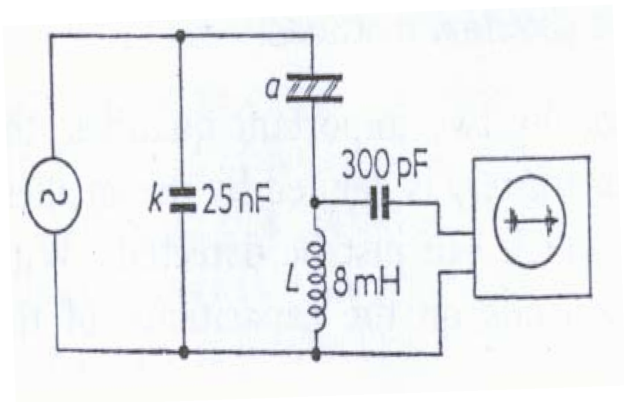


Figure 2-8 RLC circuit of Quinn Broad band amplifier

The sensitivity is not high; estimations lead to about 20 pC for an object of 1000 pF. The resolution is determined by the attenuation of the oscillatory impulses. The better the quality of the coil, the higher the resolution. No estimation for the present circuit can be made. The set-up is primitive but can easily be mounted if a quick trial is made.

Mole [12,14] published in 1952 a thoroughly designed circuit, the first with which optimum sensitivity and reproducible results could be obtained. In Figure 2.9 the circuit is shown. The high voltage source is discharge-free. Moreover, a filter is provided which blocks disturbances from the mains and from the transformer.

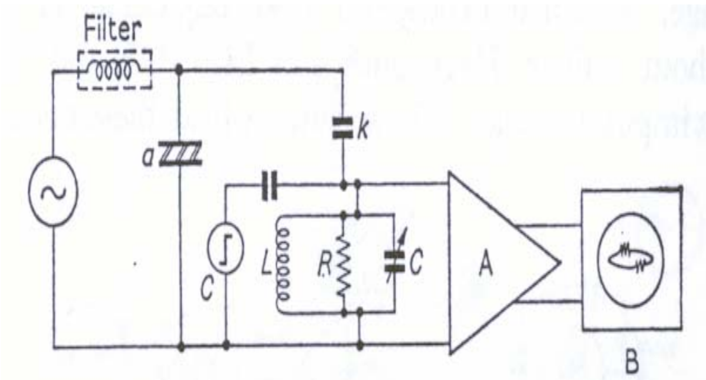

Figure 2-9 RLC circuit of Mole ERA detector Model I, tuned amplifier

**Components:**

Discharge-free transformer

Filter for suppression of disturbances

***a***: Sample, earthed

***k***: Discharge-free coupling capacitor

***RLC***: Detection impedance which is interchangeable for obtaining optimum sensitivity

***A***: Amplifier, bandwidth 10 kHz

***B***: Oscillograph: The impulses are displayed on an elliptical time base

***C***: Calibration impulse with which the discharge impulses can be calibrated (pC)

The RLC element is placed in series with a discharge-free blocking capacitor *k*; the sample ***a*** is earthed so that large capacitors can be tested without large currents running through the RLC detection element. A series of RLC elements is provided so that optimum sensitivity can be obtained for a number of capacity ranges. With these interchangeable elements and by varying C, the frequency of the oscillation can always be tuned to the midband frequency of the amplifier. For this midband frequency 500 kHz is chosen because of the absence of disturbances from radio transmissions, 500 kHz being the centre of a rescue band.

The bandwidth of the amplifier is 10 kHz, which permits the resolution of 35 impulses per quadrant of the 50 Hz wave. The sensitivity is high; in an object of 1000 pF a discharge of 0.02 pC may be detected. The discharge impulses are displayed on an elliptical trace which is recorded with a repetition frequency of 50 times per second. The resulting picture is stable and the location of the discharges with respect to the sine of the test voltage is clearly visible. An important part of the equipment is the calibration circuit. A calibration impulse of known charge content is fed into the circuit. This impulse can be varied and the resulting picture on the screen can be made as high as that of the observed discharges. In this way a direct estimation of the discharges, expressed in picocoulombs, can be made. Owing to this, calibration test results obtained by different observers can be compared.

Mole also developed new versions of ERA detector. One of these models is Model III [20]. In this model the resolution is improved by increasing the bandwidth. The midband frequency is lowered. The sensitivity is retained at the original level.

Viale [21] published in 1954 a circuit which can be seen as the counter-part of the first detector of Mole. A fixed self-inductance is placed in series with the sample; the midband frequency of the amplifier is tuned to the frequency of the oscillatory impulse. The sensitivity is less and amounts to 0.1 pC in an object of 1000 pF.

For the sake of completeness it should be mentioned that radio interference meters, which sometimes are used as discharge detectors, belong to the straight methods as well.

### 2.1.2 Balanced Detection Methods

One of the main difficulties when making discharge tests is discharges which do not occur in the sample but in other parts of the test circuit, such as in the high voltage source, in the high voltage leads, in the blocking capacitor, etc. The impulses caused by these discharges cannot be distinguished from those of discharges in the test object, so that they disturb the observation of the wanted discharges. With the straight detection methods, the effect of these external discharges can only partially be suppressed. Two methods are known for this:

**a)** A filter may be used as shown in Figure 2.9.

**b)** If the detection impedance ***Z*** is placed in series with the sample ***a***, as in Figure 2.8, and ***k*** is made larger than ***a***, the impulses of external discharges are decreased in the ratio ***a***/***k***.

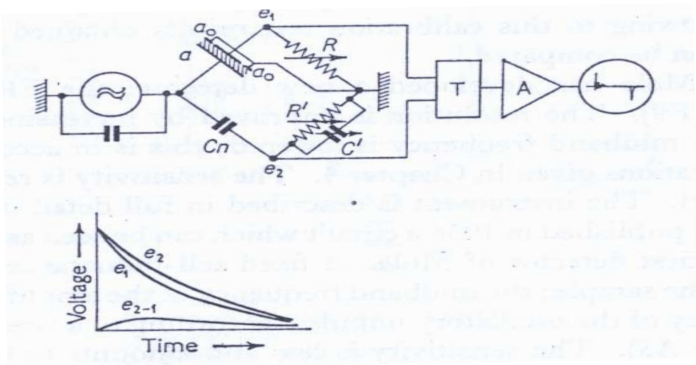


Figure 2-10 High frequency Schering bridge circuit

***T***: Transformer

***A***: Amplifier, broad band or narrow band

If the external disturbances are not sufficiently controlled, a balanced system should be used. Besides, an object sometimes comprises parts which must not be included in the test, such as bushings in a transformer and sending ends of cables. In these cases, also, unwanted discharges may be rejected.

A method which is often applied makes use of the Schering bridge which usually is present in a high voltage laboratory. It is in fact a method with a resistance as a detection element, as shown in Figure 2.10. [1] A discharge in the sample causes an impulse across resistor R. The impulse is supplied to an oscilloscope via a filter and an amplifier. A disturbance from outside causes an impulse across the resistor on either of the bridges. The difference between these impulses measured between the bridge points is smaller than the impulses themselves; impulses from the sample, however, are fully recorded. In this way external discharges and disturbances are reduced, as well as discharges at the edge electrodes which are characterized by the fact that they occur in a capacitor between high voltage and earth (see $a_0$ in Figure 2.10). A minimum is adjusted by varying R' and C'.

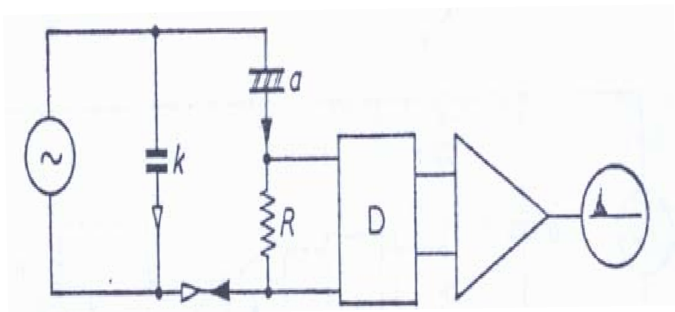

Figure 2-11 Detection circuit of Hashimoto

***D***: Discriminator which rejects impulses of one polarity during one-half of the 50 Hz sine wave.

A method which is based on a totally different principle is that of Hashimoto [22], which was published in 1960. The impulses caused by internal discharges are in opposite direction to those caused by external discharges (see Figure 2.11). By means of an electronic device, the impulses in one direction are amplified only.

Although this method seems to be excellent, it has some disadvantages which make it less useful. With this system, discharges of one half-cycle of the test frequency can be shown only, as in the other half-cycle the external discharges have changed sign and should become visible. This may cause the neglect or misinterpretation of an asymmetric discharge. Furthermore, the impulses often have an overshoot through the zero line. Consequently, the rejection of external discharges is limited. From an oscillogram of Hashimoto it appears that an impulse of 22.5 mm height is accompanied by an overshoot of 0.5 mm. Consequently, a signal caused by external discharges is reduced by a factor of 45 only.

### 2.1.3 Loss Detection

The energy is supplied to the sample by means of the current impulses in the leads. Measurement of this energy (expressed in the loss-tangent, tan δ) by means of a Schering bridge is an old and well-known method.

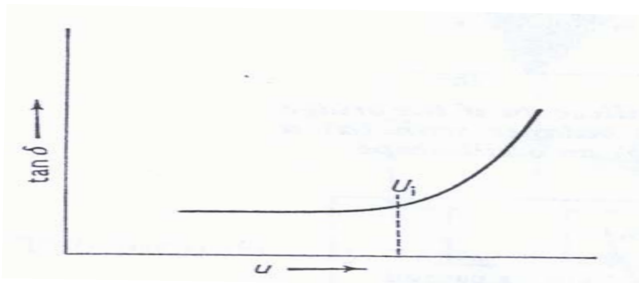

Figure 2-12 Dielectric loss as a function of voltage

$U_i$ is taken as the inception voltage. A diagram is made in which tan δ is shown as a function of the voltage U (see Figure 2.12). A sudden increase of the loss-tangent is attributed to internal discharges, the start of the increase being taken as the inception voltage. [1]

Generally many discharges are required in order to obtain a discernible increase in tan δ. If only one discharge per half-cycle occurs the sensitivity is

$q = \sqrt{(2)}\ \pi a U \Delta \tan\delta$

where $a$ = Capacity of the sample

U = Test voltage (for example, 10 kV)

$\Delta \tan\delta$ = Minimum rise in tan δ which may be discerned; with the best bridges an increase of $10^{-6}$ can be discerned.

The minimum detectable discharge in a sample of 1000 pF is then about 50 pC, so that even with the best bridges the method is quite insensitive. Moreover, not every increase in dielectric losses coincides with discharges, and the start of the increase is often difficult to determine.

Gelez [23] described in 1957 a variant of the Schering bridge. He separates the normal dielectric losses and the losses caused by discharges by means of two different adjustments of the balance.

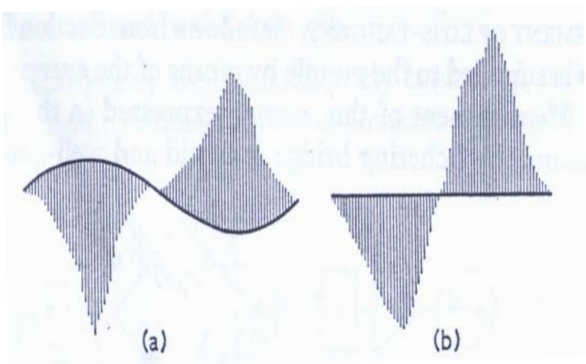


Figure 2-13 Traces on an oscilloscope

If the bridge of Gelez is adjusted at balance with

**a)** a vibration galvanometer;

**b)** an oscilloscope

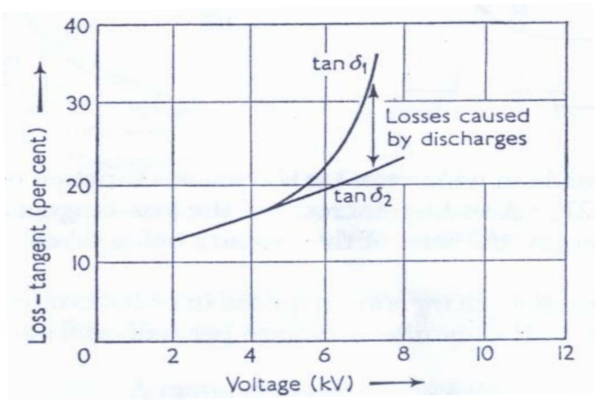


Figure 2-14 Dielectric losses as a function of voltage

$\tan \delta_1$ = Total losses $\tan \delta_2$= Total losses – losses caused by discharges

$\tan \delta_1 - \tan \delta_2$ = Losses caused by discharges

He measures the loss-tangent first in a normal way, by bringing the bridge to balance with the aid of a vibration galvanometer: $\tan \delta_{1.}$ Thereafter the galvanometer is replaced by an oscilloscope and the 50 Hz basic frequency is brought to balance: $\tan \delta_{2.}$ Figure 2.13 shows the pictures which appear on an oscilloscope at these two balance adjustments. The part of the loss-tangent which is caused by the discharge is equal to $\tan \delta_1 - \tan \delta_{2.}$ Diagrams as shown in Figure 2.14 are obtained. The sensitivity is not stated but is likely to be low.

In 1958 Veverka and Chladek [24] published an electronic device which integrates the discharge impulses and measures them in combination with the voltage over the sample with a wattmeter (see Figure 2.15).

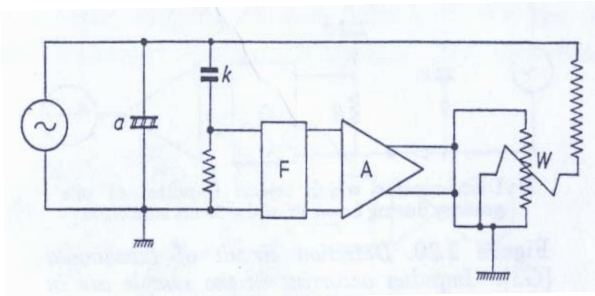

Figure 2-15 Electronic loss detector according to Veverka and Chladek

***F***: High pass filter

***A***: Amplifier

***W***: Wattmeter

The current coil carries a current which is proportional to the test voltage.

In this way they obtain a direct reading of the losses caused by discharges only. The sample is inserted in a straight detection circuit, so that precautions can be taken that no external discharges disturb the measurements. The sensitivity which can be obtained with this device is not stated.

## 2.2 Discharge Classification

When dealing with partial discharges (PD) at least three stages of information handling are needed to collect sufficient data for evaluation. These stages are:

**a)** Detection (mentioned in 2.1)

**b)** Classification

**c)** Location

Detection is usually performed with a classical discharge detector having a bandwidth of approximately 250 kHz. These detectors are commercially available or can easily be built and belong to the standard equipment of high voltage laboratories. Discharge detection is performed sometimes by acoustical or optical means, but these methods are beyond the scope of this research although the authors are convinced that equally good results can be obtained [25]. In this first stage, electrical detection shows the presence and the magnitude of the partial discharge under observations, but nothing more.

Classification aims at recognizing the defect causing the discharges, such as internal or surface discharges, corona, treeing, etc. This information is vital for estimating the harmfulness of the discharge.

Location aims at locating the position of the discharge in a dielectric construction. In an ideal case, this position reveals the type of material or the interface between materials and the local field strength where the discharge takes place, which is also vital information for the assessment of the risks involved.

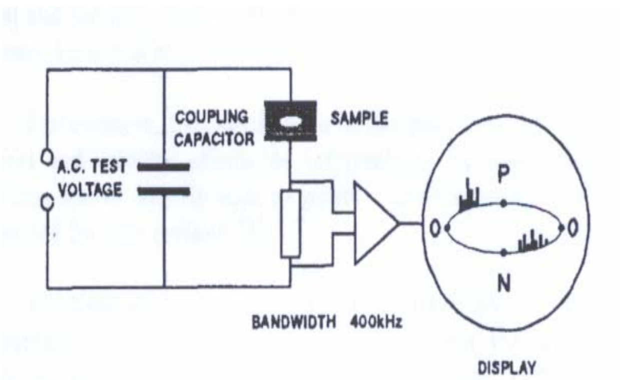


Figure 2-16 Classic discharge detection

The pulses caused by the discharges in the sample are displayed on an elliptical timebase, where 0 coincides with the zero points, P with the positive crest and N with the negative crest of the ac test voltage

All three stages are needed for evalution, which in turn leads to decision making like rejection, remaking, repair of equipment, etc.

Classification is based on recognition. There are two basic possibilities for recognizing discharges:

**a)** Phase related recognition

**b)** Time resolved recognition

### 2.2.1 Phase Related Recognition

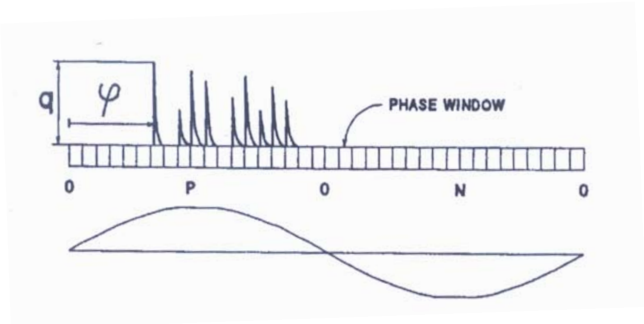


Figure 2-17 Phase Related Recognition

Each impulse on the display in Figure 2.16 is specified by its magnitude $q$ and its phase angle $\varphi$. The resulting pattern of all impulses is characteristic for the type of discharge.

This method uses the classic discharge detector and studies the patterns which occur in the 50 or 60 Hz sinewave (see Figure 2.16). These patterns are familiar to us in the shape of the widely used ellipse on a 50 or 60 Hz time base. Each discharge pulse in the pattern reflects the physical process at the discharge site and a strong relationship has been found between the shape of these patterns and the type of defect causing them. Phase related recognition offers a number of advantages, especially for use at industrial components [26].

The method is independent of the electrical path between defect and detector. As long as the detection circuit reveals the phase angle and the relative height of the impulses, it does not matter whether a discharge signal comes from a complicated set of transformer windings or from a simple capacitor: the characteristics $\varphi$ and $q$ in Figure 2.17 are of interest only.

Moreover, for the same reason this method is independent of the type of detector or its coupling circuit. The shape of the single pulses is not relevant, only their relative height and phase angle are. The only requirement is on the detector resolution, which should be in the order of ≈ 1µs.

Phase related recognition makes use of classic discharge detectors which are standard equipment in a high voltage laboratory. Equipment for recognition is added to the detector and does not replace it.

### 2.2.2 Time Resolved Recognition

In recent years very interesting results have been obtained with time resolved detection, using detection circuits with bandwidths of ≈ 500 to 1000 MHz. In Figure 2.18 simplified version of such a circuit is shown.

The same basic circuit as in Figure 2.16, but with a time constant in the order of ≈ 3 ns and a ≈ 500 MHz bandwidth. The impulses are displayed at a triggered timebase and reveal the true shape of the partial discharge current in the defect.

In this circuit the true shape of the charge displacement in the defect, e.g. a cavity, is shown at a nanosecond scale. From these shapes far-reaching conclusions can be drawn on the physical state of the discharge site, on the type of the gaseous discharge and even on the aging process which takes place in or at the dielectric. The method has some distinct differences with phase related recognition. A disadvantage is that

the VHF detection circuits are not easy to use in industrial test sites, although for GIS [27, 28] and for high voltage cables [7, 27] good circuits for industrial use have been realized.

Furthermore, pulse distortion in the path between defect and detector affects the information. Samples with complicated circuits such as power transformers are less suited for this method. [27]

The time resolved method, however, has attractive advantages. There is a direct relationship between the physics in the defect and the shape of the signal. It also has been found that stages in the aging of dielectric materials can be recognized with this method. It has been shown in [29] that the time-resolved shape of the discharge impulse changes distinctively with the aging process in a cavity. In many cases external noise is less cumbersome at these very high frequencies than in the frequency bands of classical detectors.

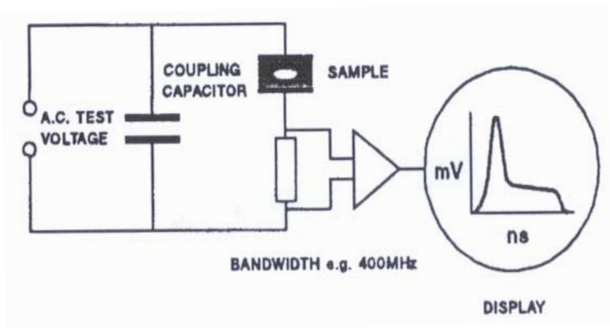


Figure 2-18 Time Related Recognition

In recent years much progress is made in time resolved recognition method and, moreover, combined use of phase-related and time-resolved methods is under development as mentioned in [30].

# CHAPTER 3

# DESIGN METHOD OF INDICATOR SYSTEM

## 3.1 System Representation

In this research it was decided to design and build a partial discharge magnitude indicator with LCD display. There were a number of design challenges with this magnitude indicator. On the analog side, a fast, low noise A/D converter was needed. In the realm of digital, it involved interfacing two microcontrollers with each other, an LCD display, and an analog to digital converter.

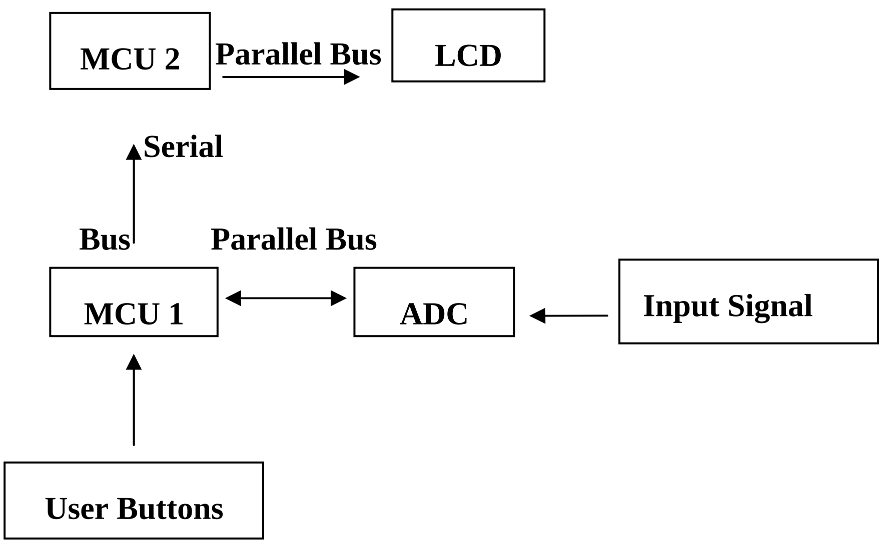


Figure 3-1 Block Diagram of the System

Above are the connections for both Microcontrollers, the LCD display, and the ADC. It can be seen as the block diagram of partial discharge magnitude indicator with LCD display design.

The use of two Microcontrollers allows distribution of the code and tasks at the expense of increased hardware and complexity. Microcontroller 1, the master, deals with data acquisition from the A/D converter, counts the number of pulses in the input voltage from the high voltage system, and calculates the maximum peak value of the pulses in the selected time interval. After this, it sends the input data from the A/D converter and all the results of these calculations to the Microcontroller 2 in serial format. Besides these, it takes in the user information about the time interval that is selectable from the switch in front of the unit. This time interval is the interval throughout which the input voltage from the high voltage system is investigated. In addition, it keeps track of the trigger level of the input voltage. Microcontroller 2, the slave, controls the LCD display communication. It takes the serial data input from the Microcontroller 1, performs the necessary calculations required to put a black pixel in the LCD display according to the value of the data (between 0 and 256) converted from the input voltage and sends this information to LCD display in parallel 8-bit format. The true necessity for two controllers is due to the fact that once the data acquisition starts, it cannot be interrupted. Only one controller can not deal with data acquisition from A/D Converter and data transmission to the LCD display at the same time. There are some ultra-fast controllers in the market but to make this discharge magnitude indicator with only one processor was not a desired solution because it was not cost effective. Additional advantages are gained with the use of two controllers. One of the main limiting factors for the Atmega32 Microcontroller is limited ports. The use of two controllers allows more ports to simplify communication with the other devices. Furthermore, having a separate controller allows the LCD refresh rate to be independent of the data acquisition rate.

## 3.2 Design Steps

### 3.2.1 LCD Display

Choosing the type of LCD display was one of the most important decisions of the project. Here are the basic points that was explored during the search for a suitable LCD display.

#### 3.2.1.1 LCD Display Controller

The most important factor to be considered in choosing an LCD display is the controller. An LCD display without a controller needs to be refreshed at a fast enough rate to prevent flickering. This would have been almost impossible using a Microcontroller due to memory and speed restrictions. Therefore, it was decided to get a display with a built-in controller. The most popular, though slightly outdated standard is the T6963C controller made by Toshiba. Another popular choice is the SED series made by Epson. Toshiba T6963C controller was chosen because it seemed relatively easy to program and among several graphic LCD displays it was generally used as a built-in controller.

#### 3.2.1.2 Size

LCD graphics displays come in a variety of sizes, ranging from 32 x 80 to 240 x 320. Larger displays offer more display area, cost more, and take longer to refresh the entire screen with new data. 240 x 128 display was chosen to have enough space to show a signal waveform while leaving room on the side to display measurement values.

#### 3.2.1.3 Display Type

There are three basic display types: TN, STN, and FSTN. Twisted Nematic (TN) is the least expensive and most basic display type. Super Twisted Nematic (STN) offers higher contrast, wider viewing angles, and is available with different background colors. Film STN (FSTN) is a black and white STN with a very high contrast ratio for large graphic panels. FSTN type was chosen because it had the best contrast ratio among the three.

#### 3.2.1.4 Backlight

Backlights also come in three basic varieties, EL, LED, and CCFL. Electro-luminescent (EL) is power efficient, but requires an inverter to operate. Light emitting diode (LED) offers even back lighting, and long life expectancy (>100,000 hrs), is simple to drive with 5 volts, and its brightness can easily be adjusted. Cold cathode florescent light (CCFL) is paper white and consumes less power than LED, but it also requires an inverter as a power supply. LED backlighting was thought to be the most suitable one because it was the easiest one to drive and it had the longest life expectancy, which was a crucial thing for the maintenance of the unit. Being the easiest one to drive was considered to be important. Otherwise, the power dissipation of the unit would have got so high while driving the other two backlights.

#### 3.2.1.5 Viewing Angle

The two basic viewing angles are defined as 12:00 and 6:00. A 12:00 display is best viewed below eye level, and a 6:00 display is best viewed above eye level. 6:00 viewing angle was chosen to view a flat screen on a desk.

Considering these issues; PG240128WRF-ATA-H-L1 graphics LCD display from Powertip Technology Corporation was bought to meet the requirements.

Here are the main features of the PG240128WRF-ATA-H-L1:

- Full dot-matrix structure with 240 dots *128 dots
- 1/128 Duty, 1/12 bias
- FSTN LCD positive type, B/W display
- Transflective LCD

- 6 o'clock viewing angle

- 8 bits parallel data input, controller IC T6963C, QFP type

- With LED backlight

**Mechanical Specifications:**

| | | |
|---|---|---|
| • Outline dimension | : | 144.0mm(L)*104.0mm(W)*19.0mm(H)max |
| • Viewing area | : | 114.0mm *64.0mm |
| • Active area | : | 107.95mm *57.55mm |
| • Dot size | : | 0.4mm *0.4mm |
| • Dot pitch | : | 0.45mm *0.45mm |

### 3.2.2 Microcontroller

After choosing the LCD display, the next thing was choosing the suitable microcontroller. The previous experiences were an important factor in choosing the microcontroller. The ATMEL processors are easy to handle and program. Besides these, they have many features that are useful for the programmer. One of its most important features is In-System Programmability. By In-System Programmability feature, the Microcontrollers are not being dislocated from the circuitry to reprogram them. By connecting this hardware from its connector to the system, the updated program was downloaded several times to microcontrollers with ease. An 8-bit Microcontroller was also needed due to the limitations of the LCD displays. All the displays with built-in controllers being investigated were dealing with 8-bit digital input. For this reason ATmega32 8-bit AVR Microcontroller from ATMEL was chosen.

The device is manufactured using Atmel's high density nonvolatile memory technology. The On-chip ISP Flash allows the program memory to be reprogrammed in-system through an SPI serial interface, by a conventional nonvolatile memory programmer, or by an On-chip Boot program running on the AVR core. The boot program can use any interface to download the application program in the Application Flash memory. Soft- ware in the Boot Flash section will continue to run while the Application Flash section is updated, providing true Read-While-Write operation. By combining an 8-bit RISC CPU with In-System Self-Programmable Flash on a monolithic chip, the Atmel ATmega32 is a powerful microcontroller that provides a highly-flexible and cost-effective solution to many embedded control applications.

The AVR core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional RISC microcontrollers. Moreover, as a special feature for only ATmega32, some instructions are faster (i.e. multiplying two numbers in 2 clock cycles) considering the other microcontrollers in the market. With this feature the instructions were done faster and thus there were less problems during the communication period of the Microcontrollers with ADC and LCD display.

The ATmega32 provides the following features: 32K bytes of In-System Programmable Flash Program memory with Read-While-Write capabilities, 1024 bytes EEPROM, 2K byte SRAM, 32 general purpose I/O lines, 32 general purpose working registers, a JTAG interface for Boundary-scan, On-chip Debugging support and programming, three flexible Timer/Counters with compare modes, Internal and External Interrupts, a serial programmable USART, a byte oriented Two-wire Serial Interface, an 8-channel, 10-bit ADC with optional differential input stage with programmable gain (TQFP package only), a programmable Watchdog Timer with Internal Oscillator, an SPI serial port, and six software selectable power saving modes. The Idle mode stops the CPU while allowing the USART, two-wire interface, A/D Converter, SRAM, Timer/Counters, SPI port, and interrupt system to continue functioning. The Power-down mode saves the register contents but freezes the oscillator, disabling all other chip functions until the next External Interrupt or Hardware Reset. In Power-save mode, the Asynchronous Timer continues to run, allowing the user to maintain a timer base while the rest of the device is sleeping. The ADC Noise Reduction mode stops the CPU and all I/O modules except Asynchronous Timer and ADC to minimize switching noise during ADC conversions. In Standby mode, the crystal/resonator oscillator is running while the rest of the device is sleeping. This allows very fast start-up combined with low-power consumption. In Extended Standby mode, both the main oscillator and the Asynchronous Timer continue to run.

Lastly; TQFP package of the Microcontroller ATmega32 was used because the Thin Quad Flat Pack (TQFP) package is a cost-effective packaging solution for moderate performance applications. By this way much more space was gained in the circuit for other hardwares used in the design.

### 3.2.2.1 In-System Programmer

Both of these Microcontrollers have an interface with the ISP. A block diagram of the AVRISP is shown in Figure 1. The AVRISP can be divided in 3 sections: The RS-232 interface, the Control section and the ISP cable. Here is a brief overview of the AVRISP interface.

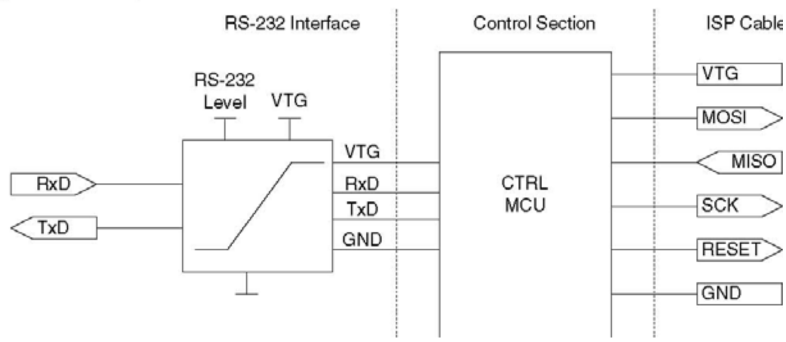


Figure 3-2 Simplified AVRISP Block Schematics

| Signal | 6-Pin | 10-Pin | I/O | Description |
|---|---|---|---|---|
| VTG | 2 | 2 | – | Power is delivered from the target board |
| GND | 6 | 3,4,6, 8,10 | – | Ground |
| MOSI | 4 | 1 | Output | Commands and data from AVRISP to target AVR |
| MISO | 1 | 9 | Input | Data from target AVR to AVRISP |
| SCK | 3 | 7 | Output | Serial Clock, Controlled by AVRISP |
| RESET | 5 | 5 | Output | Reset. Controlled by AVRISP |

Figure 3-3 AVRISP Connector Pinout

### 3.2.3 Analog-to-Digital Converter

All the LCD displays with built-in controller that were explored are operating with digital input which is at least 8 bits. So it was concluded that the input voltage which was analog should be converted to digital in order to display them in LCD display, and bit resolution for this A/D converter should be at least 8 bit. However, there were countless number of A/D converters in the market that had different speed ratings. It was decided that the discharge pulse duration would be about 10 microseconds. This was because the sampling device for the calibration of the discharge pulses produced pulses that had a duration of 10 microseconds. There should be some time needed to display these samples in LCD. For this purpose an A/D converter which has sampling resolution of 500 Ksps or 1 Msps was needed. The faster one was chosen and MAX 153 8-bit ADC from MAXIM was bought.

The MAX 153 high-speed, microprocessor (μP)-compatible, 8-bit analog-to-digital converter (ADC) uses a half-flash technique to achieve a 660 ns conversion time, and digitizes at a rate of 1M samples per second (1 Msps). It operates with single +5V or dual ±5V supplies and accepts either unipolar or bipolar inputs. A POWERDOWN pin reduces current consumption to a typical value of 1μA (with 5V supply). The part returns from power-down to normal operating mode in less than 200 ns, providing large reductions in supply current in applications with burst-mode input signals.

The MAX 153 is DC and dynamically tested. Its µP interface appears as a memory location or input/output port that requires no external interface logic. The data outputs use latched, three-state buffered circuitry for direct connection to a µP data bus or system input port. The ADC's input/reference arrangement enables ratiometric operation.

LCD display and instructions about programming the LCD display will be given in Appendix part.

### 3.2.4 Power Supply

All the hardware in the discharge magnitude indicator is operating with +5V DC. The aim was to obtain +5V DC. At this point it was decided that partial discharge magnitude indicator should be used at any desired place and for this requirement 220V 50 Hz voltage was chosen as input. Power that was required for the integrated circuits inside the unit was obtained from AC plug. A simple power supply was designed to convert the 220V 50 Hz input to +5V DC. Below is the schematic diagram of this power supply.

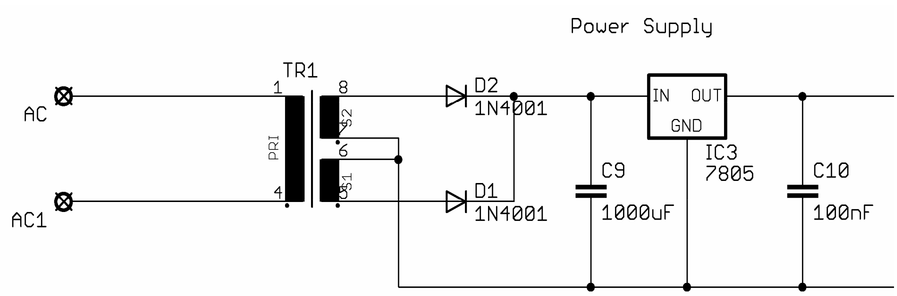


Figure 3-4 Power Supply of the System

As can be seen in the circuit diagram 220V AC coming from the plug is decreased to 9V AC and then by the rectifier diodes D1 and D2 it becomes +12V DC. After converting the AC voltage to DC it comes to the voltage regulator IC named as

LM7805. In this regulator 12V DC voltage is converted to 5V DC. This is the required power for the Microcontrollers, Analog-to-Digital Converter and LCD Display.

### 3.2.5 Other Parts of the Circuit

The input voltage that has the discharge pulses is coming to the A/D Converter (MAX153). To protect the circuit from small duration overvoltages a protector circuit was designed. This is the circuit diagram of this protector circuit:

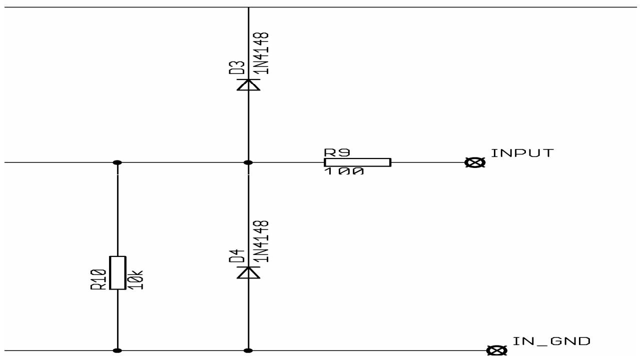


Figure 3-5 Input Protection Circuit

Here, the input voltage is coming from the R9 side. The upper line is +5V DC and the lower line is ground. For example, if an overvoltage of +30V comes to the input; D3 diode opens and input voltage becomes +5.7V. If a -30V comes, this time D4 diode opens and the input voltage becomes -0.7V. These situations hold until the diodes breaks down.

While the A/D Converter was being used, Pipe-Lined operation mode was implemented. In this type of operation making WR and RD pins low initiates a conversion and read the result of the previous conversion concurrently. So no time was lost between initiating a conversion and reads the result of the previous conversion simultaneously. The circuit diagram of the MAX153 is as follows:

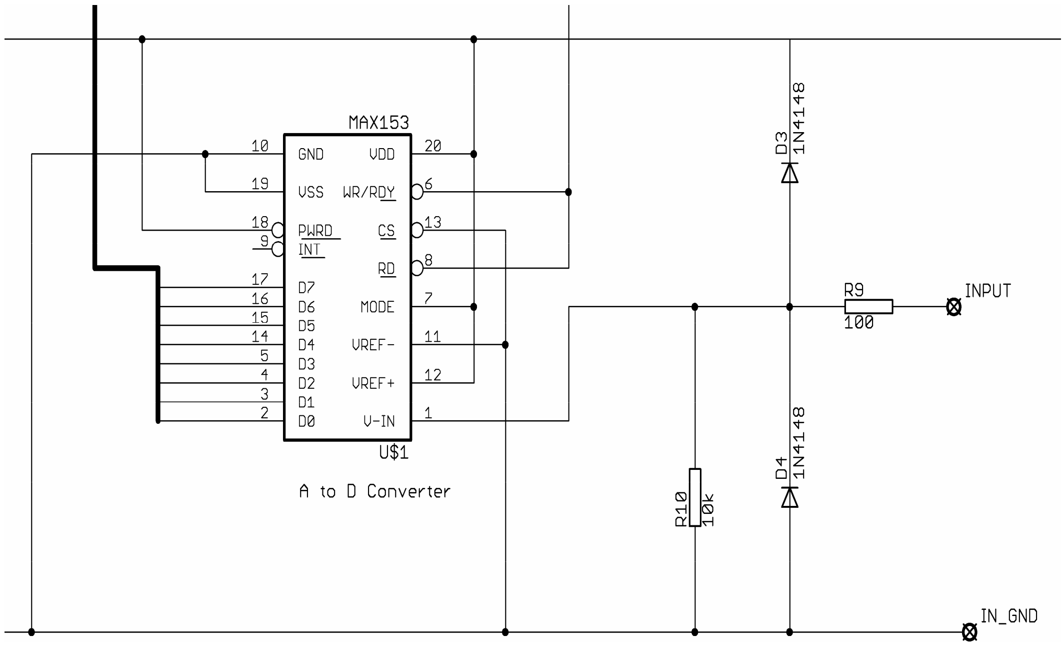


Figure 3-6 A/D Converter Circuit Diagram

WR and RD pins constitute the Control line and are connected to the Sender Microcontroller. By this way Microcontroller starts the conversion and reads the results. The results of the conversion is available at the D0 to D7 pins of the MAX153. These pins are connected to the Sender Microcontroller. Digital data is being sent to the Sender Microcontroller by this parallel bus.

The Sender Microcontroller deals with data acquisition from the A/D Converter, counts the number of pulses in the input voltage and calculates the maximum peak value of the pulses in the selected time interval. After this, it sends these calculated data to the other Microcontroller (Display Controller) in serial format.

Besides these, it takes in the user information about the time interval that is selectable from the switch in front of the unit. This time interval is the interval throughout which the input voltage from the high voltage system is investigated. It also reads the other two switches. The first one of these switches is RESET switch and the other one is the START switch that starts the investigation of the input signal.

The second Microcontroller (Display Controller) controls the LCD display communication. It takes the serial input from the Sender Microcontroller, performs the necessary calculations (i.e. where to put a black pixel in the LCD display according to the value of the data that is a number between 0 and 256) and sends this information to LCD display in parallel format.

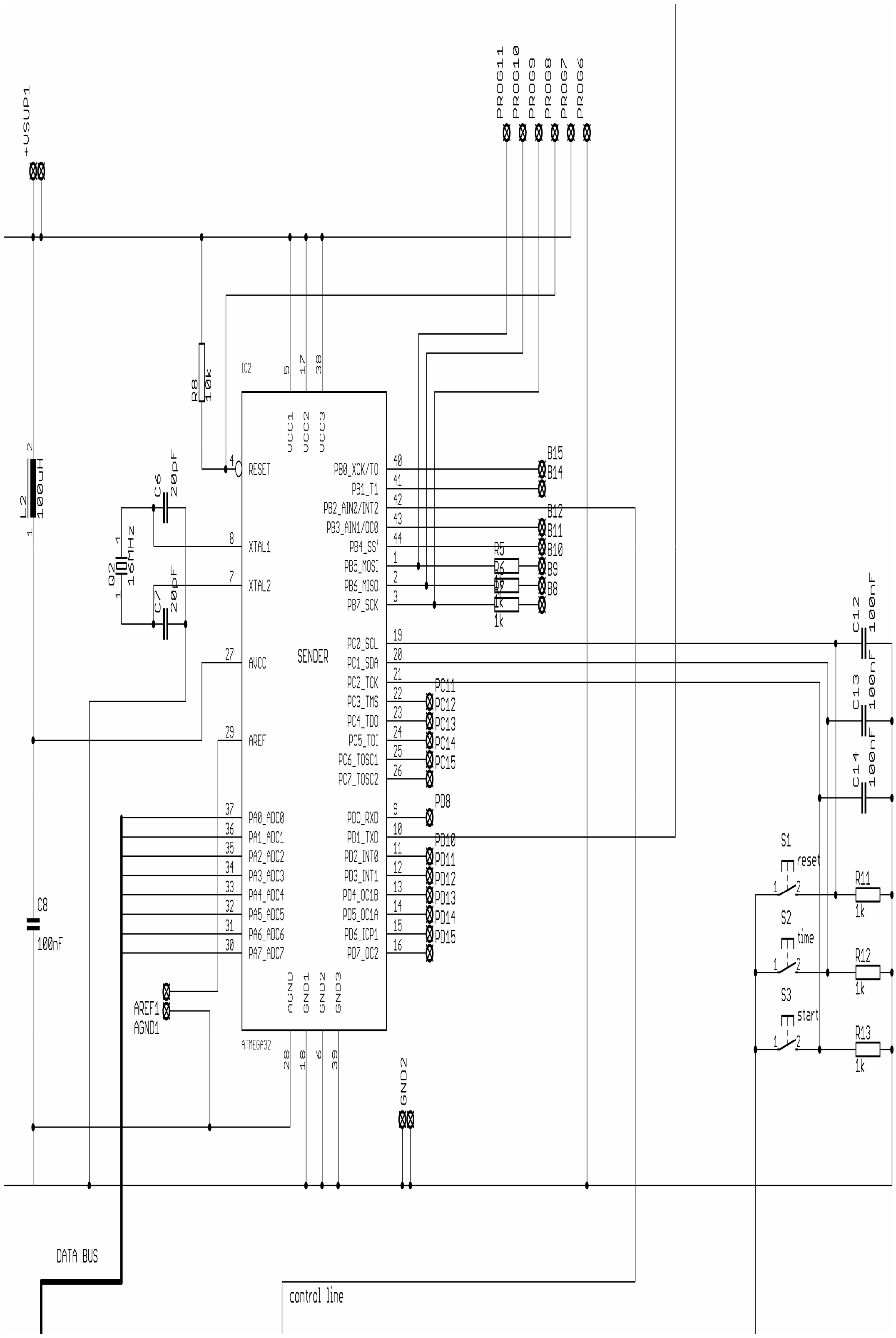


Figure 3-7 Sender Microcontroller Circuit Diagram

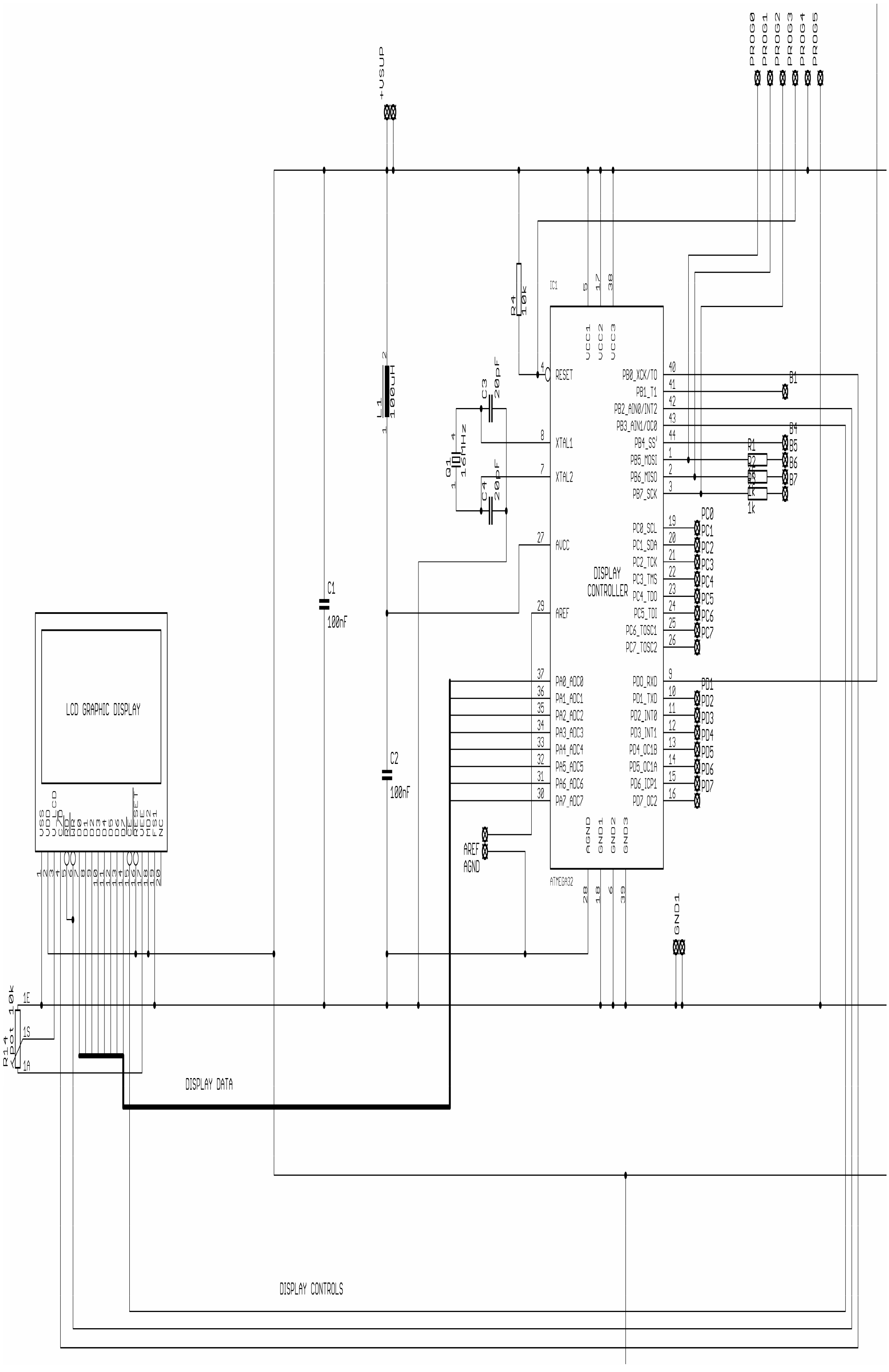


Figure 3-8 Display Controller Circuit Diagram

### 3.2.6 Software

After all the steps related with hardware, the crucial point came that was related with the software. A user-friendly and detailed software program was freeware at ATMEL's website for all of its Microcontrollers. Its name was AVR Studio. There was a user manual of it at ATMEL's web site as well. Programming was done with the latest version of the AVR Studio. Another material used for programming the microcontrollers was the Assembly instruction set for ATmega32.

AVR Studio is an Integrated Development Environment for writing and debugging AVR applications in Windows 98/XP/ME/2000 and Windows NT environments. AVR Studio provides a project management tool, source file editor and chip simulator. It also interfaces with In-Circuit Emulators and development boards available for the AVR 8-bit RISC family of microcontrollers.

Here are the main features of AVR Studio:

- Integrated development environment for writing, compiling and debugging software
- Fully symbolic source-level debugger
- Configurable memory views, including SRAM, EEPROM, Flash, Registers and I/Os
- Unlimited number of break points
- Trace buffer and trigger control
- Online HTML help
- Variable watch/edit window with drag-and-drop function
- Extensive program flow control options
- Simulator port activity logging and pin input stimuli
- File parser support for COFF, UBROF6, UBROF8 and Hex files
- Support for C, Pascal, BASIC and Assembly languages

# CHAPTER 4

# EXPERIMENTS AND RESULTS

## 4.1 Existing Discharge Detection and Measurement Systems

### 4.1.1 ERA Discharge Detector

In the high voltage laboratory there is a Discharge Detection and Measurement Unit. This system consisted of a discharge free high voltage transformer that supplied up to 80 kV, a 50 kV coupling capacitor, an input unit (pulse transformer) and a measurement unit including a high voltage meter. This system was working satisfactorily, however due to the very old design (ERA, England), discharge magnitudes were measured by comparison with a calibration pulse magnitude and by calculations or by using charts.


Figure 4-1 ERA Discharge Detector

### 4.1.2 Digital Partial Discharge Meter

In this system the same high voltage transformer was used as the high voltage source. Again a coupling capacitor (1000 pF) and an input unit were used. The output of this unit was supplied to an amplifier circuit where the signal was fed to a non-inverting amplifier that was constructed with two fast op-amps (LF353). An oscilloscope output with a BNC connector was provided from the output of the first op-amp, which supplied an analog signal of the discharge pulses. Also this non-inverting amplifier's off-set adjustment was controlled with an external potentiometer in order to nullify the back-ground noise. The output of the first non-inverting amplifier was then connected to another non-inverting amplifier also made by using LF353. The second amplified output was connected to the driver of a 7-segment display of the discharge meter. The following pictures show the other parts of the discharge measurement circuit.


Figure 4-2 Discharge Measurement Circuit

Figure 4-3 Digital Partial Discharge Meter

### 4.2 System Calibration

The partial discharge measurement systems were calibrated against standard corona electrodes which were designed to produce constant discharge magnitudes at certain voltage levels. It was determined that these electrodes generated consistently the same discharge magnitudes at the same voltages with little variation due to the existing atmospheric conditions (i.e. relative air density). The discharge magnitudes produced by these electrodes at certain voltage levels were determined by testing them with a standard discharge magnitude meter (Tettex, TSE). There are several corona electrodes with varying tip geometry and sharpness starting from a needle and finishing with a blunt electrode. As the sharpness decreases the corona discharges at the electrode tip starts at a higher voltage which produces higher magnitude pulses. Opposite to the high voltage corona electrodes a 3 cm diameter spherical ground electrode was mounted. Also some dielectric objects (i.e. plastic layers) can be put between the poles of a corona electrode system. By this way surface discharges occur between the sheets and very large discharge currents can be observed in the circuit. Figure 4-4 indicates some of the corona electrodes.

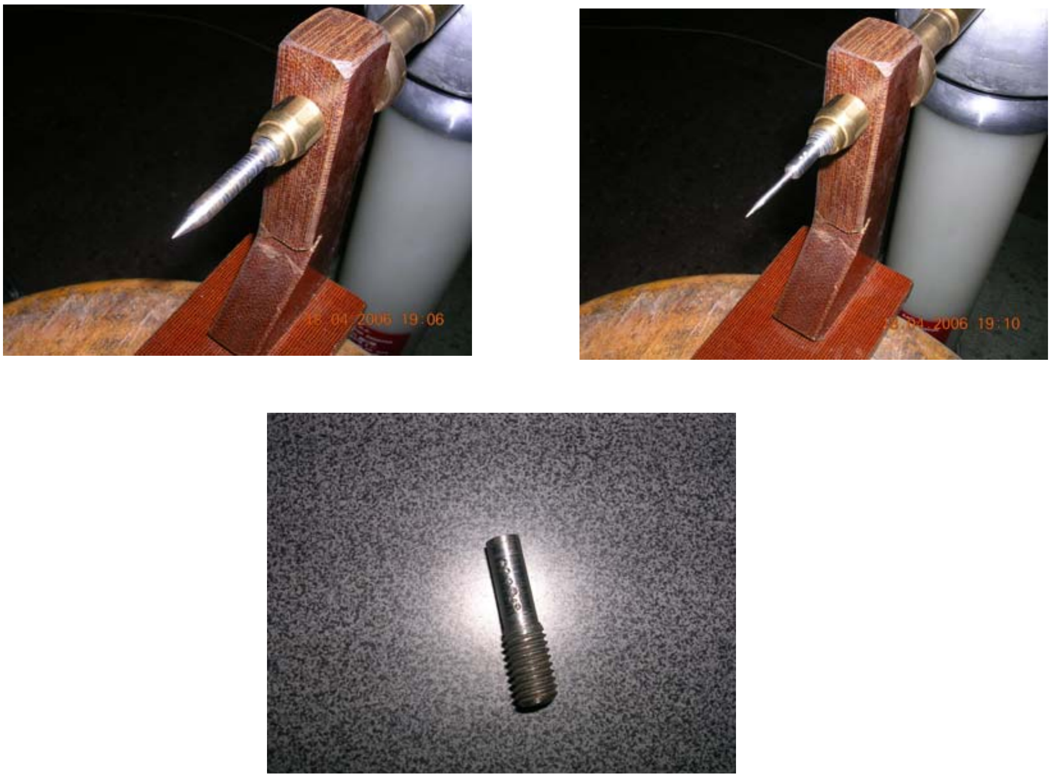

Figure 4-4 Corona Electrodes

### 4.3 Experiments

Due to the preliminary work results of the experiments it was observed that the maximum level of corona discharge pulse created was 0.5 volts. At that time the minimum level that the discharge magnitude indicator was capable of showing was 0.5 volts. As a result of this, almost nothing was seen on the LCD display. Therefore, two things were made:

**a)** An amplifier circuit was designed in order to improve the discharge level magnitudes to observe them on the LCD display. The gain of this amplifier was controlled by the knob in front of the unit. This knob was the 10K potentiometer seen below. Here is the circuit diagram of this amplifier:

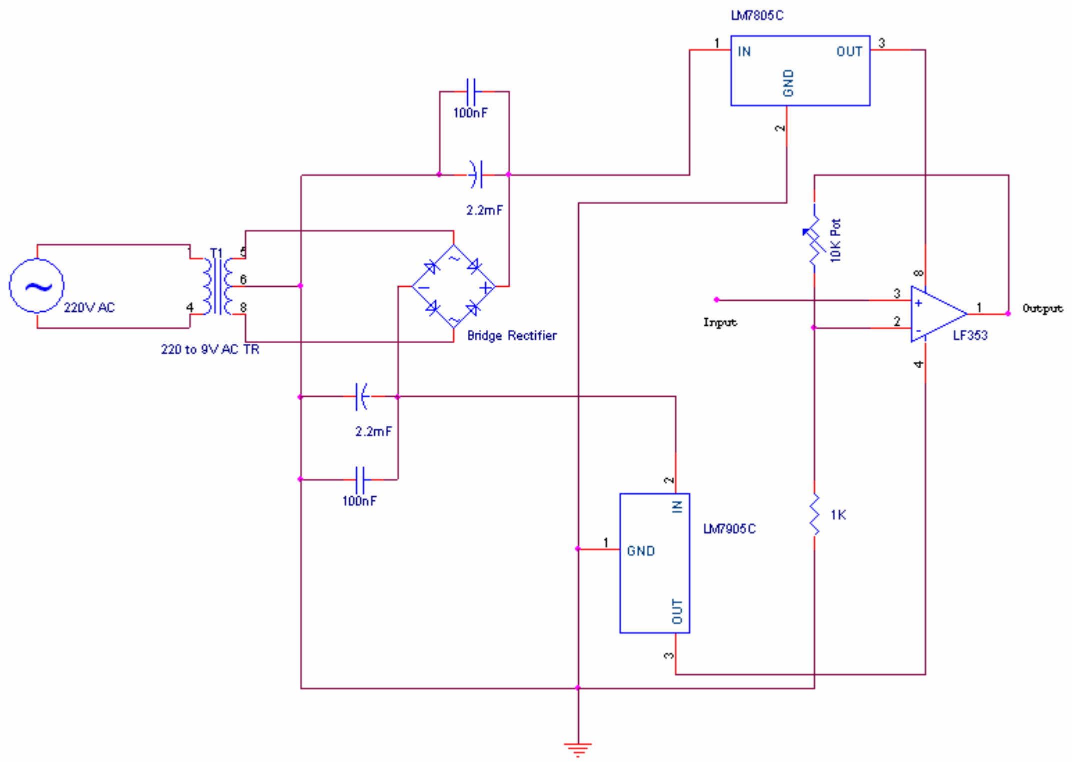


Figure 4-5 Amplifier Circuit

**b)** The discharge level sensitivity of the unit was increased from the software. Therefore, the unit sensed and showed smaller discharge pulses on the screen.

### 4.3.1 Experiment 1

The aim of Experiment 1 was to test the designed partial discharge magnitude indicator with the calibration unit outputs. This calibration unit had 5 different outputs. It produced continuously repeating signals, all of which had 10 µs duration. Pulse height was different in each. The pulse height was increasing from output 1 to output 5. The recorded results are in the table below:

| Calibration Unit Output Number | Calibration Pulse Magnitude (Volts) | Partial Discharge Meter (pC) | Partial Discharge Magnitude Indicator (pC) |
|---|---|---|---|
| 1 | 0.28 | 12 | 23 |
| 2 | 0.55 | 34 | 44 |
| 3 | 1.04 | 74 | 85 |
| 4 | 2.21 | 213 | 210 |
| 5 | 4.08 | 314 | 223 |

Figure 4-6 Readings of Units with Calibration Unit Outputs

### 4.3.2 Experiment 2

The aim of Experiment 2 was to compare the readings of the P.D.M. and the designed partial discharge magnitude indicator with the existing corona discharges created by different corona electrodes. The corona electrodes were connected to the top of the discharge-free coupling capacitor. The discharges were created in the air gap between spherical ground electrode and the corona electrode. After this, they were transmitted by the coupling capacitor and HF pulse transformer and amplified in the P.D.M. until the observation of the results. The results were recorded at the test voltages mentioned in the calibration test results table of the corona electrodes. The corona discharge readings of both the P.D.M. and the partial discharge magnitude indicator were shown on the table of Figure 4-8.

In this experiment, six different corona electrodes were used. Below is the table showing the calibration test results of these electrodes made in T.S.E laboratories. In these tests, a computer-based discharge detector whose brand name was Tettex was used.

| Corona Electrode Type | Corona Onset Voltage (kV) | Test Voltage Level (kV) | Discharge Magnitude (pC) (Tettex) |
|---|---|---|---|
| 1 | 4.5 | 5 | **2** |
| 2 | 5.8 | 6.5 | **4** |
| 3 | 8 | 9 | **15** |
| 4 | 16.5 | 17.5 | **60** |
| 5 | 24.5 | 26 | **140** |
| 6 | 37.5 | 35 | **240** |

Figure 4-7 Calibration Test Results of Corona Electrodes

| Corona Electrode Type | Partial Discharge Meter (pC) | Partial Discharge Magnitude Indicator (pC) | Test Voltage Level (kV) |
|---|---|---|---|
| 1 | **5** | **10** | 5 |
| 2 | **7** | **12** | 6 |
| 3 | **15** | **20** | 9 |
| 4 | **42** | **44** | 16 |
| 5 | **130** | **128** | 25 |
| 6 | **230** | **222** | 32 |

Figure 4-8 Readings of Units in Corona Discharge

### 4.3.3 Experiment 3

The aim of Experiment 3 was to compare the readings of the P.D.M. and the designed partial discharge magnitude indicator with the existing surface discharges created with the help of 4mm thick Perspex layer that was placed in contact with one of the HV corona electrodes used in the previous experiment. The surface discharge readings of both the P.D.M. and the partial discharge magnitude indicator were shown on the table:

| Corona Electrode Type | Partial Discharge Meter (pC) | Partial Discharge Magnitude Indicator (pC) | Test Voltage Level (kV) |
|---|---|---|---|
| 4 | 34 | 36 | 10 |
| Spherical | 219 | 212 | 20 |

Figure 4-9 Readings of Units in Surface Discharge

The magnitudes of the discharge pulses that were created was measured in terms of picocoulombs. This level was so small that any noise coming from the environment (i.e. state changes of the room lamp, small touches to the handle of the unit with a conductor etc.) would increase this level so high that the original discharge level that was coming from the corona electrode would not be observed. Because of this reason, HF noise filters were connected to the input of the high voltage transformer.

The unit was designed in a plastic cover. This also caused problems with the noise issue. To protect the unit from noise, it was put into a metal cover so that it shielded the unit from environmental noise. After making these adjustments, it was observed that the noise level was minimized. Therefore, the magnitudes of the created discharge pulses were more precisely detected.

The P.D.M. was used in parallel with the designed unit. The aim was to double check the results of the experiment. Very similar results were obtained during the experiments. The corona electrodes that were used throughout the experiments were calibrated electrodes. That is to say, the discharge levels they would produce were known at the beginning of the experiment. This information was used to calibrate both the P.D.M. and the designed unit.

### 4.3.4 Experiment 4

The aim of Experiment 4 was to compare the readings of the P.D.M. and the designed partial discharge magnitude indicator using an internal discharge producing sample which is shown in Figure 4-10. This sample consisted of a perspex piece with a cavity and two hemispherical electrodes.

Figure 4-10 Internal Discharge Electrode Sample with a cavity

In this experiment, firstly corona discharges were observed at 24 kV, after a small increase in the high voltage level, internal discharges was observed on the oscilloscope screen at 25 kV. The initial corona discharges were due to the high field generated on the external surface of the HV electrode.

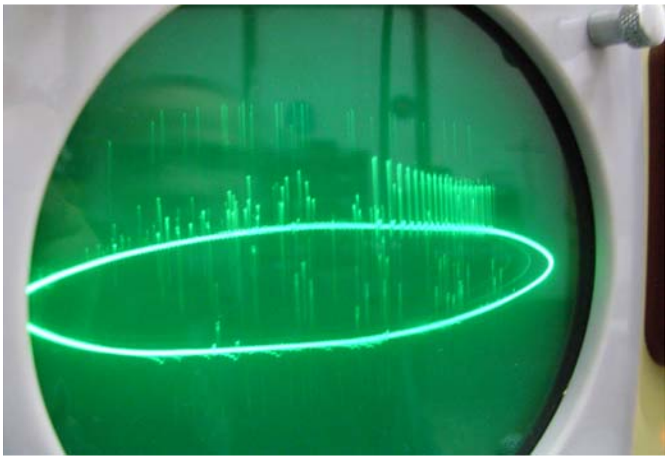

Figure 4-11 Internal and Corona Discharges on the Oscilloscope

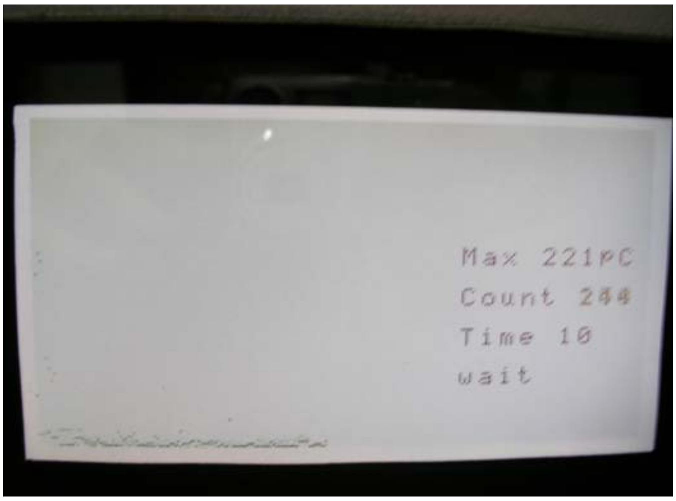


Figure 4-12 Internal Discharges on the Partial Discharge Magnitude Indicator

The internal discharge magnitude readings of both the P.D.M. and the partial discharge magnitude indicator were shown on the table:

| Electrode Type | Partial Discharge Meter (pC) | Partial Discharge Magnitude Indicator (pC) | Test Voltage Level (kV) |
|---|---|---|---|
| Perspex with a cavity inside | 329 | 221 | 25 |

Figure 4-13 Readings of Units in Internal Discharge

### 4.4 Results of the Experiments

The results of the experiments are as follows:

**a)** When there was no discharge, it was observed that the P.D.M. displayed 2 on its 7-segment display; on the other hand, partial discharge magnitude indicator displayed 7 on its LCD display. So two units had different background noise sensitivity. The P.D.M. was sensing smaller discharge levels than the partial discharge magnitude indicator because of this background noise level difference. These were observed in both units because of two reasons.

First reason was that no Faraday cage was used in order to prevent these units from environmental noise. Therefore, this noise level could be observed although there were no discharges from corona electrodes.

Second reason was the harmonic contents in the supply voltage. In order to eliminate this noise, a low pass filter was used at the input but that was not entirely effective considering the high gains used in the amplifiers. By pressing the reset buttons of the units, environmental noise could be eliminated but this was not the solution for harmonics. The harmonic contents were always there even if you pressed the reset buttons more than once. Sophisticated and expensive harmonic filters should be used in order to suppress the higher order harmonics in the 220V AC supply voltage.

Therefore, a background noise was observed in both units for not fully eliminating the harmonic contents.

**b)** Up to test voltages of 9 kV, the smallest discharge magnitude values were observed in the experiments made with the computer-based Tettex discharge detector. The biggest discharge magnitude values were observed in the experiments made with the designed partial discharge magnitude indicator. The results observed in the P.D.M. were in the middle between these two. The order was reversed when the test voltage was bigger than 9 kV. Several factors could be a reason for this. These are:

i. Environmental factors: All the atmospheric conditions like, temperature, atmospheric pressure and humidity are factors that affects the results. The ionization voltage levels for the air molecules were not the same between the two experiments mainly due to the changing relative air density as a result of different pressure and temperature. The environmental conditions were not the same between the calibration experiments made with Tettex discharge detector and the experiments made with the designed partial discharge magnitude indicator, assuming that the background noise and harmonics are eliminated in both cases. Sometimes the luminance of the bulbs or switching them ON and OFF affects the discharge magnitude. There was very little probability that these were the same between two experiments so it was expected that the results were not exactly the same.

ii. Harmonic contents of the input voltage: In both experiments 220VAC was used as input; but the harmonic levels of the two input voltages were apparently not the same. This was also a factor for different results.

iii. Harmonic filters used: In the experiments made with Tettex discharge detector more quality filters were used to suppress the harmonics in the input voltage. The filters used in the other experiment made with the designed partial discharge magnitude indicator were not enough to suppress the harmonics. Therefore, the results were more accurate in the calibration tests made with Tettex discharge detector.

iv. Type of transformers used: Different transformers were used in the two experiments. Even if both of the transformers are discharge free it was likely that the harmonic contents of the input voltage and the magnitude of the output were different.

**c)** All the recordings were taken when the discharge pulses were seen on the oscilloscope screen of the ERA Detector in order to prove that corona, surface or internal discharges exist. The partial discharge magnitude indicator also displayed these discharges on its LCD display in accordance with the oscilloscope. It was concluded that the partial discharge magnitude indicator gave reliable results both graphically and numerically.

**d)** It was observed that with increasing values of corona discharges, the frequency of the pulses increased on the LCD display of partial discharge magnitude indicator. In addition to this, it was observed that with increasing values of the surface discharges, the magnitudes of the pulses significantly increased on the screen of partial discharge magnitude indicator. Therefore, characteristic properties of different discharges were verified by the partial discharge magnitude indicator.

# CHAPTER 5

# CONCLUSIONS

## 5.1 Conclusive Remarks

Failure of high voltage insulation is the first cause of HV system failures with IEEE statistics indicating that electrical insulation deterioration causes up to 90% of electrical failures of certain high voltage equipment. On-line PD testing of HV equipment gives advance warning of pending insulation failure thus allowing the equipment owner to take remedial action during planned outages. Unlike off-line testing, on-line PD testing and monitoring gives an accurate picture of the equipment's health and performance under service conditions. This was the point that a new digital partial discharge detector was decided to built.

In this research, a partial discharge magnitude indicator was designed and tested in the high voltage laboratory. The corona electrodes caused discharges in the high voltage coming from the high voltage transformer. After these pulses' height and duration were adjusted to be observed, they became input to the designed unit. On the display of the unit; the magnitude and the number of the discharge pulses could be observed.

The aims of designing partial discharge magnitude indicator with an LCD display were:

**a)** To on-line monitor the partial discharges in any HV equipment.

**b)** To modify the oscilloscope display in the ERA Discharge Detector Model III in the high voltage laboratory.

**c)** To add some new measurements to the discharge pulse voltage waveform like counting the number of pulses or to find the maximum height of a discharge pulse in selectable time intervals. By this way corona or surface discharges would be separated from the discharges generated by external noise. This gives us this flexibility in observation.

As a result of the experiments made, the main aim of designing the unit was achieved. The partial discharge magnitude indicator was a mixture of both the oscilloscope and the P.D.M. It can be stated that steps were taken in the modification of the ERA Detector Model III in the high voltage laboratory concerning the display and measurement issue.

## 5.2 Future Work

For future work, the time resolution of the unit can be improved. In today's technology there are ultra-fast oscilloscopes that can take multiple Gigasamples per second. With a change in the microcontroller inside the unit, the speed can be significantly improved in order to monitor faster discharge pulses.

The unit can also be designed with two channel system with differential output. Both channels are identical to each other. Same circuit elements and transformers are used for this purpose. The Channel 1 only shows the external discharges coming from the environment and higher order harmonics of 220V AC . The Channel 2 shows both the partial and external discharge pulses. The output would be a differentiator that subtracts the Channel 1 value from the Channel 2. The partial discharge values that are smaller than the external discharge values would be observed by this way.

The unit was designed to be used anywhere. Yet, not all the places would have the same level of noise. For this reason, more quality filters can be put to the input side just to eliminate the harmonics. The unit can also be put into a Faraday cage and be used with it and this way the environmental factors can be minimized.

# REFERENCES


[1] Kreuger, F.H. ‘Discharge Detection in High Voltage Equipment’, pp. 1-71, Heywood Co., London, (1964)

[2] Meek and Craggs. Electrical Breakdown of Gases (Clarendon Press, Oxford, 1953)

[3] Whitehead, S. Dielectric Breakdown of Solids (Clarendon Press, Oxford, 1951)

[4] Austen, A. E. W., and Whitehead, S. ‘Discharges in Insulation under Alternating-current Stresses.’ Proc. Instn elect. Engrs Pt. II 88, 88 (1941)

[5] Austen, A. E. W., and Hackett, W. ‘Internal Discharges in Dielectrics; Their Observation and Analysis.’ (1944)

[6] Mason, J. H. ‘The Deterioration and Breakdown of Dielectrics Resulting from Internal Discharges.’ Proc. Instn elect. Engrs Pt. I, 98, 44 (1951)

[7] Kreuger, F.H. ‘Detection and Location of Discharges.’ Thesis (Delft, Holland, 1961)

[8] Junhong Chen, "Direct-Current Corona Enhanced Chemical Reactions" (PDF), Ph.D. Thesis, University of Minnesota, USA. August 2002.

[9] F.W. Peek (1929). Dielectric Phenomena in High Voltage Engineering. McGraw-Hill.

[10] Leonard Loeb (1965). Electrical Coronas Their Basic Physical Mechanisms. University of California Press.

[11] James D. Cobine (1941, reprints in 1958, 1970)). Gaseous Conductors; Theory and Engineering Applications. McGraw-Hill or Dover reprints.

[12] Mole, G. ‘Improved Methods of Test for the Insulation of Electrical Equipment.’ Proc. Instn elect. Engrs Pt. IIa 100, No. 3, 276 (1953) (Symposium of papers on insulating materials)

[13] Widmann, W. ‘Beurteilung und Messung der Korona bei Isolation-sprüfungen.’ Electrotech. Z. 801 (1960)

[14] Mole, G. ‘Design and Performance of a Portable a.c. Discharge Detector.’ Electrical Research Association Rep. V/T 115 (1952); C.I.G.R.E. Rep., Paper 105 (1954)

[15] Blanchardie, M.M.R., and Aftalion, R. 'Etude du seuil d'ionisation dans les transformateurs.' Rev. gen. Elect. 61, 485 (1952)

[16] Renaudin, D. 'Instrument for Measuring Ionization in Transformers.' C.I.G.R.E. Rep., Paper 105 (1954)

[17] Knosp, R. 'La mesure globale du phenomene d'ionisation sur les machines tournantes.' Bull. Soc. franç. Elect. (Ser. 8) 3, No. 26 (1962)

[18] Fabre, J., et al. 'Research Work on the Insulation of Large Synchronous Machines.' C.I.G.R.E. Rep. Paper 137 (1956)

[19] Quinn, G.E. 'A Method for Detecting the Ionization Point on Electrical Apparatus.' Trans. Amer. Instn elect. Engrs 59, 680 (1940)

[20] ERA Discharge Detector, Model III. (F.C. Robinson and Partners, Ltd, Cheadle)

[21] Viale, M.F. 'Detection et etude de l'ionisation dans les dielectriques industrielles.' Rev. Elect. Mecan. No. 96, 28 (1954)

[22] Hashimoto, H. 'Problems of Measurement of Void Discharge in High Voltage Cable of Full Reel Length.' (1960)

[23] Gelez, M.J.P. 'Mesure separee des pertes par ionisation gazeuse dans un isolant composite.' Bull. Soc. franç. Elect. 74, 238 (1957); Elektrotech. Z. 81 (Feb. 1960)

[24] Veverka, A., and Chladek, J. 'Eine neue Anordnung zur Messung der Leistung bei Ionisationvorgangen.' Bull. schweiz. elektrotech Ver. 49, 45 (1958)

[25] A. Bargigia, W. Koltunowicz, A. Pigini, 'Detection of Partial Discharges in G.I.S', Conf. Proc. of IEEE/PES Summer Meeting, (1991)

[26] F.H. Kreuger, E. Gulski, W.A. Sonneveld, 'Diagnosis in GIS by Statistical Analysis of Discharges', 15/23-04 in Proc. C.I.G.R.E. Conf., Paris, (1992)

[27] F.H. Kreuger, 'Partial Discharge Detection in HV Equipment', pp. 126-127, pp. 111-126, pp. 164-170, pp. 111-127, pp. 129-143, Butterworths, London, (1989)

[28] J.H. Reeves, 'Location of Partial Discharges in HV Switchgear', Proc. C.I.R.E.D. Conf., Paper 4.12, Brighton, (1981)

[29] P.H.F. Morshuis, F.H. Kreuger, 'Relation between Time-resolved Discharge Parameters and Aging', Proc. 6$^{th}$ Int. Conf. on Dielectric Materials, Measurements and Applications, Manchester, (1992)

[30] M. Albiez, M. Leijon, 'Partial Discharge Measurements in GIS with Electric Field Sensor and Acoustic Sensor', Proc. 7$^{th}$ Int. Symp. HV Eng., Dresden, (1991)

# APPENDICES

# APPENDIX A

## Writing Software for T6963C based Graphic LCDs

The name of the LCD display was PG240128-A and it had onboard microcontroller. This microcontroller was from Toshiba and its name was T6963C. Here is the detailed description of howto program the T6963C :

### 1. Basics of Writing to, and Reading from the T6963C

**1.1 Write data** The data to be written should be set on D0 - 7 and C/\D taken low, /WR taken low (/RD should be high) /CE pulsed low for greater than 80ns

**1.2 Read data** C/\D take low, /RD take low (/WR should be high) /CE take low After 150ns read the data on D0-7 /CE take high

**1.3 Write Command** To Write a Command - The command should be set on D0 - 7 and C/\D taken high, /WR taken low (/RD should be high) /CE pulsed low for greater than 80ns

### 2. Writing commands with one, two or no data byte

**2.1** Where a command requires no data, do the following:

Write Command

**2.2** Where a command requires one data byte, do the following:

Write Data

Write Command

**2.3** Where a command requires two data byte, do the following:

Write First Data Byte

Write Second Data Byte

Write Command

**2.4** In the case of sending more data bytes than is required, only the last 1 or 2 are used. This is useful if all the required instructions have been stored to set up the display as a lookup table, each instruction having 2 data bytes in the table (even if it does not need 2 data bytes), and use the write with two data bytes routine. Commands that don't need the data will ignore it. Commands only need one byte will use the last byte, and ignore the first.

## 3. Initialising the display

**3.1** To set-up the **graphics** part of the display controller, or if user is going to use TEXT ATTRIBUTE mode (which uses the graphics area to store the attribute data):

**3.1.1** Set 'GRAPHICS HOME ADDRESS' to the address that user wants to start the graphics RAM from. If user wants the graphics area of memory before the text area, or are just using the graphics area, set it to the start of memory, otherwise set it to an area out the way of the text RAM area.

| | | e.g. for start | |
|---|---|---|---|
| | | at 0000h | at 0200h |
| 1st data | Low addr byte | 00h | 00h |
| 2nd data | High addr byte | 00h | 02h |
| Command | | 42h | 42h |

**3.1.2** Set 'GRAPHICS AREA SET' to how many bytes later user wants the next line to start at. Note that this can be the same as the number of bytes to fill one line of the screen, for most efficient use of the RAM, or it can be larger, to make the calculation of the addresses easier to implement in user's routines.

For example for a 240 bit (30 bytes if font set to 8x8) user could use 30, could use 32, which is easier to use in calculations.

| | | for 30 (1Eh) | for 32 (20h) |
|---|---|---|---|
| 1st data | N° of bytes later | 1Eh | 20h |
| 2nd data | Always 00h | 00h | 00h |

| | | | |
|---|---|---|---|
| Command | | 43h | 43h |

**3.2** To set-up the **text** part of the display controller :

**3.2.1** Set 'TEXT HOME ADDRESS' to the address that user wants to start the text RAM from. If user wants the text area of memory before the graphics area, or are just using the text area, set it to the start of memory, otherwise set it to an area out the way of the graphics RAM area.

| | | e.g. for start | |
|---|---|---|---|
| | | at 0000h | at 0800h |
| 1st data | Low addr byte | 00h | 00h |
| 2nd data | High addr byte | 00h | 08h |
| Command | | 40h | 40h |

**3.2.2** Set 'TEXT AREA SET' to how many bytes later user wants the next line to start at. Note that this can be the same as the number of columns on the screen, for most efficient use of the RAM, or it can be larger, to make the calculation of the addresses easier to implement in user's routines.

For example for a 240 bit (30 columns if font set to 8x8) user could use 30, could use 32, which is easier to use in calculations.

| | | for 30 (1Eh) | for 32 (20h) |
|---|---|---|---|
| 1st data | N° of bytes later | 1Eh | 20h |
| 2nd data | Always 00h | 00h | 00h |
| Command | | 41h | 41h |

**3.3** To set-up the display:

**3.3.1** Set 'MODE SET' to logical OR, EXOR or AND of the text and graphics as required. To use only the text, but with extra display options, there is also TEXT ATTRIBUTE mode (note in this mode, there is no graphics display - the attribute data is in the graphics area instead.) MODE SET also selects whether text characters 00h-7F come from the controller's built in character generator ROM, or from RAM i.e. user-defined. (characters 80h-FFh always come from the RAM).

MSB

| D7 | D6 | D5 | D4 | D3 | D2 | D1 | D0 |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | CG | MD2 | MD1 | MD0 |

MD0-2

000 = OR mode.

001 = XOR mode.

010 = AND mode.

100 = TEXT ATTRIBUTE mode.

CG 0 = Internal ROM CG, 1 = RAM CG

For example, for OR mode, and internal CG ROM = 1000 0 000 = 80h

Command 80h

**3.3.2** Set 'DISPLAY MODE' to set whether the graphic, text or both displays are on, and to set the cursor on or off, and cursor blink on or off

MSB

| D7 | D6 | D5 | D4 | D3 | D2 | D1 | D0 |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | GRPH | TEXT | CUR | BLK |

GRPH 1 = graphics display on.[1]

TEXT 1 = text display on.

CUR 1 = cursor displayed.

BLK 1 = cursor blink on.

Notes; [1] - If using TEXT ATTRIBUTE mode, this bit must be set as well as TEXT

For example, graphics and text display on, with cursor, no blink = 1001 1110 = 9Eh

Command 9Eh

**3.4** If user has followed the above steps, now should have a display full of rubbish. If not, check the contrast level, the wiring and the software.

**3.5** Display data write and read commands

**3.5.1** The ADDRESS POINTER is used for pointing in memory, before writing / reading text byte, graphic bytes, attribute bytes or user-character bytes (depends where it is pointing, and whether graphics or attribute mode is on). To set the ADDRESS POINTER to a memory address, ready for reading or writing bytes, e.g. to set it to address 0123h

| | | |
|---|---|---|
| 1st data | Low addr byte | 23h |
| 2nd data | High addr byte | 01h |
| Command | | 24h |

**3.5.2** To then send a byte of data, there are 3 command, depending whether user wants the pointer address to decrease, stay the same or increase.

Write then decrease address pointer command is C2h

Write, no change to address pointer command is C4h

Write then increase address pointer command is C0h

For example if the address pointer is set to an address in the text RAM area, to display an 'A' (character 21h - note the character set is not ASCII, but ASCII - 20hex) and move the address pointer to the next address:

| | | |
|---|---|---|
| Data | byte to send | 21h |
| Command | | C0h |

**3.5.3** Similarly, to read a byte of data from the disp lay RAM, again there are 3 command, depending whether user wants the pointer address to decrease, stay the same or increase.

Read then decrease address pointer command is C3h

Read, no change to address pointer command is C5h

Read then increase address pointer command is C1h

For example if the address pointer is set to an address in the text RAM area, to read the code of the character at that address and move the address pointer to the next address:

Command C1h

Read data

**3.5.4** To set or reset an individual bit, use the 'BIT SET/RESET' command. Only one bit can be set at a time.

MSB

| D7 | D6 | D5 | D4 | D3 | D2 | D1 | D0 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | S/R | B2 | B1 | B0 |

S/R 1 = Set the bit, 0 = Reset the bit

B2-B0

000 - Bit 0 (Right hand bit of byte)

001 - Bit 1

010 - Bit 2

011 - Bit 3

100 - Bit 4

101 - Bit 5

110 - Bit 6

111 - Bit 7 (Left hand bit of byte)

For example, to set bit 3

Command FBh

**3.6** Cursor Commands

**3.6.1** Cursor Pattern Select - To select the number of line high the cursor is, from the bottom of the character, use:

1 Line Cursor is A0h

2 Line Cursor is A1h

3 Line Cursor is A2h

4 Line Cursor is A3h

5 Line Cursor is A4h

6 Line Cursor is A5h

7 Line Cursor is A6h

8 Line Cursor is A7h

For example, for a 4 line cursor,

Command A4h

**3.6.2** To set the position of the cursor onscreen, use 'CURSOR POINTER SET'

For example for the cursor at 24h across, 03h down

| | | |
|---|---|---|
| 1st data | Xadrs | 24h |
| 2nd data | Yadrs | 03h |
| Command | | 21h |

# APPENDIX B

**Code between Microcontroller and ADC:**

```
#include "m32def.inc"
;init variables
.def ADCDAT        = r10
.def LOWT          = r20
.def HIGT          = r21
.def DSTA          = r22
.def COUNT         = r23
.def TIME          = r24
.def MAXVAL        = r25
.equ plevel        = 0
.equ upflag        = 1
.equ wrtflag       = 2
;interrupt handler table
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp main
jmp reset
jmp reset
```

```
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
jmp reset
;ISR
main:
tst TIME
breq non
cbi PORTB, 2                  ;read data from ADC and start new conversion
sbis PINC, 0
rjmp strad
clr COUNT
clr MAXVAL
strad:
in  ADCDAT, PINA
sbi PORTB, 2
sbrc DSTA, plevel              ;count up event handler
rjmp lev1
lev0:
cp  ADCDAT, HIGT
brlo PC+6
sbr DSTA, 7                    ;plevel + upflag + wrtflag
rjmp PC+4
lev1:
cp  ADCDAT, LOWT
brsh PC+2
cbr DSTA, 1
```

```
sbrc DSTA, upflag          ;count up if flagged then flag down
inc COUNT
cbr DSTA, 2
cp ADCDAT, MAXVAL          ;store maximum value of ADC data 3_clk_constant
brlo PC+2
mov MAXVAL, ADCDAT
sbrs DSTA, wrtflag         ;store ADC data when triggered
rjmp PC+5
st Y, ADCDAT
inc r28
brne PC+2
cbr DSTA, 4
non:
inc r0
breq PC+2
reti
ldi r16, lut1
add r16, r17
inc r17
ldi r18, 120
sub r18, r17
brne PC+2
clr  r17
mov r30, r16
ijmp
lut1:
rjmp datazero                                  ;1
rjmp status
rjmp datacll
rjmp dataclh
rjmp timer
```

```
rjmp datachh
rjmp dataml
rjmp datamh
rjmp sADCdat                                                  ;2
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                  ;3
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                  ;4
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                  ;5
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
```

```
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                    ;6
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                    ;7
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                    ;8
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                                    ;9
rjmp sADCdat
rjmp sADCdat
```

```
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                         ;10
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                         ;11
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                         ;12
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                                         ;13
rjmp sADCdat
```

```
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                    ;14
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                    ;15
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat                    ;16
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
rjmp sADCdat
datazero:
```

```
nop
clr r26
andi r16, 0b00000000
ori r16, 0b00010000
out UDR, r16
reti
datacll:
mov r16, COUNT
nop
andi r16, 0b00001111
ori r16, 0b01000000
out UDR, r16
reti
dataclh:
mov r16, COUNT
swap r16
andi r16, 0b00001111
ori r16, 0b01010000
out UDR, r16
reti
datachh:
nop
reti
dataml:
mov r16, MAXVAL
nop
andi r16, 0b00001111
ori r16, 0b00100000
out UDR, r16
reti
datamh:
```

```
mov r16, MAXVAL
swap r16
andi r16, 0b00001111
ori r16, 0b00110000
out UDR, r16
reti
sADCDat:
ld r16, X
lsr r16
ori r16, 0b10000000
out UDR, r16
inc r26
reti
timer:
tst TIME
breq PC+2
dec TIME
reti
status:
mov r16, r5
andi r16, 0b00001111
ori r16, 0b01101000
tst TIME
brne PC+2
andi r16, 0b11110111
out UDR, r16
reti
self:
cli
tst TIME
brne wrk
```

```
sbic PINC, 0
call grst
sbic PINC, 1
call ltm
sbic PINC, 2
call intv
wrk:
sei
jmp self
grst:
clr COUNT
clr MAXVAL
clr r17
clr r26
st X, r17
inc r26
breq PC+2
rjmp PC-3
ret
ltm:
mov r16, r5
lsl r16
inc r16
inc r16
lsl r16
lsl r16
lsl r16
mov TIME, r16
ret
intv:
inc r5
```

```
ldi r16, 5
cp r5, r16
brlo PC+2
clr r5
sbic PINC, 2
rjmp PC-1
call delay
ret
delay:
ldi r16, 25
mov r4, r16
delay1:
dec r2
breq delay2
rjmp delay1
delay2:
dec r3
breq delay3
rjmp delay1
delay3:
dec r4
breq endlode
rjmp delay1
endlode:
ret
;initialize registers
reset:
clr r0
clr r5
clr r10
ldi LOWT, 4
```

```
ldi HIGT, 8
clr DSTA
clr COUNT
clr TIME
clr MAXVAL
ldi r29, 1
ldi r27, 1
clr r28
clr r26
clr r30
clr r31
;initialize call stack
ntstck:
ldi r16, 0x6F
out SPL, r16
ldi r16, 5
out SPH, r16
;initialize timer interrupt
ldi r16, 0b00001001                ;no prescaler, clear timer on compare
out TCCR0, r16
ldi r16, 0b01000000
out OCR0, r16
ldi r16, 0b00000010                ;set compare match interrupt
out TIMSK, r16
;initialize portb
ports:
ldi r16, 0b00000100                ;portb(2) control for ADC
out DDRB, r16
out PORTB, r16
;initialize rs-232 communication
usart:
```

```
ldi r16, 0                      ;250 kbps
out UBRRH, r16
ldi r16, 4
out UBRRL, r16
ldi r16, 0b00001000
out UCSRB, r16
ldi r16, 0b10000110             ;8bit data, 1bit stop
out UCSRC, r16
;initialize ADC first conversion
cbi PORTB, 2
nop
nop
nop
in  ADCDAT, PINA
sbi PORTB, 2
inc r0
brne PC-1
;enable interrupts
sei
jmp self
```

# APPENDIX C

**Code between Microcontroller and LCD Display:**

```
#include "m32def.inc"
clr r0
clr r1
clr r2
ldi r21, 0
clr r26
ldi r27, 1
clr r28
ldi r29, 2
ldi r16, 0x6F
out SPL, r16
call delay1
ports:
ldi r16, 0b00001111
out PORTB, r16
out DDRB, r16
ldi r16, 0b11111111
out DDRA, r16
usart:
ldi r16, 0
out UBRRH, r16
ldi r16, 4
out UBRRL, r16
ldi r16, 0b00010000
out UCSRB, r16
ldi r16, 0b10000110
```

```
out UCSRC, r16
call indsp
main:
ldi r20, 0b11010100                          ;set address pointer
call wdata
ldi r20, 0b00010000
call wdata
ldi r20, 0b00100100
call wcomm
ldi r20, 'M'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'a'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'x'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, ' '-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, ' '-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, ' '-0x20
call wdata
```

```
ldi r20, 0b11000000
call wcomm
ldi r20, ' '-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'p'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'C'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 0b00010100                    ;set address pointer
call wdata
ldi r20, 0b00010001
call wdata
ldi r20, 0b00100100
call wcomm
ldi r20, 'C'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'o'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'u'-0x20
call wdata
ldi r20, 0b11000000
```

```
call wcomm
ldi r20, 'n'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 't'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 0b01010100                     ;set address pointer
call wdata
ldi r20, 0b00010001
call wdata
ldi r20, 0b00100100
call wcomm
ldi r20, 'T'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'i'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'm'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'e'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
```

```
ldi r20, 0b00000000                    ;set address pointer
call wdata
call wdata
ldi r20, 0b00100100
call wcomm
bef:
call r_print
sbrc r25, 0
call screen
sbrc r25, 1
call mxprn
sbrc r25, 2
call cnprn
sbrc r25, 3
call stprn
sbrc r25, 4
call wrprn
jmp bef
;initialize display (sub)
indsp:
ldi r20, 0b00000000                    ;set graphic home address
call wdata
call wdata
ldi r20, 0b01000010
call wcomm
ldi r20, 0b00100000                    ;set graphic area
call wdata
ldi r20, 0b00000000
call wdata
ldi r20, 0b01000011
call wcomm
```

```
ldi r20, 0b00000000                 ;set text home address
call wdata
ldi r20, 0b00010000                 ;1000 h
call wdata
ldi r20, 0b01000000
call wcomm
ldi r20, 0b00100000                 ;set text area
call wdata
ldi r20, 0b00000000
call wdata
ldi r20, 0b01000001
call wcomm
ldi r20, 0b10000001                 ;mode set or mode
call wcomm
ldi r20, 0b10011100                 ;display mode
call wcomm
ldi r20, 0b00000000                 ;set address pointer
call wdata
call wdata
ldi r20, 0b00100100
call wcomm
ldi r19, 128+1
upp:
dec r19
breq endof
str:
ldi r18, 32+1
aaa:
dec r18
breq endf
call dataa
```

```
jmp aaa
endf:
jmp upp
endof:
nop
ldi r20, 0b00000000                    ;set cursor adress
call wdata
ldi r20, 0b00000000
call wdata
ldi r20, 0b00100001
call wcomm
ldi r19, 16+1
upp2:
dec r19
breq endof2
str2:
ldi r18, 32+1
aaa2:
dec r18
breq endf2
call tblnk
jmp aaa2
endf2:
jmp upp2
endof2:
nop
ret
;blank graphic data
dataa:
ldi r20, 0b00000000                    ;data
call wdata
```

```
ldi                                     r20, 0b11000000
call wcomm
ret
;blank text data
tblnk:
ldi r20, ' '-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ret
;delay routine
lcd_d:
ldi r17, 125
eld1:
dec r17
breq eld
jmp eld1
eld:
ret
;receive and print to lcd (sub)
r_print:
sbis UCSRA, RXC
ret
in r21, UDR
mov r22, r21
andi r22, 0b11110000
subi r22, 0b00010000
breq clr_reg
mov r22, r21
andi r22, 0b10000000
subi r22, 0b10000000
```

```
breq inc_reg
mov r22, r21
andi r22, 0b11110000
subi r22, 0b00100000
breq maxlo
mov r22, r21
andi r22, 0b11110000
subi r22, 0b00110000
breq maxhi
mov r22, r21
andi r22, 0b11110000
subi r22, 0b01000000
breq cntlo
mov r22, r21
andi r22, 0b11110000
subi r22, 0b01010000
breq cnthi
mov r22, r21
andi r22, 0b11110000
subi r22, 0b01100000
breq stat
ret
clr_reg:
clr r26
clr r28
sbr r25, 16
ret
inc_reg:
ld r16, X
st Y, r16
mov r22, r21
```

```
andi r22, 0b011111111
st X, r22
inc r26
inc r28
sbr r25, 1
ret
maxlo:
andi r21, 0b00001111
mov r30, r21
ret
maxhi:
andi r21, 0b00001111
swap r21
or r30, r21
sbr r25, 2
ret
cntlo:
andi r21, 0b00001111
mov r31, r21
ret
cnthi:
andi r21, 0b00001111
swap r21
or r31, r21
sbr r25, 4
ret
stat:
andi r21, 0b00001111
mov r5, r21
sbr r25, 8
ret
```

```
;write data to display (sub)
wdata:
out PORTA, r20
cbi PORTB, 0
cbi PORTB, 2
nop
cbi PORTB, 3
nop
sbi PORTB, 3
call lcd_d
ret
;write command to display (sub)
wcomm:
out PORTA, r20
sbi PORTB, 0
cbi PORTB, 2
nop
cbi PORTB, 3
nop
sbi PORTB, 3
call lcd_d
ret
;long delay routine
delay1:
dec r0
breq delay2
rjmp delay1
delay2:
dec r1
breq delay3
rjmp delay1
```

```
delay3:
dec r2
breq endlode
rjmp delay1
endlode:
ret
screen:
dec r26
dec r28
ld r22, Y
ldi r23, 127
sub r23, r22
lsl r23
swap r23
mov r24, r26
lsr r24
lsr r24
lsr r24
mov r20, r24
mov r24, r23
andi r24, 0b11100000
or r20, r24
call wdata
mov r20, r23
andi r20, 0b00001111
call wdata
ldi r20, 0b00100100
call wcomm
mov r20, r26
com r20
andi r20, 0b00000111
```

```
ori r20, 0b11110000
call wcomm
ld r22, X
ldi r23, 127
sub r23, r22
lsl r23
swap r23
mov r24, r26
lsr r24
lsr r24
lsr r24
mov r20, r24
mov r24, r23
andi r24, 0b11100000
or r20, r24
call wdata
mov r20, r23
andi r20, 0b00001111
call wdata
ldi r20, 0b00100100
call wcomm
mov r20, r26
com r20
andi r20, 0b00000111
ori r20, 0b11111000
call wcomm
inc r26
inc r28
cbr r25, 1
ret
mxprn:
```

```
clr r23
clr r24
clr r25
mov r21, r30
ldi r22, 100
cp r21, r22
brlo PC+3
sub r21, r22
inc r23
ldi r22, 100
cp r21, r22
brlo PC+3
sub r21, r22
inc r23
ldi r22, 80
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00001000
ldi r22, 40
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00000100
ldi r22, 20
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00000010
ldi r22, 10
cp r21, r22
```

```
brlo PC+3
sub r21, r22
ori r24, 0b00000001
mov r25, r21
ldi r20, 0b11011000                ;set address pointer
call wdata
ldi r20, 0b00010000
call wdata
ldi r20, 0b00100100
call wcomm
mov r20, r23
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
mov r20, r24
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
mov r20, r25
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
cbr r25, 2
ret
cnprn:
clr r23
clr r24
clr r25
```

```
mov r21, r31
ldi r22, 100
cp r21, r22
brlo PC+3
sub r21, r22
inc r23
ldi r22, 100
cp r21, r22
brlo PC+3
sub r21, r22
inc r23
ldi r22, 80
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00001000
ldi r22, 40
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00000100
ldi r22, 20
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00000010
ldi r22, 10
cp r21, r22
brlo PC+3
sub r21, r22
ori r24, 0b00000001
```

```
mov r25, r21
ldi r20, 0b00011010                         ;set address pointer
call wdata
ldi r20, 0b00010001
call wdata
ldi r20, 0b00100100
call wcomm
mov r20, r23
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
mov r20, r24
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
mov r20, r25
ori r20, 0b00010000
call wdata
ldi r20, 0b11000000
call wcomm
cbr r25, 4
ret
stprn:
ldi r20, 0b01011001                         ;set address pointer
call wdata
ldi r20, 0b00010001
call wdata
ldi r20, 0b00100100
call wcomm
```

```
clr r23
mov r21, r5
andi r21, 0b00000111
lsl r21
inc r21
inc r21
ldi r22, 10
cp r21, r22
brlo PC+3
sub r21, r22
inc r23
ori r23, 0b00010000
mov r20, r23
call wdata
ldi r20, 0b11000000
call wcomm
ori r21, 0b00010000
mov r20, r21
call wdata
ldi r20, 0b11000000
call wcomm
cbr r25, 8
ret
wrprn:
ldi r20, 0b10010100                    ;set address pointer
call wdata
ldi r20, 0b00010001
call wdata
ldi r20, 0b00100100
call wcomm
cbr r25, 16
```

```
mov r21, r5
andi r21, 0b00001000
tst r21
breq scmsg
ldi r20, 'w'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'a'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'i'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 't'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ret
scmsg:
ldi r20, 'i'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'd'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'l'-0x20
```

```
call wdata
ldi r20, 0b11000000
call wcomm
ldi r20, 'e'-0x20
call wdata
ldi r20, 0b11000000
call wcomm
ret
```