DESIGN AND REALIZATION
OF
A HIGH VOLTAGE RADIO INTERFERENCE VOLTAGE (RIV) MEASUREMENT SYSTEM

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DESIGN AND REALIZATION OF A HIGH VOLTAGE RADIO INTERFERENCE VOLTAGE (RIV) MEASUREMENT SYSTEM

submitted by **MUTLU ÖZER** in partial fulfilment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen _____
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmet Erkmen _____
Head of Department, **Electrical and Electronics Engineering**

Prof. Dr. Mirzahan Hızal _____
Supervisor, **Electrical and Electronics Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Arif Ertaş ________________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Mirzahan Hızal ________________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Ahmet Rumeli ________________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Muammer Ermiş ________________
Electrical and Electronics Engineering Dept., METU

M.Sc. Mehmet Ülger ________________
Chief Engineer, TOBB

Date: 04.02.2010
____

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.

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ABSTRACT

DESIGN AND REALIZATION OF A HIGH VOLTAGE RADIO INTERFERENCE VOLTAGE (RIV) MEASUREMENT SYSTEM

Özer, Mutlu
M.Sc., Department of Electrical and Electronics Engineering
Supervisor: Prof. Dr. Mirzahan Hızal

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This thesis aims the design and the realization of a radio noise meter which can be used to measure radio interference of a high-voltage transmission line due to partial discharges like conductor corona. The radio noise meter is the common equipment for radio noise and radio interference voltage measurements.

The corona of transmission lines, its characteristics, its effects on radio interference and measurement of corona caused radio noise in the scope of relevant international standards are investigated.

A radio noise meter fed by a monopole antenna, centered to 1 MHz with a bandwidth of 4.5 KHz and using a Quasi-Peak detector having 1 ms charge time and 600 ms discharge time is realized.

The conductor corona from the radio interference point of view is observed, measured and analyzed with the help of the realized radio noise meter.

Keywords: RIV, RI, RN, Corona, Quasi-Peak

ÖZ

RADYO GİRİŞİM GERİLİMİ (RIV) ÖLÇÜM SİSTEMİ
TASARIM VE GERÇEKLEMESİ

Özer, Mutlu
Yüksek Lisans, Elektrik-Elektronik Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Mirzahan Hızal

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Bu tez, yüksek gerilim hatlarında kısmi deşarj nedeniyle gerçekleşen koronaların oluşturduğu radyo girişimini ölçmeye yarayan bir radyo gürültü ölçüm sisteminin tasarımını ve gerçeklemesini hedeflemektedir. Radyo gürültü ölçüm sistemi hem radyo gürültüsünü hem de radyo girişim voltajlarını ölçebilen ortak bir donanımdır.

İletim hatlarının koronaları, karakteristikleri, radyo girişimi üzerindeki etkileri ve korona kaynaklı radyo gürültülerinin ilgili standartlara göre ölçülmesi incelenmiştir.

Bir monopol anten alıcısına sahip, 1 MHz merkez frekansına ayarlanmış ve bu frekansta 4.5 KHz'lik bir bant genişliğine sahip olan ve 1 milisaniye şarj ve 600 milisaniye deşarj değişkenlerine sahip bir Quasi-Peak dedektörü olan bir radyo girişim ölçüm sistemi gerçeklenmiştir.

Gerçekleştirilen radyo girişim ölçüm cihazı yardımı ile iletken koronaları radyo girişimi açısından gözlenmiş, ölçülmüş ve analiz edilmiştir.

Anahtar Kelimeler: Radyo Girişim, RI, RN, Korona, Quasi-Peak

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LIST OF ABBREVIATIONS

AC	:	Alternating Current
AF	:	Antenna Factor
AM	:	Amplitude Modulation
ANSI	:	American National Standards Institute
ARRL	:	American Radio Relay League
BJT	:	Bipolar Junction Transistor
CB	:	Citizen's Band
CIGRE	:	International Council on Large Electric Systems
CISPR	:	Comité International Spécial des Perturbations Radioélectriques
CIV	:	Corona Inception Voltage
CSA	:	The Canadian Standards Association
EHV	:	Extra High Voltage
EIR	:	Environmental Impact Report
ELF	:	Extra Low Frequency
EMC	:	Electromagnetic Compatibility
FCC	:	The Federal Communications Commission
HV	:	High Voltage
IARU	:	International Amateur Radio Union
IEC	:	The International Electrotechnical Commission
IEEE	:	The Institute of Electrical and Electronics Engineers
kV	:	Kilovolts
NEMA	:	National Electrical Manufacturers Association
OHL	:	Overhead Transmission Line
OPAMP	:	Operational Amplifier
pC	:	Picocoulomb
PD	:	Partial Discharge
pF	:	Picofarads
QP	:	Quasi-Peak
RIV	:	Radio Interference Voltage
RN	:	Radio Noise
SNR	:	Signal-to-Noise Ratio
SSB	:	Single Side Band Modulation
TEIAS	:	Turkish Electricity Transmission Company
TRAC	:	Turkish Radio Amateurs Society
TVI	:	Television Interference
uV	:	Microvolt

CHAPTER 1

INTRODUCTION

The history of technical developments always shows trade-offs. If there is a benefit from a new invention or technology, there is a disadvantage on the other hand. Same is applicable for high voltage transmission lines. The transmission lines are used since the invention of electric. They are the one of the most critical property of a country that they carry all the electrical demand of a country's people and the industry. The electrical transmission grid of a country is one of its key development factor. As a country develops, industry develops and people rush into industrial areas. This rush with the development of the industry leads into both an increase and a centralized demand of electricity. The power line engineers do not have lots of options to play with. They have only the aluminium and the steel. They have to supply this demand with these well-known materials. To supply the high demand of those industrial and centralized zones from a distant bulk power generation, some solutions have been found and going to be found. These solutions came with their trade-offs. The simplest solution is as simple as Kirchhoff's famous formula. You have to increase either the current or the voltage to carry more power. Both of them can be increased, but to what extent?

The extent of that increase raises the trade-offs naturally. One of the major trade-off is the conductor corona, as the conductor is the main element of an electrical transmission line. Conductor corona is the interaction of the line voltage with the surrounding dielectric, air. It is defined as "*A luminous discharge due to ionization of the air surrounding an electrode caused by a voltage gradient exceeding a certain critical value*" [1]. Our demand for power is always at the highest rate that the conductor manifests this with audio-visual response. The air, as being the natural dielectric, is ionized due to high voltage levels of the conductor it surrounds. This ionization is so huge that the electrons and the air molecules change their state and position in harmony with the power line frequency. Corona is the result of these electrons and the molecules response to this harmony. The heavy air molecules and the light electrons collide and change their position, exchange power from each other. So, a current and a voltage are formed apart from the line's current and the voltage. When there is a current and the voltage, electric and the magnetic fields appear immediately.

This thesis focuses on these fields due to conductor corona. These fields produce electrical noises in vicinity. Communication infrastructure is another value of a country. Both of transmission line and the communication infrastructure should be taken in care. It has been found that corona electrical noises interfere with a narrow portion, sometimes a wide portion of the communication infrastructure. So, power line engineers have one more design constraint in hand. It is the corona as the main interference source for radio broadcast. Because the transmission line itself behaves as an antenna and produces radiated radio interference which is "*Radio noise that is propagated by radiation from a source into space in the form of electromagnetic waves, e.g., the undesired electromagnetic waves generated by corona sources on a transmission line*" [1]. It also wants to broadcasts its manifestation of carrying huge power. So, what was the solution? The answer is the standards offering standard measuring equipments.

Engineers on different continents started to write standards so as to limit the interaction in between, at the same time the corona noise was being investigated. It was observed that corona caused electrical noise is more effective on middle-wave radio broadcast band. That is AM band. This coincidence as a natural result of fast movement of lightweight electrons in the electrical field of a conductor and the other electrons that form an alternating signal that carry voice information by having a special frequency range that gives the signal the ability of reflecting from the ground and the sky. Both use the same frequency. One is to interfere, the other is to carry. The interfering one should be under control; a number of standards defined to limit the electromagnetic interference coming from the transmission line.

But, when I put my AM radio in my pocket and travel the world, is it still guaranteed that the transmission lines will not disturb me? The standards defined measuring equipments that are standardized accordingly. Years of extensive studies bring the standards to a combined point and the international and the valid ones appeared. Two major standards are followed throughout this thesis to achieve RN measurements. The first one is ANSI/IEEE Std. 430-1986 “IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations”[6]. This standard offers the way to measure the Radio Noise. The second one is ANSI C63.2-1996 “American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz—Specifications”[5]. This standard defines the characteristics of the radio noise measuring equipment which will be used according to IEEE 430-1986[6].

Those measuring equipments, which are radio noise meters, do have almost the similar characteristics throughout the world. The major importance is given to the interference in the AM band when the corona pulses are taken into consideration. The detecting unit inside is defined according to human-ear response to a noise and the pulse characteristics of corona.

Combining the above, this thesis is aiming to understand the relation in between the electron that causes corona radio noise and the electron that moves the analogue meter installed on the radio noise meter. The transmission lines, their corona performances, the result of these performances for radio interference, the measurement of these performances in the scope of the measuring standards, realization of a metering device and observing the corona noise on that device form the main concerns of this thesis. To achieve this, below chapter structure is used.

- Chapter 2 gives preliminary information on transmission lines' electrical noises and then the corona is investigated in detail.
- Chapter 3 intends to give information of radio interference voltage and radio interference. The standards and examples of Radio Interference Voltage (RIV) and Radio Noise (RN) applications are given. And also, the limits for RIV and RN levels are explained. The RIV and RN requirements for Turkey are also outlined. RN, as being pollution, is analyzed from the point of environmental impact view.
- Chapter 4 is the migration from theory to application. The subsystems of the realized RN meter are investigated and major design considerations are detailed.
- Chapter 5 focuses on the measurements that are done with the realized meter. The comments for the measurements are given.
- Chapter 6 concludes this thesis which has roots from four main areas of Electrical and Electronics Engineering, which are Power Systems, Telecommunication, Microwave and Electronics Engineering.

CHAPTER 2

ELECTRICAL NOISES of TRANSMISSION LINES

2.1 Transmission Lines

Electrical power demand has been growing since the invention of electric. As this demand grows up, power generation and power supply to the clients are always in the center of discussion. The technology brought us lots of electrical equipments in our houses and it led usage of electric powered production machines instead of pure manned labor. These all resulted in several power plants of various types with bigger capacities. Those produced huge power are always supplied to the final user by straight wired connection throughout years while other technological inventions went in to connectionless or wireless transmission.

The produced power has been being transferred via conductors, or with its known name, the transmission lines through decades. There is no alternative found, yet. This unchanged situation still continues to be unchanged while the demand of power transfer is rising. A transmission line is capable of transferring the high demand of power load to its final location. The all that the power transmission engineers discuss is transferring more power through a well-known medium, the conductor.

A conductor is the medium to transfer electrical current, namely the electrical power. And, it is the major part of the transmission lines. A conductor due its physical nature has a limited current transfer capacity.

This is the major limit of transferring power. The current carrying capacity of a conductor is a result of its resistance to the electrical current. The resistance of a conductor can be found with below formula;

$$R = \frac{\ell.\rho}{A} \tag{2.1}$$

where;

ℓ is the length in meters,

ρ is the cross section in mm^{2,}

A is the electrical resistivity of material in ohmmeter.

The natural current limit that a conductor can carry is defined as ampacity of the conductor and the amount of current passing through the conductor is related with Kirchhoff's famous formula;

$$V = I.R \tag{2.2}$$

where;

V is voltage applied to the conductor, in volts,

I is the current passing through the conductor, in amperes,

R is resistance of the conductor in ohms.

As far as power transmission is concerned, this formula is derived into

$$S = V.I \tag{2.3}$$

where;

S is the apparent power in kVA,

V is the voltage of transmission line, in kV,

I is the current in amperes.

It has been stated that there is a continuous increase in power demand, S, from year to year. These huge powers should be transferred to far-most locations via limited current capable conductors. Since I is limited, the first idea to transfer more power is to increase line voltage, V. And the second one is to use multiple conductors to increase current carrying capacity. These both statements can be derived from the Equation 2.3.

This is the basic start of power transmission engineering. All is to produce power, step it up to many kilovolts, transfer it via conductors, step-down the voltage and then supply it to its final location.

Various levels of voltages are used world-wide to transfer power. The national grid voltages worldwide are varying from 115kV to 765 kVs (even higher). These Extra High Voltage (EHV) levels enable huge bulk power transmission with below disadvantages;

- Resistive Losses
    - Due to conductor's nature according to Equation 2.1
- Inductive and capacitive formation of a transmission line
    - Due to conductor formation (bundles, etc.)
- Corona discharge losses
    - Due to non-insulated conductors' direct connection with air and the excessive electrical gradient formation because of EHV induced excessive current
- Transmission line electrical noise disturbances
    - Corona discharges' electrical noise spectrum
    - Due to mechanical properties of transmission line, gap type discharges, sparks.
- Transmission line audible noises

All disadvantages given above are the natural results of EHV level of transmission and they have been investigated in detail since the start of bulk power transmission.

Corona discharges and its contribution to electrical noise disturbances is a major problem in above disadvantages. The main focus of this thesis will be given to corona discharges which produce noises in Radio Broadcast Band, that is Radio Interference, and the Radio Interference Voltages which is the conducted measurement quantity of that noise will be discussed from this point.

2.2 Electrical Noises of Transmission Lines

Electrical noises (or the radio noises) of the transmission lines can be separated into two major causes. The first is the partial discharges which forms corona. The second one is electrical discharges across small gaps. Gap types of resources can be defined as sparking noises and can be seen on insulators, at tie wires between transmission line hardware parts, at small gaps between neutral or ground wires, at defective or corroded joints or in improperly designed defective HV electrical apparatus. Both of these radio noise sources are given in detail below.

2.2.1 Conductor Corona

According to "IEEE Standard Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines (ANSI/EEEE Std. 539-2005)", the corona is "*A luminous discharge due to ionization of the air surrounding an electrode caused by a voltage gradient exceeding a certain critical value*"[1]. The familiar definition is "*Corona is a discharge caused by electrical overstress*".

Actually corona is one type of partial discharge. When the electrical intensity of a transmission line conductor is higher than the limit of the insulation (air for transmission lines) partial discharges appear. These electrical breakdowns are called as corona since it resembles the corona surrounding the sun when we look at it behind a smoked glass.

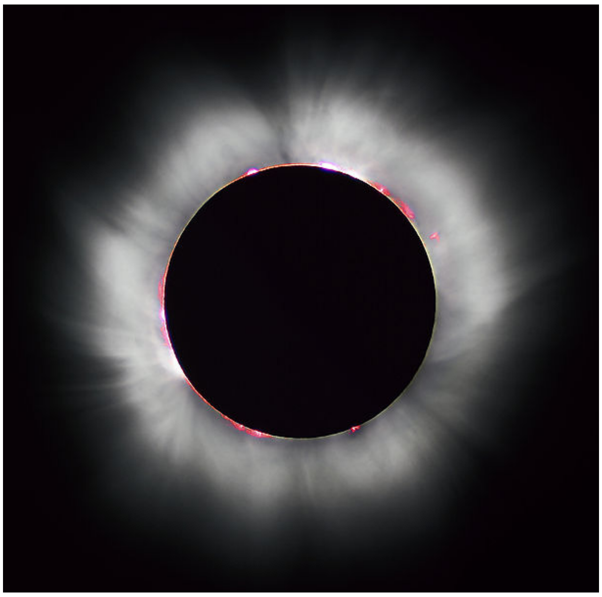


Figure 2.1 Corona Ring of the Sun

Corona can be seen in all types of insulations. When the corona appears the insulation is accepted to be electrically disturbed. For solid insulations, the material is electrically damaged but for liquid or gaseous insulations, the insulation can return to its normal state when the electrical stress or the corona is eliminated. The corona appearance gradient is changed according to the electrical breakdown of the insulation type, so the occurrence depends majorly on the insulation type as well as other external affects like humidity, rain, dirt.

2.2.2 Corona Mechanism

Experimental results had shown that the electrical breakdown voltage of air is;

$$E_{peak} = 29.8 \quad kV/cm \quad [12] \tag{2.4}$$

where E_{peak} is the electrical breakdown voltage of the dry air at normal atmospheric pressure and temperature (25 ^{o}C and 76 mm barometric pressure). When the electrical field intensity of the conductor is higher than the limiting value, formation of electron avalanches occur which leads the corona at the conductor surface.

As a natural result of radioactive materials, cosmic ray bombardment and ultraviolet radiation from the sun some free electrons exist in the air. Those free electrons nearby the transmission line conductor move toward the conductor when the conductor is energized positive (positive cycles of AC) and move away from the conductor when the conductor is energized negative. The AC state change (from negative to positive or the reverse) is related with AC frequency (50 or 60 Hz) but the velocity of those electrons to move toward and away is directly dependent on the electrical field intensity of the conductor. If the electrical field intensity is under the breakdown limits, these travelling electrons hit the air molecules and both change their direction but nothing happens in electrical manner. If the electrical intensity above a limit, these travelling electrons hit air molecule so fast that the air molecule (either O_2 or N_2) looses one of its outer electron. This process is called “ionization”.

The ionization is "*The process by which an atom or molecule receives enough energy (by collision with electrons, photons, etc.) to split it into one or more free electrons and a positive ion. Ionization is a special case of charging*"[1]. The air molecule which looses its electron is ionized and called as positive ion. The electron which has lost its velocity in the first collision and the new electron knocked out of the orbit are still under the effect of electrical intensity, so both of them get velocity with the intense of electric field and both knock out electrons from two other air molecules. So, four electrons appear to ready to knock out another four air molecules. This process doubles in each step and lead into electron avalanche. The avalanched electrons are now under the effect of intense electrical field.

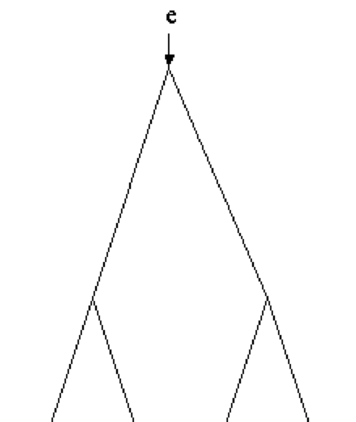


Figure 2.2 Formation of Electron Avalanche

The non-uniform structure of the electrical intensity (highest nearby the conductor and decreases with the distance when going away from the conductor) causes the first discharges to be take place nearby the conductor when the voltage of the conductor is raised until a breakdown limit. For the positive cycle electron avalanches go on to grow and finally hit the conductor, for the negative cycle the electron avalanches continue to loose its power since the electrical intensity tend to reduce. The positive ions which have much more weight when compared to electrons travel very slowly. These slowly travelling positive ions attract electrons and when one electron is accepted the molecule goes into neutral position. The charge of the positive ion is higher than the neutral ion, so a kind of energy emitted when the electron is accepted. The emitted energy is exactly the same as the energy to knock one electron out. The emitted energy is radiated as electromagnetic wave and can be visible for air molecules. This electromagnetic radiation is the main reason for corona related electrical interferences. Corona on a transmission line can be seen in Figure 2.3.

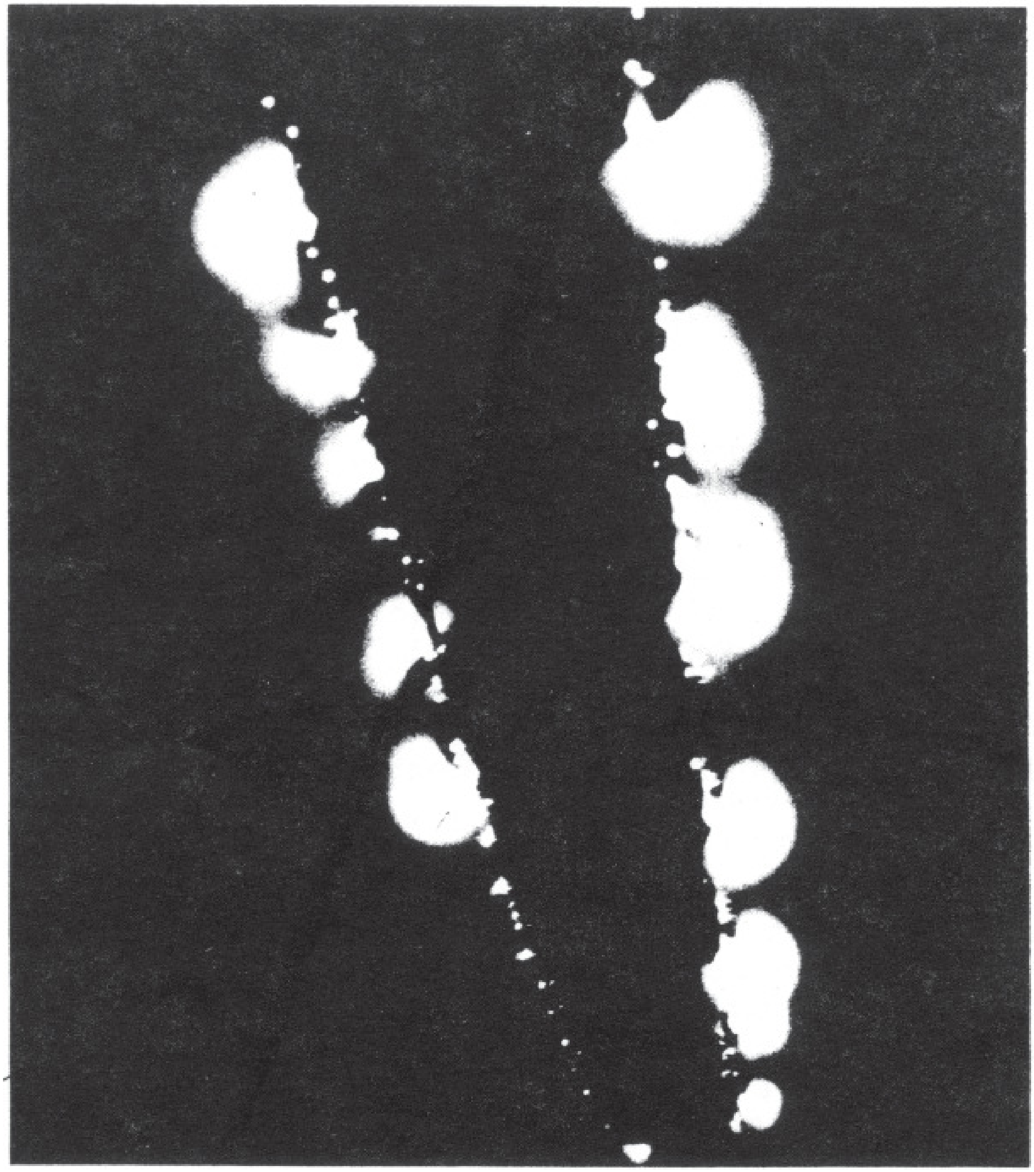


Figure 2.3 Visual Observation of Corona on an EHV Line[14]

2.2.2.1 Corona Modes

Corona modes differ due to below characteristic defining effects;

- Polarity of the electrode
- Basic ionization characteristic of the ambient air
- Electric field intensity
- Distribution of the electric field
- The geometry of the electrodes
- The ambient weather conditions

The combination of above effects leads into known corona modes. Corona modes are defined with their visual resemblance to plume, glow and brushes. But, a standardized definition for all-modes is clarified by IEEE Std. 539-2005 [1].

According to IEEE 539-2005, the two types of principal corona modes exist, which are;

- Glow Corona
- Streamer Corona

Glow corona is “*stable, essentially steady discharge of constant luminosity occurring either positive or negative electrodes*” [1]. It has 3 sub-types which are burst corona, positive glow and the negative glow.

Streamer corona is “*A repetitive corona discharge characterized by luminous filaments extending into the low electric field strength region near either a positive or a negative electrode, but not completely bridging the gap*”[1]. It has 3 sub-types which are positive onset streamers, Trichel streamers and positive pre-breakdown streamers.

A table including all types with their defined characteristics according to IEEE 539-2005 is given in Table 2.1. The order of the corona modes is given according to level of voltage applied.

Table 2.1 Corona Modes [1]

Positive (anode) corona		Negative (cathode) corona	
Mode	**Characteristic**	**Mode**	**Characteristic**
Burst corona, onset streamer[a]	Moderate amplitude, moderate repetition rate	Trichel streamer (pulse)	Small amplitude, high repetition rate
Glow[b]	Essentially pulseless	Glow[c]	Essentially pulseless
Prebreakdown streamer	High amplitude, low repetition rate	Prebreakdown streamer[d]	Moderate amplitude, moderate repetition rate

[a]With alternating voltage, positive onset streamers often become suppressed by space charge created during the negative half-cycles.
[b]With alternating voltage, when onset streamers are suppressed the positive glow will be the first corona mode as the applied voltage is raised.
[c]With alternating voltage, negative glow may be difficult to observe because of the predominance of Trichel streamers.
[d]With alternating voltage, breakdown usually occurs during the positive half-cycle before the development of any negative prebreakdown streamers.

Most important corona modes are as follows:

2.2.2.1.1 Glow Coronas

The glow discharges are essentially pulseless, very faint and weak light that hugs the conductor surface. It may also appear on insulator surface during high humid environment. It may appear on both positive and negative cycles. A typical glow corona is given in Figure 2.4.

Figure 2.4 Visual Observation of a Typical Glow Corona [15]

2.2.2.1.2 Positive Onset Streamers (Brush) Coronas

Brush discharge is a streamer type that occurs radially from the conductor surface. It is observed in all sections of the conductor. The fraction length of the corona is highly dependent on the voltage level of the conductor. The brush corona can be observed with continuous hissing sound.

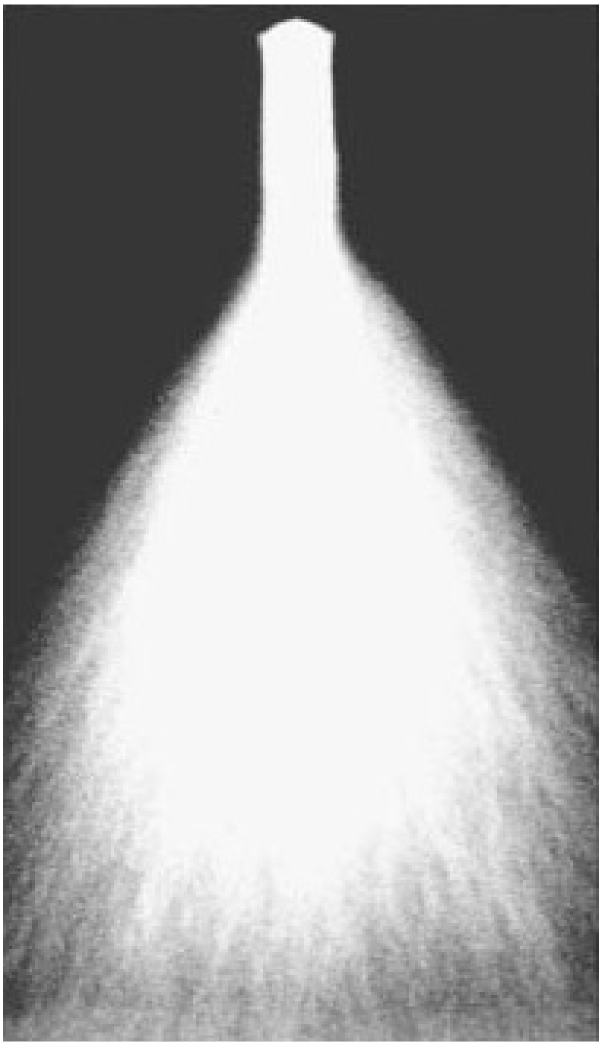


Figure 2.5 Visual Observation of a Typical Brush Corona[15]

2.2.2.1.3 Trichel Streamers

G.W.Trichel is one of the first who worked on coronas. His earliest studies were mostly focused on negative coronas. At a certain voltage above the dark region (or above the saturation current) that no ionization occurs, there starts a development of some forms of ionization currents. This formation of ionization leads into regular current pulses. These pulses are "*small amplitude, short duration (in the range of a hundred nanoseconds) and high repetition rate (in the range of tens of kilohertz or more)"* [1] and extensively studied by Trichel and so-called Trichel pulses.

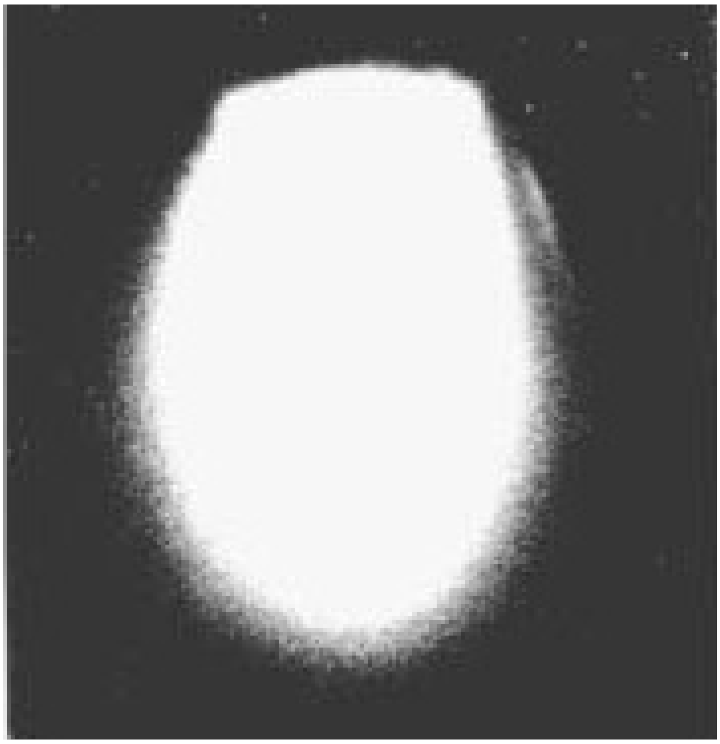


Figure 2.6 Visual Observation of a Typical Trichel Pulse [15]

2.2.2.1.4 Positive Pre-Breakdown Streamers (Plume) Coronas

Plume corona is the most easily observed and most powerful corona. It resembles a plume that has a concentrated stem. The length of the stem is dependent on the voltage applied. The stem goes into too many branches that can be very long. The plume corona can be observed with violet-colored tree like halo and intense snapping and hissing sound.

This powerful corona type forms high amplitude of discharge currents which causes one of the unwanted results of conductor corona, which is electrical interference.

Figure 2.7 Visual Observation of a Typical Plume Corona[15]

The corona modes according to applied voltage and the line polarity can be observed below.

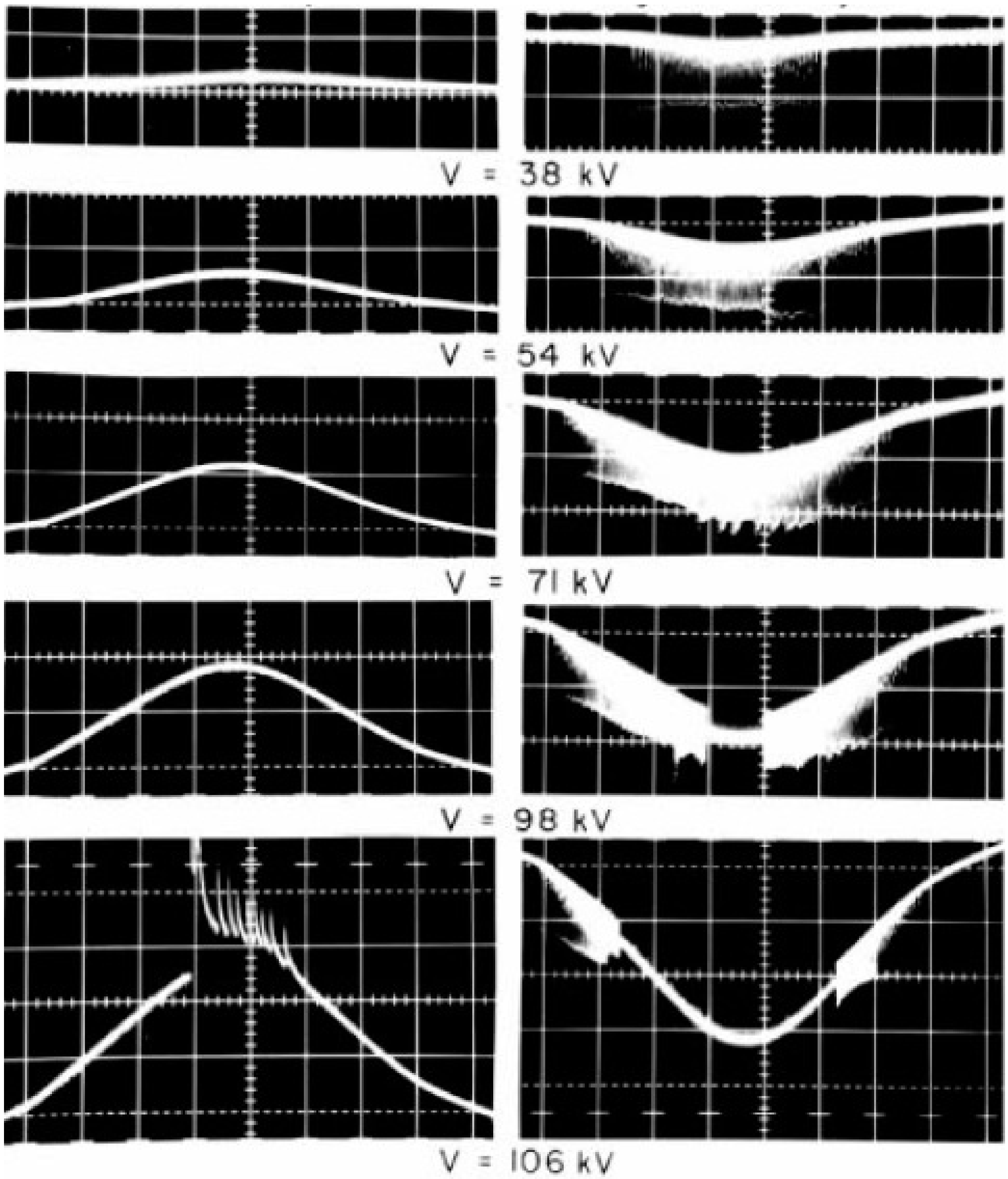


Figure 2.8 Negative and Positive Coronas According to Voltage Level (Left Column Positive, Right Column Negative Half Cycle) [15]

It can be derived from Figure 2.8 that negative coronas are effective on line voltage levels up to 100 kV, after 100 kV positive coronas are effective. The positive corona which occurs above a line voltage above 100 kV is the major reason for radio noise. Due to excessive line voltage and its powerful characteristics, the induced corona current forms powerful electromagnetic fields in the vicinity.

2.2.2.2 Advantages of Corona

Corona mechanism has been studied in detail over the years. By the introduction of new equipments that are capable of producing controllable corona (or the plasma equipment), some industrial usage for corona have been found. Corona based equipments are used in below industrial applications;

- Ozone manufacturing (with negative corona)
- Air, water sanitizers with plasma technology
- Air ionizers for different health applications
- Photocopy machines
- Nitrogen laser
- Surface flattening
- Solid state fans for cooling microchips

2.2.2.3 Disadvantages of Corona

The corona is one of the major problems of power transmission engineering. Definite precautions should be undertaken about the corona. The negative effects of the corona can be reduced but it can not be eliminated. There is a trade-off for the corona level of the conductor and the cost of the transmission line. Eliminating the corona totally will cost an expensive transmission line. So, a careful study should be done before the transmission line design. The corona occurs on the transmission lines leads into below problems.

2.2.2.3.1 Visual Corona

The well-known observation of the corona is the visual appearance of it. The appearance shows itself with bluish and violet light coming from the regions that are under electrical stress. The reason of this light emitting is the free electron entrance to positive nitrogen ions. The tuff streamer or glow like light is appeared through the conductor with irregular shapes.

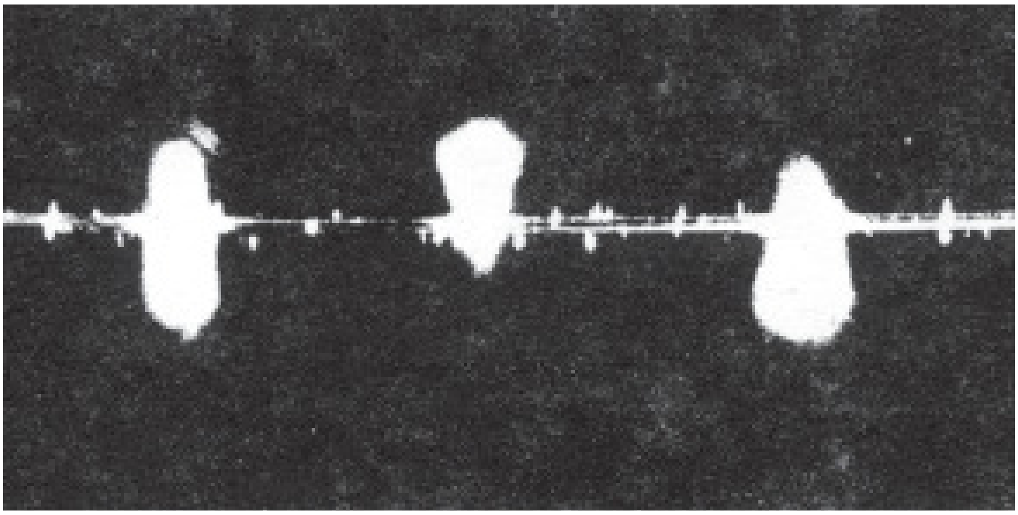


Figure 2.9 Visual Appearance of Corona on a HV Line[14]

2.2.2.3.2 Audible Corona

When the conductor is above the threshold voltage a hissing, frying even snapping sound is produced since the air dielectric is being disrupted. The glow discharges generally produce no sounds.

As the voltage on the overhead lines goes upwards, the audible noise is started to be the main concern in the transmission line design. There is not much corona appearance in the fair weather. But, when the weather goes into more humid and rainy stage, the water droplets form very intensive corona which leads major audible noise. The range of frequencies of these randomly produced audible noises starts in the audible range and goes far beyond of sonic range. Figure 2.10 shows the frequency spectrum of audible corona.

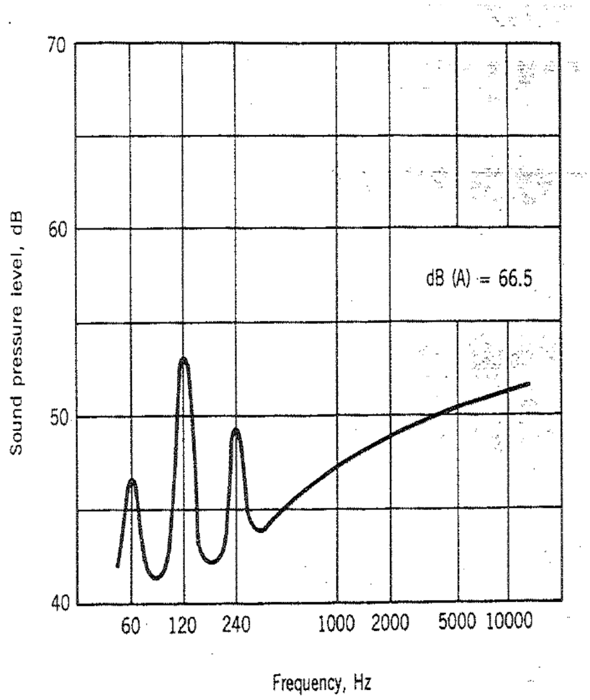


Figure 2.10 Audible Noise Spectrum of Corona [12]

2.2.2.3.3 Ozone Production

Corona results in odor of ozone. When the strength of the corona is high with some humidity nitrogenous oxidation will follow. This nitrous acid leads corrosion in the conductor. This ozone production occurs inside some major power engineering components like generators, transformers, etc. The ozone formation inside these power equipments harms the internal insulation and results into failure of the equipment.

2.2.2.3.4 Power Loss

Power loss is the unavoidable result of the conductor corona. Since the conductor interacts with the surrounding insulation due to intense electrical field, there occur power losses due to production of electrical noise, visual and audible corona. Some portion of the transferred energy is spent on some major formation of coronas.

Power loss is calculated with different empirical formulas, the well-known formula belongs to Peek [2]. According to Peek;

$$P_c = \frac{241}{\delta}(f + 25)\left(\frac{r}{D}\right)^{1/2}(V - V_0)^2 x10^{-5}\ kW/km \quad [2] \qquad (2.5)$$

where;

P_c is fair weather corona loss,

δ is air density factor found with atmospheric pressure and temperature,

f is the line frequency,

r is the radius of the conductor,

D is the spacing between conductor,

V is the line-to-neutral operating voltage,

V_0 is the disruptive critical voltage to neutral.

Below comments can be derived from above equation about the power loss related with conductor corona;

- If the air density decreases, the conductor corona loss is increased. The air density is directly proportional with barometric pressure and reversely proportional with temperature. If the barometric pressure gets lower, the loss will increase. If the temperature gets higher, corona loss will be higher.
- The operating frequency of the line is directly proportional with the corona loss. The 60 Hz systems have more loss when compared to 50 Hz systems.
- If the radius of the conductor gets higher, the corona loss will increase. This can be understood from that the surface that is prone to corona is increased when the radius is increased. More the surface, more the corona, hence the corona loss. On the opposite, when the spacing between the bundle conductors is increased, the loss will be decreased. This is the result of middle conductor's decrease of exposition to electrical field due to nearby conductors. So, conductor bundling is a way to decrease or eliminate corona.
- If the operating voltage is increased, the corona loss is increased. This can be understood from corona mechanism explained above. When the voltage applied to conductor is too high, the velocities of the electrons that will form the avalanche increase very quickly. The faster the electrons, the faster and the powerful the corona formation. So, there is a direct result in between.

2.2.2.3.5 Electromagnetic Interference

The serious effect of the corona is its electromagnetic interference. The powerful electron avalanches form electrical currents in the air and resulting current formations lead electrostatic and magnetic fields in the vicinity of transmission lines. These sudden and short duration pulses, hence the coronas, can induce high frequency voltage pulses on the nearby radio antennas. These generated radio interferences can be measured and it is called Radio Noise (or RN). The RN is the main scope of this thesis and RN and its coupled measured value Radio Interference Voltage (RIV) will be explored in detail within the next chapter.

The frequency spectrum of corona noise may cover a wide band and can be investigated on Figure 2.11.

The corona noise spectrum is more powerful between 0.5 to 1 MHz and it tends to decrease at frequencies above.

Finally, conductor corona is a serious phenomenon for the design of the transmission line. Necessary design precautions should be taken into consideration during the transmission line design. The corona formation is highly dependent on;

- Line configuration
- Conductor type
- Condition of conductor surface
- Weather

Above conditions lead into unwanted results of visual and audible noise, power loss and the radio interference which leads the definition of RN and RIV when it is measured with the related standards.

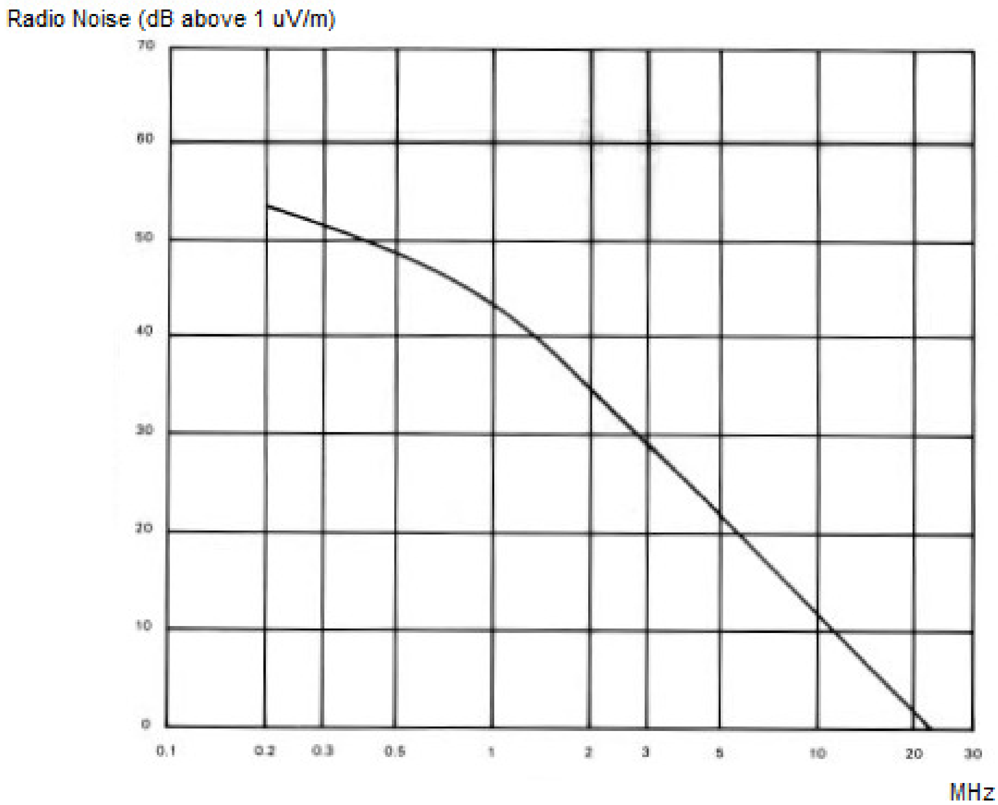


Figure 2.11 Typical Frequency Spectrum of Corona [6]

2.2.3 Gap Type Discharges

Apart from conductor corona which is due to “partial” discharges, the gap type noises are generally referred as spark type discharges and they occur when “complete” discharge process happens. It generally exists between two metallic parts of the transmission line separated with air as dielectric medium.

The gap discharges are named as microsparks in [1] and defined as “*breakdown occurring in the miniature air gap formed by two conducting or insulating surfaces*”. And the spark is defined as “*A sudden and irreversible* *transition from a stable corona discharge to a stable arc discharge. It is a luminous electrical discharge of short duration between two electrodes in an insulating medium. It is generally brighter and carries more current than corona, and its color is mainly determined by the type of insulating medium. It generates radio noise of wider frequency spectrum (extending into hundreds of megahertz) and wider magnitude range than corona. A spark is not classified as corona* [1]". According to this definition the gap type discharges should be separated from corona and different approaches for observing and metering should be applied.

This type of discharge leads into very low currents cycling at the power frequency. This current amount is low because of high impedance of arcing part according to other conductor or the ground. These sparks can be observed at a single point (may be due to lose connection of the insulators) or along the transmission line. But, they can be observed majorly around the power pole. This is due to lots of mechanical connections around the pole.

Gap discharges can be accepted as white noise. This is because of its frequency spectrum. Gap type noises can have frequencies up to some GHz.

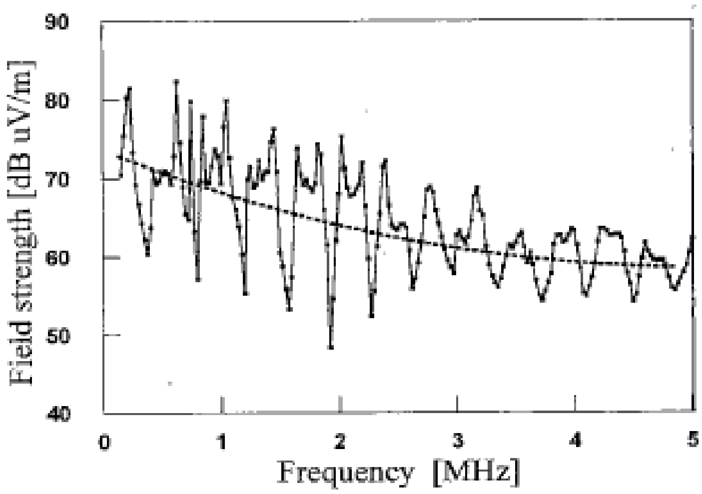


Figure 2.12 Typical Frequency Spectrum of a Gap Noise

Gap type noises are powerful when compared with the noise levels of the conductor corona. So, if there is a gap type noise discharge nearby a corona noise, the gap type discharge noise can be metered since it is more powerful on a broadband frequency spectrum. However, gap type noises are seen very rare when compared to corona noise and can be eliminated. The behavior of a transmission line from the gap discharge point of view can be observed with an artificial gap type radio noise generator. An artificial gap type noise generator is given in Figure 2.13.

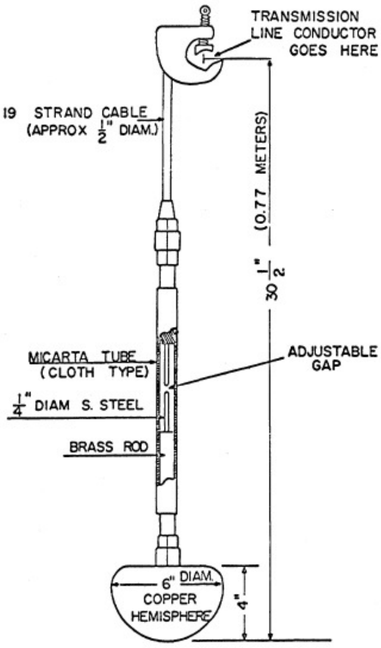


Figure 2.13 Artificial Gap Type Noise Generator [3]

This gap type noise generator's one side is connected to the power transmission line and the other side left floating. By this, it can simulate broadband and the powerful characteristics of a natural gap on a transmission line. The longitudinal and lateral properties of gap type discharges or noises can be observed with the help of artificial gap type noise generators.

Intensive experimental results have been showed that gap type noises are effective on radio broadcast band below 70 kV [3]. Since, they occur rarely and can be eliminated; their observation and metering have less importance when compared to naturally occurring, long-lasting and repetitive corona noise. Because of this, the RN measurements in the scope of this thesis are based on corona noises.

CHAPTER 3

RADIO INTERFERENCE VOLTAGE (RIV)
and
RADIO NOISE (RN)

3.1 Radio Interference in General

Radio interference in general is the static electrical or thermal noise on the reception of a receiver antenna. The interference is superimposed on the received signal and the receiver is disturbed. The interference is defined as “impairment of a useful signal produced by natural or man-made sources”. The interference can be as effective as to harm the receiving device if the receiver sensitivity is too high. Proper filtering techniques can be used to eliminate interference produced by noise but some types of noises superimpose on the received frequency so that filtering the noise will decrease the signal reception performance. Extensive studies are being held since the invention of wireless transmission. The best way to eliminate the noise is to eliminate the noise itself. But, in some cases in can not possible to eliminate the noise and some standards are defined to clarify the extent that these noises are acceptable.

The wireless transmission is based on the frequency of the signals. The frequency of a signal is the basic function to start with. The frequency spectrum is a natural resource that contains all frequencies that exists in the nature. Current frequency spectrum is divided into frequency bands according to natural allowances on these bands. For example, for long distance communication low frequencies (LF) are used because of the characteristic of the LF signals reflection from ionosphere of the earth. The signal is transmitted to very long distances because of this specifically chosen frequency band. Known and standardized frequency bands for total broadcast spectrum are given in Figure 3.1.

3.1.1 Electromagnetic Compatibility (EMC)

The Electromagnetic Compatibility (EMC) studies are used for this standardization for noise radiation from electrical equipments. The EMC standards define the maximum permissible noise level of an electrical device (like a washing machine's motor). With the help of EMC standards, all equipments which work together can perform without disturbing each other. The noise meters used for EMC and the corona radio noise have some common characteristics.

3.1.2 Amplitude Modulation (AM) Broadcast Band

As clarified in detail, Chapter 1 explains the noise sources produced by a transmission line. The noises produced by transmission line (corona or micro-sparks) have importance because of their characteristics. They naturally occur in a major part of radio frequency band which is 3 kHz to 30 GHz. The corona noises occur especially in AM Radio and TV broadcast bands. So, radio interference and TV interference definitions of a transmission line arise.

This thesis is focusing on radio noise disturbances of transmission lines so the radio interferences occurring in AM broadcast band taken into account. The TV interferences are not investigated.

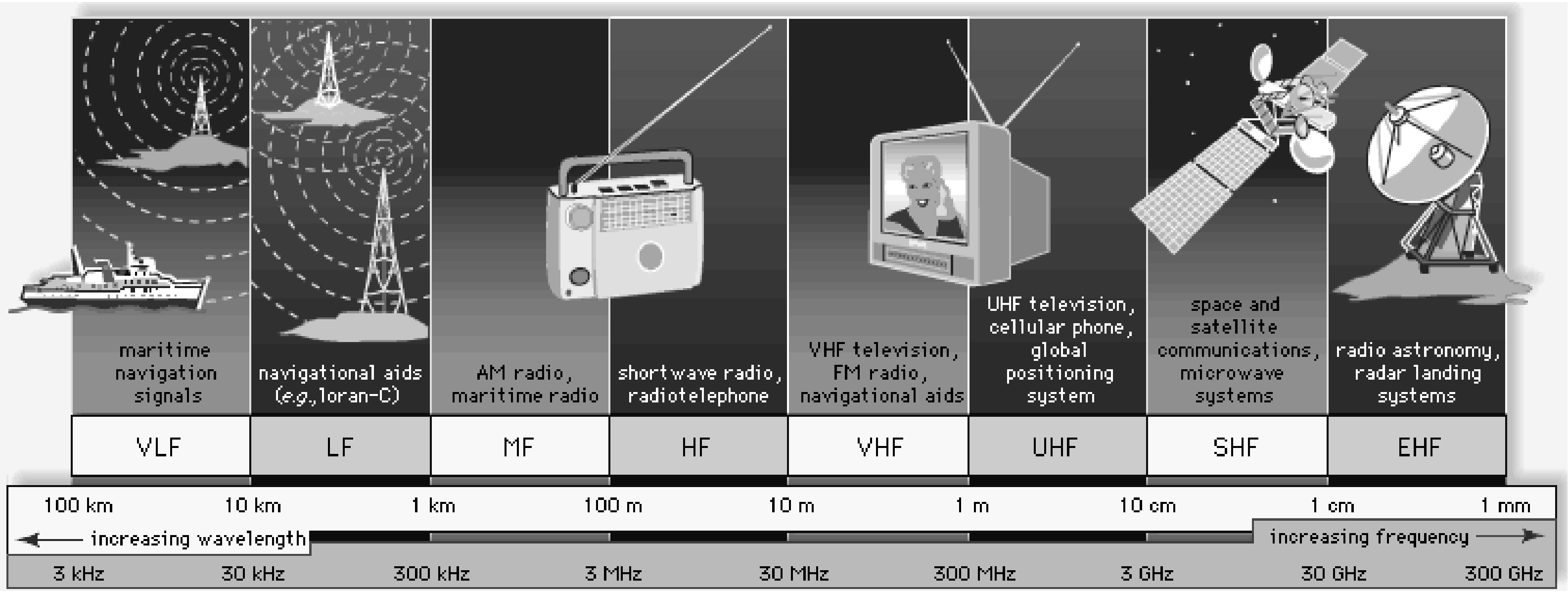


Figure 3.1 The Frequency Spectrum and Its Applications

The AM broadcast band is used for radio broadcast using the amplitude modulation technique. It is defined as "*A band of frequencies assigned for amplitude-modulated broadcasting to the general public*" [1]. The AM band's upper and lower frequencies are defined by International Telecommunications Union (ITU) and that is in between 535 to 1605 kHz. This band is very important since it is highly vulnerable to transmission line (as well as HV apparatus) noises.

Amplitude Modulation is an information transmission technique which is defined as "*Modulation in which the amplitude of a carrier is caused to depart from its reference value by an amount proportional to the instantaneous value of the modulating signal*" [1]. The carrier's amplitude is modulated (or altered) with the information signal (generally analogue voice signal). The information signal is carried with this and demodulated according to the peak level of the carrier. Amplitude modulation schematic is given in Figure 3.2.

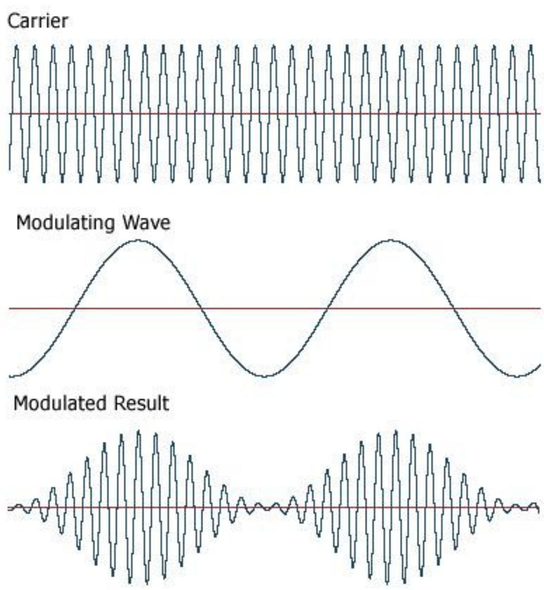


Figure 3.2 Amplitude Modulation

The frequency band that AM is in called as “Medium Wave” band. The band has the major benefit to use ionosphere reflection and earth’s ground reflection which enables long distance broadcasting. The received signal quality highly depends on the time of the day. During day time, shorter distance (around 300-400 km) broadcast is available due to ground wave reflection. During night time, this broadcast length can go up more than 600 kilometers due to ionosphere reflection. Since the AM signal travels that much distance, it takes all the noise on the way.

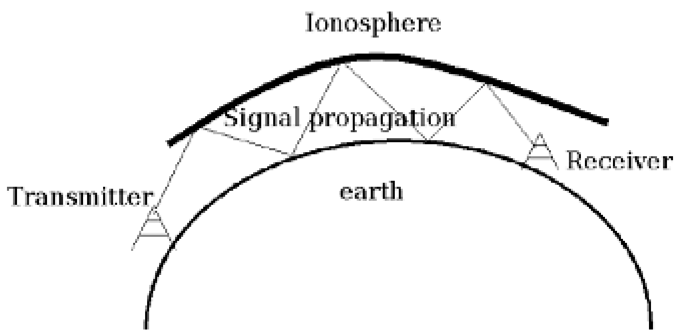


Figure 3.3 Sky and Ground Wave Reflection

The AM is vulnerable to noise because of its simplicity as a modulation technique. Since the noise is an addition on the carrier, the receiver can not separate the noise from the carrier. The noise is added to the modulated carrier, and the receiver demodulates noise added carrier. So, the noise is heard or transferred very easily. Due this noise problem AM broadcasting started to loose its popularity for public sector. Only talk or news stations are using the AM broadcasting now. But, the AM is used very wide for military broadcasting. The major advantage of AM is the usability with the low frequencies. So, high power output AM radios are used for long distance communication whether it has low audio fidelity. Also, AM modulated HF radios has the data transfer capability with the HF AM modems. So, a long distance and very low rate data transfer is also available.

Figure 3.4 Military HF-SSB AM Radio

This radio with a 5-15 meters mast antenna is capable of broadcasting up to 1000 km. The signal is ping-ponged between sky and the ground. The signal takes all the noises on its path. Cosmic noises are added to carrier while reflecting from sky and man-made noises (line transmission line, HV apparatus, fluorescent lighting, motors, etc.) are added to carrier while reflected from the ground. So, the transmission line design shows its importance at this point. The transmission line noises in one of the major noise that affects military band AM HF Radios.

Also, the amateur Citizen Band Radios (CB) are very popular for amateur usage. The CB Radios are legally used by radio enthusiasts and CB transmission is used as a hobby worldwide. The CB also uses AM techniques and it is vulnerable to transmission line noises. The CB radios are widely used at worldwide or countrywide crisis. They are necessary as an alternative to known communication means and the popularity is growing up. The CB rules are defined by non-profit organizations worldwide or countywide. International Amateur Radio Union (IARU) is the international non-profit amateur radio organization. American Radio Relay Language (ARRL) is the organization for North America. The same organization in Turkey is called TRAC (Turkish Radio Amateurs Society). The TRAC is very popular in Turkey and they have completed several projects and volunteer affairs. The TRAC is a government approved official organization that the amateur radio user certificates and its necessary trainings are given by TRAC. The TRAC achieved important success during the Gölcük earthquake in 1999. Since all of the communication means were down after the earthquake, the amateur radio users were major information shares right after the earthquake. The same is applicable for current Haiti earthquake. TRAC has already announced the necessary CB frequencies to talk with Haitian amateur radios. So, the noise levels of Turkey's transmission lines are important for such kind of preparedness.

3.1.3 The Types of Noises from Transmission Lines

The generated noise by transmission line or high voltage apparatus by corona or partial discharges are effective on AM broadcast bands by three means;

- Conduction
- Induction
- Radiation

The noise can travel by conduction as a direct wire connection with the receiver's power supply connection. The noise is superimposed on the power feed of the receiver.

The noise can travel by induction, when the induced noise field can be as near as to produce coupling noise on the receiver power or receiving circuitry.

The noise can be radiated through the free space as the transmission line or the HV apparatus can behave as a noise radiating antenna.

Due to nature of conducted transmission, the power of the conducted noise gets a very low value when the receiving frequency is increased. But, the radiated noise is not the same as conducted noise. The radiated noise can have frequency spectrum as high as some GHz for spark type noises, and as high as 30 MHz for corona type noises. The radiated noise is also powerful and can affect all receivers that are around 40-50 km perimeter.

The types of interferences of transmission lines are given in Figure 3.5.

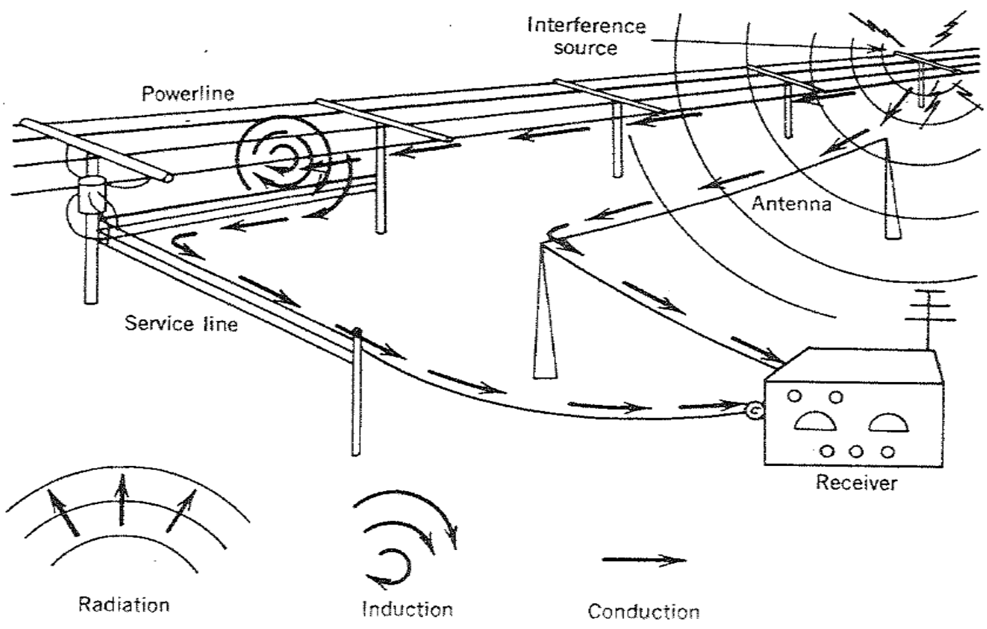


Figure 3.5 The Types of Interferences from Transmission Lines

So, the interference is observed;

- By the line frequency line to ground voltage, which is known as Radio Interference Voltage, RIV,
- As an interference measured by an antenna, known as radiated interference causing Radio Noise, RN.

3.2 Radio Interference Voltage (RIV)

By definition Radio Interference Voltage is *"The radio frequency voltage appearing on conductors of electrical equipment or circuits, as measured using a radio noise meter as a two-terminal voltmeter in accordance with specified methods (generally termed conducted measurements)*"[1].

RIV offers a voltage that can be measured with conducting probes to the equipments tested. RIV is the magnitude of the line-to-ground voltage that exists due to noise at power line or HV apparatus at any specified frequency below 30 MHz. The magnitude of RIV depends on the noise occurring in the transmission line or HV apparatus.

RIV is a measure of conducted interference and it is defined as "*Interference resulting from conducted radio noise or unwanted radio signals entering a transducer (receiver) via the electrical connections*" [1].

The RIV term has gained its importance because of the increasing of electrical transmission voltages and the trend of compacting (or reducing the weight) the HV apparatus. Due these effects, non-destructive partial discharge tests are utilized to help power suppliers and the final users.

At the earliest years, the safest way to control an electrical apparatus' insulation was to apply more voltage than its operating voltage for a long period and wait for the insulation to break. If the insulation is reliable enough to withstand to test, the apparatus was accepted to pass the test. But, applying excessive voltage to those apparatus generally weakens the insulation and the apparatus breaks down quicker after it starts to operate in the field. With the increase of transmission voltage levels and the trend of HV apparatus compacting the problem went bigger. The quality of the equipments should be satisfactory with the economic incentives. The optimum limits were needed. So, some sets of standards were started to be defined to overcome this problem. The standards were covering (and still) which tests should be applied to what type of equipment and which method should be applied. The method and the test types are so important that the apparatus should not be harmed during the test. Some sort of non-destructive test standards were arisen. Those standards have been discussed through the years and mostly revised until they got their final states. Current existing and accepted standard are a result of extensive experiments on the RIV and the initial standards. Since, the radio noise is a very complex phenomenon serious discussions have been made to find out the standards. Even standardizing the standards have been achieved.

3.2.1 RIV Standards

RIV standards are offering the methods of calculating RIV voltage with a test setup. Since the main cause of the RIV production is partial discharge, the standards are based on narrowband partial discharge measuring test setups. Later on, some broadband setup techniques were standardized and an alternative to RIV was found. The broadband detectors which are called “Partial Discharge Detectors” are not in the main scope of this thesis and some preliminary information can be found in [11]. This broadband measuring technique offered with IEC 60270[17] is a type of charge injection which led to a comparison between NEMA RIV Circuit and Broadband RIV Circuit. IEC 270 offers that charge injection calibration simulates the partial discharge better than the narrowband technique. The injected charges can be calculated with pC (Picocoulomb) so that a correlation between pC and uV (microvolts, which is the RIV unit) needed. This correlation is hard to observe since too many factors are effective.

NEMA 107 standard was the first that offered a standard setup for narrowband RIV measurement. The measurement is held at a frequency of 1 MHz. NEMA 107 standard was co-developed by some major institutes like Radio Manufacturers’ Association.

Released in 1940, the NEMA 107 standard was being used for measuring radio band disturbances of electrical apparatus to form a coordination in between. Since then, some improvements have been made on the standards and it is now used also for electrical integrity of the HV insulations. Last revision in the standard was made in 1987. The schematic for conductor and insulator RIV measurements and a typical NEMA 107 test circuit is given in Figure 3.6.

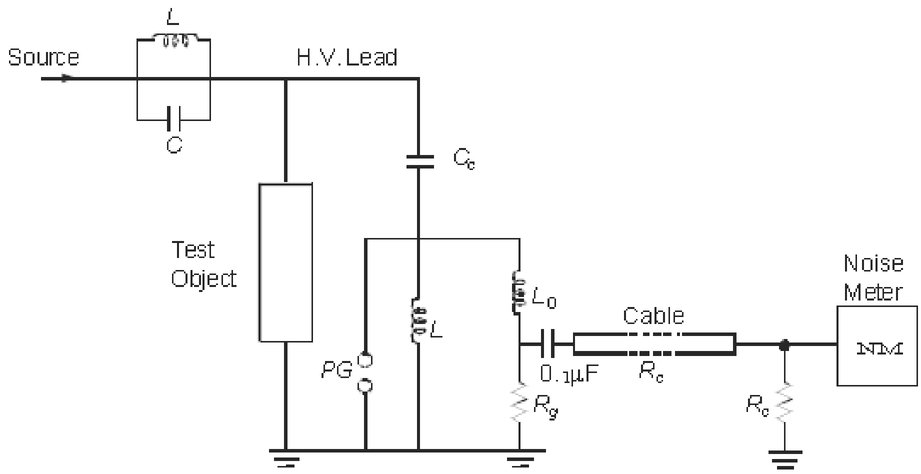


Figure 3.6 Typical NEMA 107 RIV Test Circuit

The preliminary NEMA 107 was intensively used by power utility companies. In 1978, a paper [4] was announced. The paper took attention to RIV results for physically large EHV (Extra High Voltage) test circuits. According to results, the found RIV levels according to NEMA 107 were much exaggerated. These wrong results could not be eliminated with the existing conditions of the standard.

In 1982, ANSI C63 is released to overcome the problem of wrong results of NEMA 107 for physically large circuits. The ANSI C63 was defining the measurement equipment standards. The ANSI C63.4 offered a new circuit which also suits with European IEC/CISPR test setup and main difference was the RF circuit impedance. The new NEMA circuit uses 150 ohms for RF circuit impedance whereas IEC uses 300 ohms [8].

3.2.2 RIV Meters

The test setup given in above NEMA and IEC/CISPR contains the main measuring equipment for conducted measurements. A RIV meter is used to define the RIV level of the equipment under test.

Two major RIV meters are used worldwide. They are US ANSI standard and European CISPR standard radio noise meters. Both have some common characteristics and their outputs can be converted to each other with subtracting some known dB values.

A standard RIV meter monitors only a very narrow portion of the frequency spectrum of the noise of the interference signal. All RIV meters contain a band-pass filter to achieve narrowband reading, a quasi-peak detector with time constants changing according to standards and an analogue meter to show the RIV level. All RIV meters are radio noise measurement devices which are tuned for power transmission noises. The bandwidth and the quasi-peak detector reading are chosen according the spectral characteristic of the partial or complete discharges occurring in the power transmission lines of HV apparatus.

The main scope of this thesis is measuring radiated Radio Noise (radio interference of power transmission lines). The RIV meter has the same characteristics with the RN meter. The RN meters will be detailed in further sections.

But conducted measurement application of a radio noise meter, that is RIV meter, needs some clarifications because of its coupling with the test circuit.

3.2.3 RIV Measurements

The RIV level is measured as uV at a fixed frequency (1 MHz for NEMA). The frequency is chosen as 1 MHz because of AM broadcast band (which is 535 kHz to 1605 kHz) effect of the radio noise. Different frequencies can also be used within the AM broadcast band.

The RIV is also expressed in dBuV which can be calculated with below logarithmic formula;

$$dBuV = 20 \log uV \tag{3.1}$$

Conducted RIV measurement test setup, the procedure for it and the RIV meter characteristics are clearly defined in regarding Radio Interference Measurement Standards which are specific to that test specimen. For instance, IEC 60437 [18] defines the "Radio Interference Tests for High Voltage Insulators". The standards for types of HV apparatus have similar characteristics so an example standard outline will be given here. Some major definitions of the IEC 60437 are as follows:

- Scope : The standard specifies the procedure for a radio interference (RI) test carried out in a laboratory on clean and dry insulators at a frequency of 0.5 MHz or 1 MHz.
- Measurement Frequency: The measurement frequency shall be in between 0.5 to 2 MHz and 0.5 or 1 MHz should be chosen. As an alternative the manufacturer and the customer can chose another specific frequency in between 0.5 to 1 MHz. The frequencies 0.5 or 1 MHz is preferred because that part of the spectrum of radio noise is high to represent the RI level.
- RI limits: Standard did not give any limits. These limits are country specific and can be found in national regulations. Of course, the national regulations can base another limitation standard.
- Measuring Instruments: Standard CISPR measuring apparatus or other measuring apparatus (decided between manufacturer and the customer, ANSI measuring equipment is also applicable) can be used.

- Measuring circuit: Laboratory measurement shall be made by measuring conducted quantities, either current or voltage. CISPR 18-2 measuring circuit (or NEMA 107 circuit) shall be used.
- Test Voltage: RI measurements shall be made with power-frequency voltage applied to test object. The RI level of the test transformer or the other equipments shall be insignificant not to affect the measurements.
- Atmospheric Conditions: Standard atmospheric conditions are not valid for this test. The atmospheric conditions shall be in the ranges of the values given below and should be recorded at the time of the test.

    - Temperature : Between 10 – 35 ^{o}C
    - Pressure : Between 87 – 107 kPa
    - Relative Humidity : Between 45% and 75%

And also, if the customer requires different atmospheric conditions, the manufacturer shall supply the test under those atmospheric conditions.

- Test Area : The test should be achieved inside a screened room. Any noise source (like lighting fixtures, power switching) should be filtered or eliminated.
- Mounting: The insulators shall be mounted according to relevant standards (standard method of mounting in real life) with all accessories (like arcing horns, grading rings, conductor bundles, etc.)
- Insulator Quantities: The quantities of insulators should be the same as the type test standards. If more than one insulator is tested, the RI characteristic is the mean value of the test results for each insulator.
- Procedure for the test :
    - Calibration of the test circuit shall be made according to CISPR 18-2 (or NEMA 107).
    - A voltage 10% higher than the specified test voltage shall be applied to the insulator under test and maintained for at least 5

minutes. The voltage then shall be decreased in steps to 30% of the specified test voltage, raised in steps to the initial value, maintained there for 1 minute and finally decreased in steps to the 30% value. Each voltage step shall be approximately 10% of the specified test voltage.
    - The voltage versus RI level shall be plotted to obtain RI characteristic of the insulator.
- Test Report : A report containing below details should be given :
    - Name of the manufacturer
    - Type designation of the insulator tested
    - Details of the test arrangement and the dimensions
    - Atmospheric conditions
    - RI characteristic (plot)

3.2.3.1 RIV Measuring Example: 170 kV Silicone Rubber Insulator

For further clarification a real-life results of a conducted RIV test is outlined below. The test was performed for 170 kV silicone-rubber insulator in a HV laboratory in Turkey.

The test was held in accordance with “IEC 61109 Insulators for overhead lines – Composite suspension and tension insulators for AC systems with a nominal voltage greater than 1000 Volts – Definitions, test methods and acceptance criteria”[19].

The test procedure applied as follows;

- Test voltage is increased by 10 kV steps from zero to 150 kV_{rms} maintained 5 minutes and decreased to zero with 10 kV steps. At each step RIV measurement was held at 0.97 MHz through a 150 ohms coupling quadripole (quadripole is a circuit arrangement that assures firm level of input and output impedance of the test circuit). The test cycled three times. The ambient weather conditions were;

- Atmospheric Pressure : 756 mmHg
- Ambient Temperature : 29,4 ^oC
- Absolute Humidity : 16,7 g/m^3

Below RIV results found for a 170 kV silicone rubber insulator.

Table 3.1 RIV Test Results

Voltage kV_{rms}	**RIV (dB/150 Ohm)**	**RIV (uV/150 Ohm)**
150	67.6	2392
140	65.5	1889
130	64.0	1582
120	58.8	867
110	52.8	436
98	**41.0**	**112**
90	36.1	64
80	22.5	13

The RIV level at $1,1xU_r/\sqrt{3} = 97,8kV$ is taken as the basis. So, the RIV level at 98 kV is 112 uV (at 150 ohms) which is less than 2500 uV (limits defined in the national regulations comply with relative NEMA standards). The picture of the tested insulator is given in Figure 3.7.

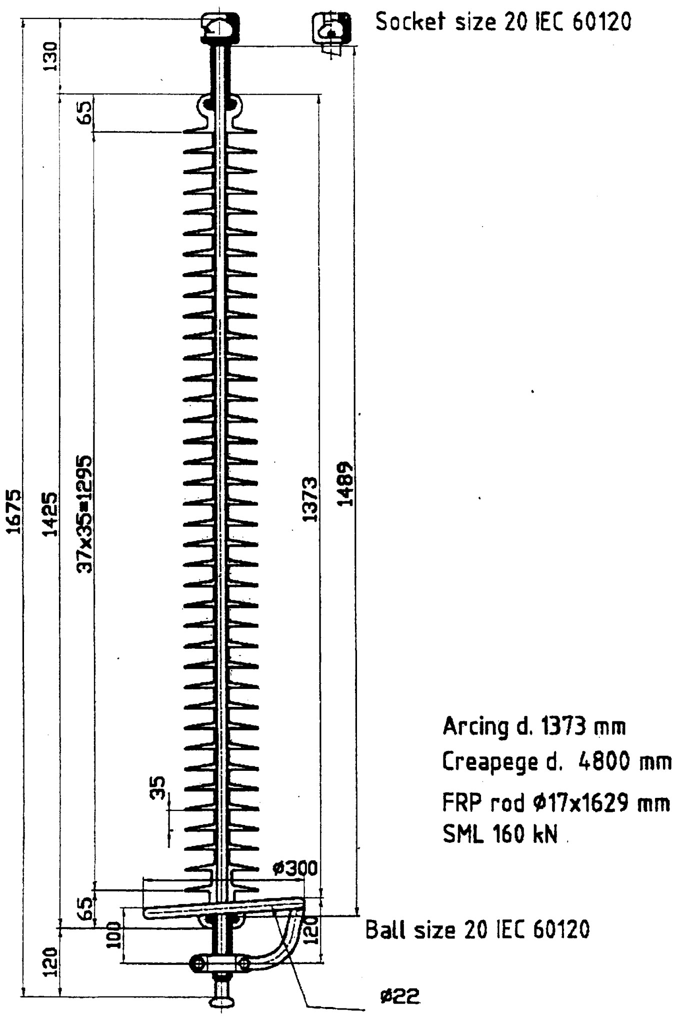


Figure 3.7 Diagram of Tested Insulator

For conducted measurements, the measured values are used for quality assurance of the equipment. So, the RIV limits for various HV apparatus should be investigated.

3.2.3.2 RIV Limits

The aim of RIV measurements is to force the HV apparatus manufacturers and transmission line designers to produce equipments and make designs within the predefined RIV levels. Those RIV levels are found with years of experiments and finally given in the regarding standards. As a result of inventions in new materials RIV limits tend to decrease.

Each HV apparatus has a design standard. Each design standard has a requirement of maximum permissible RIV level. The levels of conducted RIV measurements are clarified with national regulations which are generally formed according to relevant standards.

For high-voltage insulators, IEC60437 is accepted as the standard. The standard requires maximum permissible RIV level for insulators as 2500 uV (with the test setup, measurement circuit and measurement device given in the standard). 2500 uV should not be exceeded at

$$1{,}1xU_r \big/ \sqrt{3} \tag{3.2}$$

where;

U_r is the line operating voltage.

In Turkey, 380 kV and 154 kV line operating voltage levels are used. The maximum RIV level is defined as “The permissible RIV level which is calculated according to IEC60437 and between 0.5 to 2 MHz should be 2500 uV (or from equation 3.1, 68 dB) at $1{,}1xU_r \big/ \sqrt{3}$” in the regarding technical specification paper of Turkish Electricity Transmission Company (TEIAS).

For the disconnectors, the IEC 62271-102 [20] is valid. According to standard, the maximum permissible RIV level is 2500 uV (or from equation

3.1, 68 dB) when it is measured at $U_r / \sqrt{3}$. (IEC 62271-102 clause 6.3). The same is accepted and given in the regarding technical specification paper of Turkish Electricity Transmission Company (TEIAS). The test should be applied 3 times for each phases of the disconnector.

For the lightning arresters, IEC 60099 [21] are valid in general. According to that standard, porcelain enclosures should produce minimum level of RIV. This situation is accepted as the same in Turkey with the National Authorities.

For power transformers, partial discharges (PD) occur within the insulation of the transformers. Two major types of calculating PD in transformers are applicable. The first method formed according to IEEE C57.113 “Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors” and it is used to measure apparent charge (picocoulombs). This technique is more sensitive to measure the PD in the winding but more susceptible to external noise. The second method is NEMA 107 as it was discussed earlier. NEMA offers measuring the equivalent high frequency conducted voltage level at 1 Mhz. Excessive PD activity can interfere with radio communication. According to Federal Communication Commission (FCC) and the NEMA Publication TR 1, the permissible RIV levels are given below (at 110% operating voltage and at 1 MHz)

- 250 uV up to 14.4 kV operating voltage,
- 650 uV up to 34.5 kV operating voltage,
- 1250 uV up to 69 kV operating voltage,
- 5000 uV up to 345 kV operating voltage.

In Turkey, broadband PD technique (IEEE C57.113) is accepted and regarding specification levels are around 200-300 pC which differs according to operating voltage and capacity of the transformer. The required levels are given in the power transformer technical specifications. There is a procedure to test the transformer. The left column of the table shows the procedure with the time order. An example of permissible level for a power transformer is given in the in Table 3.2.

Table 3.2 PD Limits for a Power Transformers (as given in the Regulation)

Transformer type : 380/33.25 kV Power Transformer (90/125 MVA)	
Voltage Level (Un=420 kV, rms)	**Permissible pC level**
1.2 Un (15 min)	<200
1.5 Un (60 sec)	<300
1.2 Un (15 min)	<200

3.3 Radio Noise

The main concern of this thesis is radiated noises from transmission lines. Up to this point common noises (due to partial or complete discharges like corona or spark type discharges) are investigated. And regarding conducted measurements which give RIV level are given in detail. From this point, the radiated interference RI will be investigated in detail. And, the radio noise (RN) meter realized in this scope will be detailed.

The RIV and RN measurement devices are principally the same devices. They work in 0.5 to 2 MHz band with a very narrow bandwidth (4.5 kHz or 9 kHz) and a quasi-peak detector. The test scheme for conducted RIV measurements (needs a test laboratory) and radiated RI (needs field surveys) are different. But, both measured concept is the same, the partial discharges.

The electrical interference, radio interference and the radio noises are different definition derived from each other. They should be carefully used to define any noise specific existence.

General electrical interference phenomenon was given in Section 3.1. Radio interference is the interference occurs on a radio signal and defined as “impairment of the reception of a wanted radio signal caused by an unwanted radio signal or the radio disturbance”. So, radio interference is noise acceptance of a radio signal by another radio signal. Another radio signal should have the same characteristics to form a noise on the original radio signal. The radio noise is the radio interference that affects the portion of AM broadcast band. When the man-made and natural noises are taken into consideration, nearly all frequency spectrum (which contains radio bands) is vulnerable to radio interference. Static noises do have white noise (that is the noise that has flat frequency spectrum and can affect all frequencies) that can affect AM broadcast band as well as other broadcast bands. So, the radio noise is the noise that is taken into account in the window of AM broadcast band which is in between 535 to 1605 kHz.

By definition, the radiated radio noise is "*Radio noise that is propagated by radiation from a source into space in the form of electromagnetic waves, e.g., the undesired electromagnetic waves generated by corona sources on a transmission line*" [1]. The radio noise definition for the scope of this thesis is "measurement of radio noise which affects AM broadcast band from overhead power lines".

The electrical noises of the transmission lines and the HV apparatus investigated in detail in Chapter 2. The reasons why transmission line noises produce radio noise, their characteristics, mathematics and the standard for measuring this corona produced radio noise will be clarified in this section.

The radio noise is expressed in uV/m or in decibels above 1 uV/m. For dB conversion, below equation is used.

$$dB \quad above \quad 1uV/m = 20\log uV/m \quad [1] \tag{3.3}$$

3.3.1 Conductor Corona and Radio Noise Relation

Corona, its mechanism and types were given in Chapter 2. In this section, the relation between the corona and the radio noise will be investigated.

Two major types of coronas occur on the HV transmission lines. They are;

- Glow coronas which are pulseless
- Streamer coronas which are pulse type

Pulseless glow type coronas have no effect on radio noise due to its weak and non-repetitive characteristic. The pulse type coronas have major effect on radio noise due to its repetitive and powerful characteristics.

The pulse characteristic and its repetition are the first result of the radio noise. A corona cloud contains very light free negative electrons (electron avalanches) and very heavy positive ions. When the conductor goes into positive state with respect to ground, the free electrons nearby run into the conductor, causing a rise in the pulse. This rise is the positive corona pulse front. The tail of the pulse is formed due to heavy ions' drift due to positive charge. At the start of this drift, the electrical field intensity is very low due to positive ion existence nearby a positive conductor. When the positive ions go far away from the conductor, the attracted the free electrons (which can not be attracted by positive conductor) and sudden re-rise of the pulse is achieved. Then the tail is formed when the ion goes more away from the conductor (also the electrical field intensity goes lower). This cycle continues to form the pulse trains until the positive ions called back due to negative state of the conductor. In fair weather, generally one corona pulse per positive cycle is observed. When the weather condition goes into a state that corona can be observed, tens of pulses per positive conductor cycles can be observed.

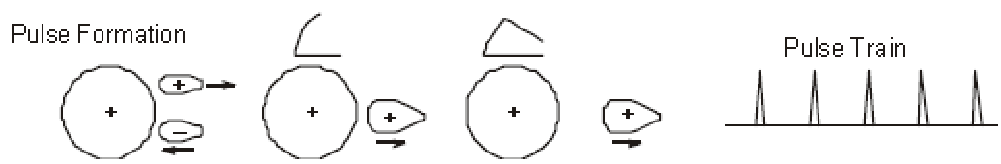


Figure 3.8 Pulse Train Formations

When the conductor goes into negative polarity with reference to ground, reverse process is applicable. The heavy positive ions nearby the conductor run into negative polarity conductor faster than the case of their speed in the positive polarity conductor. This is because; the electrical field intensity goes up progressively while the ions get nearby the conductor. And, the free electron avalanches drift very fast due to their lightweight structure. This gives a very sharp pulse front. After this quick process, the electric field intensity returns immediately to its first state, and the cycle of pulse re-formation is achieved again very quickly. So, the negative coronas are smaller in amplitude, have very sharp rise and fall times and high repetition rates when compared to positive coronas.

This main difference in the positive and negative coronas is a result of ionization and electron avalanche immobility and the electrical field strength (or the voltage applied to conductor). Pulses tend to go larger when the diameter of the conductor is increased since the electrical field intensity is lower. When the electrical field intensity is low the positive ions can drift more, resulting in a larger pulse. For small diameter wires, pulsative positive coronas tend to be eliminated due to high level of electrical field intensity. But, glow coronas may appear. In small wires, negative coronas are effective due to small pulses. These small pulses are called Trichel pulses (given in Chapter 2). This small amplitude, high repetitive coronas are not effective on radio noise. But, it should be kept in mind that defining the corona with some variables is correct up to an extent. Due to randomness of corona, random variables must bear in mind. General characteristics of positive and negative pulses are given in Table 3.3.

Table 3.3 General Positive and Negative Pulse Characteristics [13]

Type	*Time to Crest*	*Time to 50% on Tail*	*Peak Value of Current*	*Repetition Rate Pulses per Second*	
				A.C.	*D.C.*
Positive	50 ns	200 ns	100 mA	Power Freq.	1,000
Negative	20 ns	50 ns	10 mA	100 × P.F.	10,000

From the pulse phenomenon given above, it can be said that RN of HV transmission lines occurs due to these short current pulses. A pulse's spectral frequency shows so many sinusoidal (can be seen with Fourier transforms) components with different alternating frequencies. The pulses are not continuous and occur at the peak region of the applied AC voltage. The length of these pulses are effected according to electrical intensity, conductor diameter and as well as surface conditions (due to weather or surface contamination).

The magnitude of positive pulses (due to positive corona) is several times higher (sometimes more than 1000 times) and it can increase with the applied voltage to the conductor. So, RN of HV transmission lines occurs because of positive corona.

The observed RN levels of positive corona discharge can be in between 100 uV/m to 5000 uV/m. These levels are interpreted to RN levels of (from Eq. 3.1) 40 dB above 1 uV/m to 74 dB above 1 uV/m.

The RN level of a nearby transmission line is measured with a noise meter having a center frequency of 1 MHz (which is in AM Broadcast Band) and a bandwidth of 4.5 kHz. The radio noise meter contains a quasi-peak detector for weighting the noise. The quasi-peak detector has a rise time of 1 ms and a discharge time of 600 ms. A monopole vertical rod antenna is used for field measurement of RN electrical field component. This radio noise meter and the relevant standard to measure radio noise will be detailed in subsequent sections.

3.3.2 Insulator Corona and Radio Noise Relation

Generally, insulator corona does not give higher contributions to RN. This is because of corona phenomena and insulation medium. In the insulators, the corona is observed very rare because of high dielectric properties of the insulator. But, if the transmission line conductor is chosen to produce low corona, the insulator corona level can gain importance.

During the design of a transmission line all elements should be chosen to satisfy predefined noise characteristics, such as corona. The insulators are tested with RIV values in laboratory environment and their RIV limitations are as low as 250 or 500 uV. If the insulator is mounted perfectly, it is not expected to have a RN level more than the conductor corona. If the mounting is not perfect (or due to apparatus aging) the RN level can be very high due to gap-type noises.

3.3.3 Radio Noise Calculations

Since the transmission line voltage levels tend to go higher, the RN levels gain so much importance. In the design of a transmission line, the RN levels should also be calculated. The RN phenomenon is very complex and can occur randomly. The RN level can be affected from several factors so it is very hard to find a formula. During several years of surveys and experiments eight different empirical formulas have been used. The famous and most trusted formula is CIGRE formula.

The estimated level of RN can be found with below formula:

$$RN = 50 + K(E_m - 16.95) + 17.3686\ln\left(\frac{d}{3.93}\right) + F_n + 13.8949\ln\left(\frac{20}{D}\right) + F_{FW} \quad [12] \quad (3.4)$$

where;

RN is radio noise in dB above 1 uV/m at 1 MHz.

K is 3 for 750 kV class

3.5 for others, gradient limits between 15-19 kV/cm

E_m is maximum electric field at conductor (gradient) in kV_{rms}/cm

d is (sub)conductor diameter in cm.

F_n is -4 dB for single conductors

is "$4.3422\ln(n/4)$" for n>1, n=number of conductors in bundle

D is radial distance from conductor to antenna, $D=\sqrt{h^2+R^2}$

h is line height in meters

R is lateral distance from antenna to nearest phase in meters

F_{FW} 17 for foul weather, 0 for fair weather

If any given transmission lines' RN level is known (under the same meteorological conditions), another formula can be used. The formula is as follows:

$$RN = RN_0 + 120\log_{10}(\frac{g}{g_0}) + 40\log_{10}(\frac{d}{d_0}) + 20\log_{10}(\frac{hD_0^2}{hD^2} \quad [12] \quad (3.5)$$

where;

RN is radio noise line in dB above 1 uV/m at 1 MHz.

RN_0 is radio noise of reference line in dB above 1 uV/m at 1 MHz.

g is average maximum(bundle) gradient in kV/cm

d is (sub)conductor diameter in cm.

D is radial distance from conductor to antenna, $D=\sqrt{h^2+R^2}$

h is line height in meters

R is lateral distance from antenna to nearest phase in meters

The terms with subscript "0" denotes the values of the reference line.

Below comments can be derived from above equations,

- The RN level is directly proportional to conductor diameter and electrical gradient (line voltage) of the line.
- Conductor bundling can reduce the RN level of the line.
- The RN level reduces when going away from the line.

- The lowest RN level occurs in fair weather. When the weather condition goes more humid or rainy the RN level of the line increases.

The RN characteristic of the power transmission line in scope of corona pulses, above equations and weather conditions will be detailed in next section.

3.3.4 Power Line Radio Noise Characteristics

As discussed earlier power line noises occur due to partial discharges like corona and gap-type discharges that happens in insulator, conductor connections and corrosion. Transmission lines can be classified into two main group for contribution of radio noise. The first class has line-to-neutral operating voltage up to 70 kV (may go up to 100 kV). In this class, the transmission line hardly produces conductor corona since its electrical gradient is very low. In this class, gap-type noises are effective which can be cured to eliminate the noise. The second class is the lines that have operating voltages more than 110 kV. These lines are called Extra High Voltage (EHV) lines in general and they are the major producers of conductor corona.

The second class having a line voltage above 110 kV, the conductor corona is the one of the major design considerations for the conductor diameter and bundling design.

The classification of transmission lines according to line voltage levels are defined according to IEEE Std. 141-1993 [16] and given in Table 3.4.

Table 3.4 Nominal System Voltages [16]

Standard nominal system voltages	Associated nonstandard nominal system voltages
Low voltages	
120	110, 115, 125
120/240	110/220, 115/230, 125/250
208Y/120	216Y/125
240/120	
240	230, 250
480Y/277	460Y/265
480	440
600	550, 575
Medium voltages	
2400	2200, 2300
4160Y/2400	
4160	4000
4800	4600
6900	6600, 7200
8320Y/4800	11 000, 11 500
12 000Y/6930	
12 470Y/7200	
13 200Y/7620	
13 200	
13 800Y/7970	14 400
13 800	
20 780Y/12 000	
22 860Y/13 200	
23 000	
24 940Y/14 400	
34 500Y/19 920	
34 500	33 000
46 000	44 000
69 000	66 000
High voltages	
115 000	110 000, 120 000
138 000	132 000
161 000	154 000
230 000	220 000
Extra-high voltages	
345 000	
500 000	
765 000	

To analyze the power line RN contribution three different aspects arise. Those are;

- RN generation
- RN propagation
- RN radiation

RN generation is the main discuss of the corona up to this point. RN generation is affected with two sub-factors. The first is the line design and the second is the atmospheric and environmental conditions. The first factor defines the electrical gradient of the line. This factor is effective on the conductor itself as well as nearby the conductor. This factor can be outlined from the Equation 3.4 with below major points;

- Spacing of conductors
- Phase spacing and phase configuration
- Diameter of the conductor

Taking above factors into account, the lines are generally designed not to produce corona at fair weather conditions. But, corona formation at foul weather can not be eliminated and the design is done accordingly.

The second factor of RN generating is the weather and environmental conditions. The Equation 3.4 proposes 17 dB addition for foul weather. This 17 dB addition is a general acceptance and a result of experiments. This approach is correct when the foul weather conditions and their effects on transmission lines are considered. The rain or fog water droplets, snowflakes, organic or inorganic pollution affect the conductor gradient as they intensify the electrical stress at the point they occur.

RN propagation is a result of travelling of produced radio interference along the transmission line. These noises which can travel along the line are influenced by the attenuation of the line and the earth resistivity.

Existing line designs are offering elimination of that propagation. So, RN propagation through the line (conducted interference) can be ignored.

RN radiation which is the main concern of this thesis is important in the vicinity of the line. The radiation pattern and radiation intensivity are varied according to characteristic of the corona noise. Another factor is the positions of the phases according to each other. The pattern (to a static observer or the antenna) is highly affected due to phase configurations.

All these measures are combined to form the RN characteristic of the transmission line. The RN level measured at a fixed location is a combination of three major characteristics.

3.3.5 RN Measurements from Overhead Power Lines

The RN measurements from overhead power transmission lines are a need for design and quality of transmission line in service. The RN measurement applies to all radiated type noises produced by transmission lines. The noises are especially arising from conductor corona which is non-uniform with the type of occurrence statistics.

The standard to measure RN noise propagating from transmission line is IEEE 430-1986 which is reaffirmed in 1991 and still in charge. The standard is called “IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations”. The standard gives all definitions, limitations, measurement instrument characteristics and the procedure for measuring RN.

The RN and RIV meter realized in the scope of this thesis fully based on IEEE 430-1986 and further measurements are done accordingly.

3.3.5.1 IEEE 430-1986 Brief

The IEEE 430-1986 standard is produced for defining the procedures measuring noise from overhead lines and substations. The standard has below sections in brief. The sections are investigated with the scope of this thesis and the RN meter produced as a result of this thesis.

3.3.5.1.1 Scope

The scope of the standard is to establish uniform procedures for the measurement of radio noise generated by corona from overhead power lines with RN meters conforming to ANSI C63.2.

The procedure is also valid for other power line noise arises from gaps. But, the primary focus is on corona. The procedures are not valid for transient noises such us breakers or disconnectors in operation.

The standard covers the full frequency spectrum in between 0.010 MHz to 1 GHz. But, primary focus will be given on AM broadcasting band which lies in between 0.535 to 1.605 MHz.

The standard is also valid for TV broadcast bands which lies in UHF or VHF band. Since the primary focus in this thesis is given on AM radio broadcast band, the TV broadcast interference (TVI) is not investigated here.

The reference standards which the standard refers will be given in subsections. The definitions of this standard are taken from IEEE 539-2005[1].

3.3.5.1.2 Measuring Instrumentation

The standard offers the usage of the RN meters conforming to ANSI C63.2-1980, "*Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz—Specifications*". The ANSI C63.2 is very famous for defining radiated measuring instrumentation.

The C63.2 has been revised in 1996 and it is fully in charge when this thesis is written. The ANSI standard C63.2 is an American standard. The European standard is produced by CISPR (The International Special

Committee on Radio Interference) of IEC (International Electrotechnical Commission). The CISPR 16-1 having a subject of "Radio Disturbance and Immunity Measuring Apparatus" has similar characteristics (not at all) with ANSI C63.2.

In 2009, ANSI C63.2-2009 released to eliminate the major duplication efforts of national and international electromagnetic compatibility technical bodies. The ANSI C63.2-2009 adopted some main features of CISPR 16-1. The ANSI C63.2-2009 has deviation and comparison tables prepared according to CISPR16-1.

In this thesis ANSI C63.2-1996 is adopted fully for measurement instrument. According to ANSI C63.2, a quasi-peak (QP) detector should be used for the measuring instrumentations' detector function for the measurement of transmission line noise (peak or average detector can be used for EMC tests). QP detector functions and their nature for measurements will be discussed in Chapter 4. QP detectors have some unique characteristics like;

- Bandwidth (at -6 dB)
- Charge time constant
- Discharge time constant

A table indicating the QP detector function according to ANSI C63.2 is given below.

Table 3.5 QP Detector Characteristics According to ANSI C63.2-1996[5]

Frequency Range (MHz)	Bandwidth –6dB (kHz)	Charge Time Constant (ms)	Discharge Time Constant	Optional Discharge Time Constant (bandwidth)
0.010–0.15	200	45	500 ms ± 20%	
0.15–30	9	1	160 ms ± 20%	600 ms ± 20% (4.5 kHz)
30–515	120	1	550 ms ± 20%	
470–1000	120	1	550 ms ± 20%	

The optional QP characteristic for the frequency band of 0.15 to 30 MHz (that contains the AM Broadcast band) is defined specially for transmission line noises. This is because of unique characteristics of corona pulse trains. This QP based meter has below characteristics.

- 1 ms charge time,
- 600 ms discharge time,
- 4.5 kHz bandwidth.

Since ANSI C63.2 is produced for all type noise measurement devices of a very wide frequency spectrum, the standard has aimed to find a uniform measurement instrument for each of frequency bands (the bands according to the standards' separation). But, transmission line noises has special interest and the ANSI C63.2 has a special definition for the transmission line noise, which is "*In the special case of interference or radio-interference voltage (RIV) measurement associated with electrical power apparatus, interference meters with quasi-peak detector time constants of 1 ms charge and 600 ms discharge and having 6 dB bandwidths of 4.5 kHz are also used at frequencies near 1 MHz*" [5].

And this situation is explained with the below further explanation note "*In the United States, radio-interference meters operating at a frequency near 1 MHz are used for quality control and radio-interference measurements from high-voltage (HV) electrical power apparatus, such as extra-high-voltage (EHV) power lines, power transformers and switchgear. The most common interference instruments used in the power industry in the past had quasi-peak detector time constants of 1 ms charge and 600 ms discharge, and 6 dB bandwidths of 4.5 kHz. In contrast, CISPR requirements have quasi-peak detector time constants of 1 ms charge, 160 ms discharge, and a 6 dB bandwidth of 9 kHz*."[5]

So, the QP designation used with the RN meter is clarified. Moreover, due to differences between European CISPR detectors and the

American ANSI detectors, extensive comparison studies were held. The studies showed that when the pulse trains' repetition rates are in between (50/60 Hz to 180 Hz), both detectors give identical results. When the pulse train repetition rate goes higher different readings can be achieved. This condition is concluded with the below statement of ANSI 430-1986. The statement is "*Measurements of power line noise made with the optional QP detector, which has 1 ms charge and 600 ms discharge time constants and a 4.5 kHz bandwidth, shall be reduced by 2 dB to agree with CISPR QP*"[6].

The unit indicated by radio noise meters is dB above 1 uV/m or just V/m. All calibration (due to antenna factor, attenuation, etc.) should be taken into account for the meter readings.

3.3.5.1.3 Measurement Procedures of RN from Overhead Power Lines (0.010 MHz to 30 MHz)

The ANSI 430 Standard has separated the measurement procedures into two different frequency bands. They are;

- Between 0.010 MHz to 30 MHz (which RN and RIV is applicable over the AM band)
- Between 30 MHz to 1 GHz (in which TVI is applicable).

Main distinguishing factors of this frequency band measurements procedure is the centre frequency. For the first frequency band 1 MHz center frequency is used for the measurement instrumentation. For the second band, 73.5 and 100 MHz are used.

For the measurement of RN, the overhead line that is free from buildings, fences, pipelines, other overhead lines is preferred as much as possible.

The measurement procedure is divided into short-term and long-term surveys.

3.3.5.1.3.1 Short-term Surveys

Short term surveys are generally done for measuring the instantaneous response of the noises arising from the overhead power line with a recorded weather condition at the time the line is being measured. Following conditions are taken into account while making a short-term survey. A lateral profile should be plotted with below requirements.

- The standard measurement frequency is 0.5 MHz (This condition is eliminated due to a newer version of C63.2 is released. The C63.2 offers 1 MHz as the center frequency as given above).
- The lateral length starts from outmost conductor to 80 m apart. The middle conductor is taken as at d=0 m.
- A QP detector (with the special arrangement for transmission lines) is used.
- A rod antenna or a loop antenna may be used. The height of the antenna is not critical but the base of the antenna should be at 2 meters maximum from the ground.
- A sketch given Figure 3.9 should be given as a result.

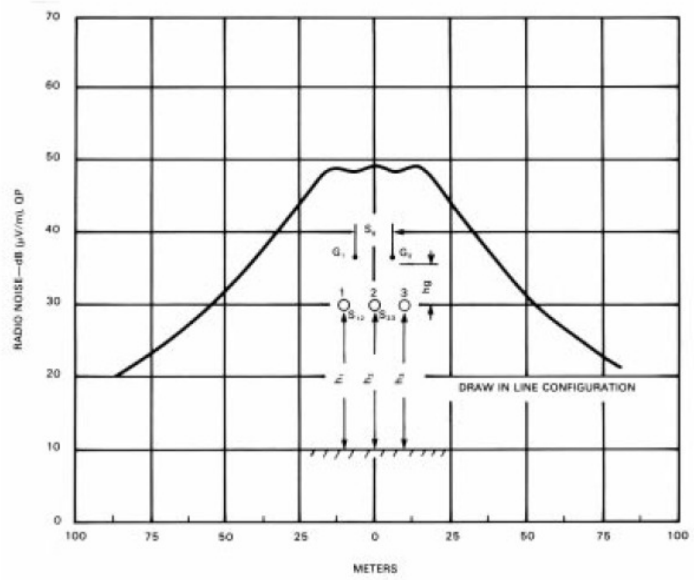


Figure 3.9 Lateral Plot Sketch

3.3.5.1.3.2 Long-term Surveys

Long-term surveys are held to get the all weather related necessary data through a long period. Long term surveys have the same principal with the short-term surveys with the following differences;

- The span length for the measurements is 15 m not 80 m.
- A loop antenna must be used (in short-term surveys a rod antenna or a loop antenna can be used).

3.3.6 RN Limits

RN is a type of pollution that should have an official or legislative limit. Until now, the theory and the measurements of RN were given. The main study is to measure RN levels to design a transmission line. This design, of course, is needed for economical reasons at first. But, public pollution of transmission line when the RN is taken into account should be investigated. The subject comes to an important issue during the recent years. Some countries have formed public awareness for the subject and this resulted in RN limits for the country. Some countries have defined their RN limits with some definite RN values in close approaches.

In USA, the regulation of RN design of a transmission line defined by Federal Communication Commission (FCC). According to FCC; the transmission line is an “incidental radiation device” [9] that produce radio frequency energy during some portion of its operation although it is not designed for this intention. A clear requirement is not given by FCC, but the effect of RN of transmission line is required to be at minimum on broadcast channels. Also, Environmental Impact Statements of Department of Agriculture requires the corona, transformer, circuit breaker operation noise “estimated levels” prior to power line manufacturing.

In Canada, Canadian Standards Association (CSA) has clarified the limits for lines up to 765 kV within the frequency range of 0.15 to 30 MHz. Below table is used for RN limits and the values can be increased by 10 dB in urban regions where the radio broadcast stations has more signal strength. Below limits are valid at 50 feet (15m) apart from the transmission line. The limits should not exceed 1700 hours annually.

Table 3.6 Canadian RN Limits [9]

Nominal Phase-to-Phase Voltage (kV)	Interference Field Strength (dB above 1 μV/m)
Below 70	40
70 - 200	46
200 - 300	50
300 - 400	53
400 - 600	57
Above 600	60

In former USSR (Russia), below limitation is given with full frequency range.

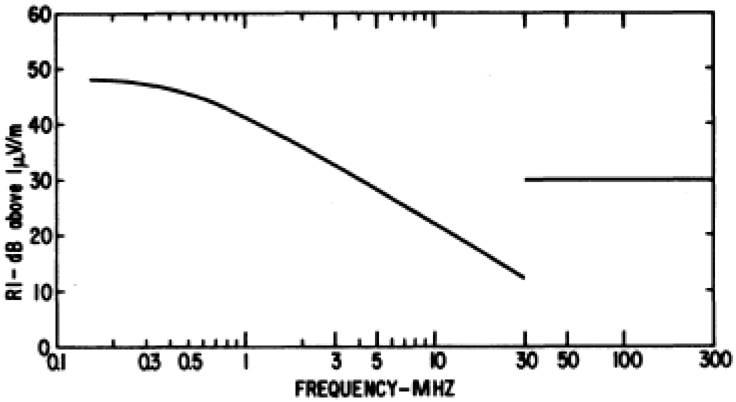


Figure 3.10 Russia RN Limits versus Frequency [9]

Above limits are applicable for fixed distances from the line. The distance is 10 m for lines 35 kV and below, 50 m for lines in between 110 to 220 kV and 100 m for lines 300 kV and above.

In Switzerland, the limit is 34 dB for lines below 100 kV and 46 dB for lines above 100 kV.

The examples can be increased. Some countries do not have RN limits. But for a general understanding and general RN Limit requirements, some design guides are offered by IEEE and CIGRE. Some countries adopted the offered guidelines of IEEE or CIGRE.

3.3.6.1 IEEE Radio Design Guide

This guide intends to give a reliable RN Limit levels as well as other design requirement for transmission lines. The design guide offers electrical gradient limits of a transmission line according to conductor diameter. And, the RN limits for fair weather can be derived from this gradient requirement. The approach does not give clear values but 40 dB above 1 uV/m at 100 ft (30.48 m) is accepted as an RN limit according to this guide.

3.3.6.2 CIGRE Guide

The CIGRE Guide hesitates to give an RN limit. It offers that transmission line interferences should be solved according to a country's transmission line design requirements which are formed according to human data, economical reasons and local climatic conditions. According to CIGRE each country has specific line design due to its primary line design requirements. So, the RN limit requirements can be altered accordingly. The RN limit should be defined by national authorities in the scope of country's general broadcast services and the conditions of country's power line network.

3.3.6.3 RN Limits in Turkey

Unfortunately, there is no limit defined for RN in Turkey. RIV, that is a measure of quality of the transmission line or HV apparatus, is much known in our country. As discussed in the RIV section of this chapter, all technical specifications of individual HV apparatus has a RIV limit according to International Standards.

The RN limits are investigated with two separate meetings in August 2009 and September 2009 from TEIAS (Turkish Electricity Company). Their responses were limited to RIV. According to those meetings, there have been no RN surveys achieved in Turkey. And, there is no definitive input for RN limits from the current existing technical requirements offered by TEIAS.

Due to European Union Compliance Laws, a new directorate which is called "Environmental Impact Assessment and Planning Directorate (EIA)" is formed under the Ministry of Environment and Forestry. This directorate is a mirror of European Environment Agency (EEA).

The main focus of this directorate is to assess environmental effects of the projects (from any project from any sector) from the environmental point of view. To achieve this, a report called Environmental Impact Report (EIR)" is required from the projects' main contractor. The project types which should supply EIR prior to start up are defined by EIA. One of the project type arises from this list is "*Construction of overhead electrical power lines with a voltage of 154 kV or more and a length of more than 15 km (transmission line, transformer centre, switch areas)*" [7]. By this statement, any transmission line contractor should prepare an EIR to the directorate.

Several reports had been prepared since. When those reports investigated in detail, it can be seen that corona and RN disturbances are rarely mentioned. Some EIR accepts corona and RN as an environmental pollution but those reports advise to keep the corona at minimum. A level of RN is not given.

In Turkey, there is no legislative concern about the electromagnetic field generated by EHV lines. Such electromagnetic field occurs in the power frequency band (ELF. Extra Low Frequency, 50 Hz for Turkey). Some definitive limits for this 50 Hz electromagnetic field are declared by some countries. And, the maximum levels are given. The only limitation that our regulations have is the clear distances of power lines with the environment (river, road, building, other transmission line, etc). Some public concern has been formed during the years for ELF produced electromagnetic waves but no study has been done for corona produced noise.

Due to integration with EU laws, limitation for RN for Turkey may appear in several years.

CHAPTER 4

REALIZATION OF RN METER

4.1 RN Meter Design Considerations

A RN meter is the key equipment of RN and RIV calculations. Migration from theory to practical application, a RN meter is realized according to the specifications mentioned in previous chapters.

Realizing such metering equipment needs some design specifications. The standards regulating the metering equipments are released to make the metering equipment readings uniform.

The RN metering instrument in the scope of this thesis designed according to below standards;

- ANSI IEEE 430-1986 IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations[6],
- ANSI C63.2-1996 American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz—Specifications[5].

In the scope of above standards, a RN meter having design considerations given in Table 4.1 has been realized.

Table 4.1 RN Meter Design Characteristics

Characteristics	Explanation
RN Meter	In the scope of IEEE 430-1986 and ANSI C63.2
Operating frequency band according to IEEE 430-1986	0.010 to 30 MHz
Center frequency for measurements (According to ANSI C63.2)	1 MHz
Bandwidth (According to ANSI C63.2)	4.5 KHz
Detector Type (According to ANSI C63.2)	Quasi Peak Detector Charge Time : 1 ms Discharge Time : 600 ms
Antenna type (IEEE 430-1986)	Rod antenna (Vertical Monopole Antenna with Ground Plane)
Antenna Connector	BNC
Range Attenuators	4 levels
Meter installed	Analogue
Metering Unit	uV/m
Chassis	Metallic Chassis, the metering circuit inside has another metallic chassis.
Power Supply	DC 12V (with separate battery)
Other	-Power LED -Grounding Terminal

4.2 Block Diagram

The block diagram of the realized system is given below.

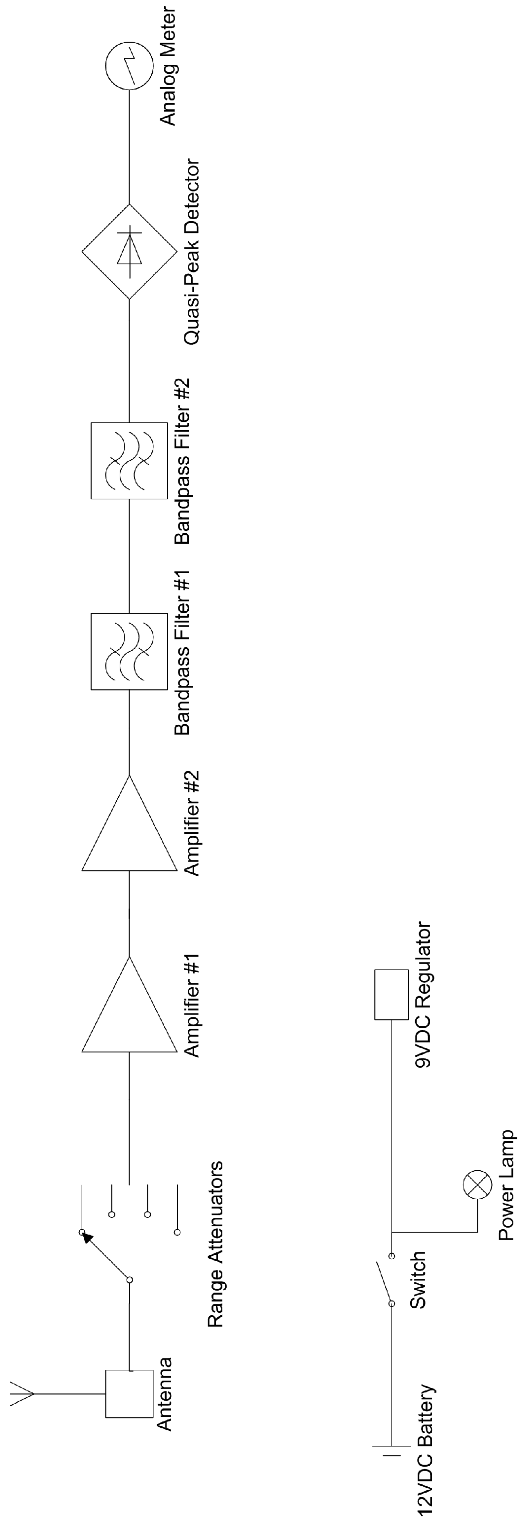


Figure 4.1 System Block Diagram

According to block diagram signal flows like this;

- When the transmission line conductor goes into corona state, the positive corona streamers occur with repetitive pulse trains. These pulse trains form currents that lead in a radiated interference at some frequencies. The transmission line itself behaves like a radiating antenna.
- The antenna in the vicinity of electric field of the transmission line collects the radiated power and radiated power is converted into voltage.
- A set of range levels can be adjusted with range attenuators. If attenuation is needed, the voltage level of the incoming signal is reduced by the help of range attenuators.
- After the attenuation stage, two broadband amplifiers amplify the signal coming from antenna through range attenuators. The amplifiers work as pre-amplifiers to prepare the signal for band-pass filtering.
- Two cascade bandpass filters are used to achieve more selective narrow-band requirement (4.5 KHz) of the RN meter. And also, these filters' center frequencies are set to 1 MHz. These filters are the first that complies with the standards' requirements.
- Then, the filtered signal is delivered to detector section that will decide what the RN meter will measure. The QP detector having 1 ms charge and 600 ms discharge time is used in between the bandpass filter and the analogue meter. QP detection characteristic will be investigated in detail.
- The next is the buffer amplifier which is used to isolate the metering loading factor from the QP detector. By this, QP detector will not be affected by the meter's electrical loading.
- The last is the analogue meter. An analogue meter is preferred because of the nature of the noise that is metered. The rise and fall of the meter, the speed of this rise and fall can give extra information to the operator.

The block of the circuits will be investigated in detail hereafter.

4.2.1 Antenna

A passive vertical monopole antenna with the height of 104 cm is used for the RN meter. This antenna is very famous for electromagnetic interference measurements and its design is clearly given in MIL-STD 461E which is “Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment”. The standard offers 104 cm monopole rod antenna with 60x60 cm ground plane within the frequency band of 10 kHz to 30 MHz [10]. Since the antenna calculations are very complex, this antenna type is adopted instead of designing a new antenna. The antenna is compatible with our measuring frequency (which is 1 MHz) and application type which is an interference measurement. This antenna type is produced by famous worldwide antenna manufacturers and its defining characteristics are well-known.

4.2.1.1 Monopole Antenna

The antenna is the major part of the RN meter. Antennas are the transducers to convert the corona repetitive pulse generated electric fields in to voltages. Of course, the converted signal has alternating current characteristic.

The monopole antenna is a dipole antenna that has only one side as a radiating element. The other side is simulated with a ground plane. The monopole antenna measures the electrical field along with its axis. The rod is vertical so the vertical electrical polarization is sensed. The antenna can be used in a very broad frequency range. It is simple to use and design so most of the antennas are monopole antennas. The length of the antenna may vary according to frequency. One of the famous types of this antenna is Marconi antenna which is also called quarter-wave antenna. This antenna is also used by AM broadcast stations.

The standard IEEE 430-1986 offers rod or loop antenna usage for the RN meter. The second constraint of the IEEE 430 is the length of the antenna. The standard requires a minimum 50 cm of antenna length (the rod length or one side of the loop antenna). The rod antenna complying with MIL-STD 461E is used for this thesis.

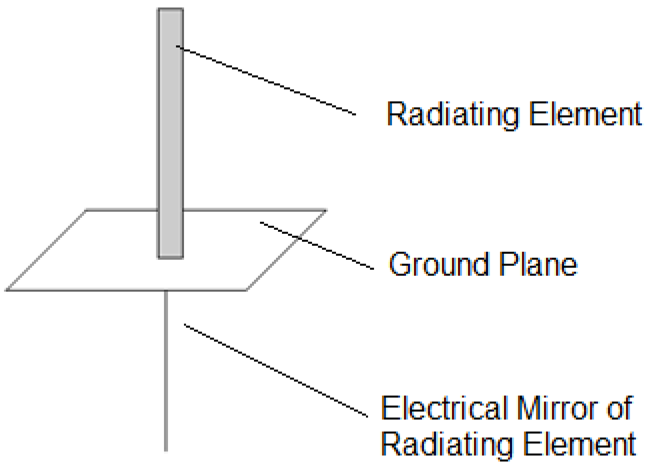
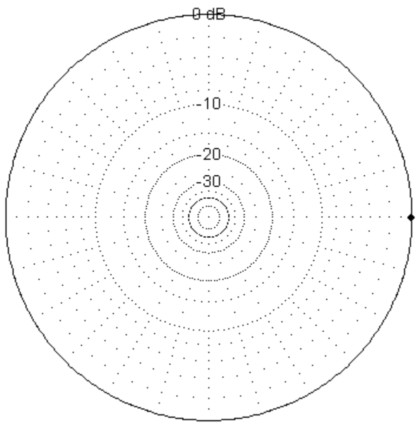


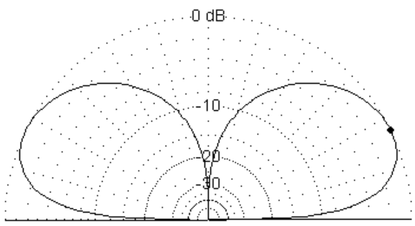
Figure 4.2 Basic Diagram of a Monopole Antenna

The monopole antennas have omni-directional (homogenous to each direction) pattern which gives the advantage of receiving and transmitting to all directions. The radiation pattern of the monopole antenna is highly dependent of the radiating element and the ground plane. The earth can also be used for a perfect ground. If the length of the antenna is increased with the fixed transmitting/receiving frequency, the gain of the antenna increases because the antenna radiating element can receive or transmit the longer portion (or the full portion) of the wavelength.

Typical radiation pattern for a quarter-wave monopole is given in Figure 4.3.



Azimuth Plot



Elevation Plot

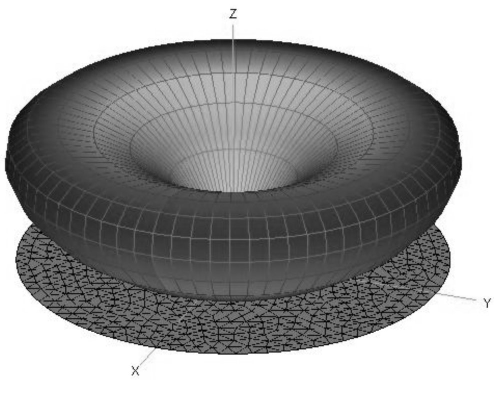


Figure 4.3 Radiation Patterns of a Quarter-Wave Monopole Antenna

4.2.1.1.1 Antenna Factor

The aim of using a standard and well-known antenna is to use its defined and standardized characteristics for our measurement calculations. The monopole antennas have a lot of defining characteristics but the major characteristic that will be focused on is the antenna factor. The antenna factor is the only requirement for our calculations because the antenna is only used in receiving state.

The antenna factor (AF) is the expression of electric field to produce 1 Volt at the terminals of the antenna. Antenna factor gives the voltage produced on the antenna terminals according to electrical field. Antenna factor is expressed as;

$$AF = \frac{E_{incident}}{V_{received}} \tag{4.1}$$

where;

AF	is Antenna Factor in 1/m,
$E_{incident}$	is electrical field in volts/m,
$V_{received}$	is the antenna terminal voltage in volts.

Generally AF is expressed in dB/meter which is;

$$AF(dB/m) = 20\log AF \tag{4.2}$$

Various antennas have different AF levels. Even for a single type of antenna the AF is dependent on the frequency it receives. So, AF plots vs. frequency are given by the antenna manufacturers.

The standard 104 cm monopole antenna is used for our project. So, accepted AF levels for our antenna are given below.

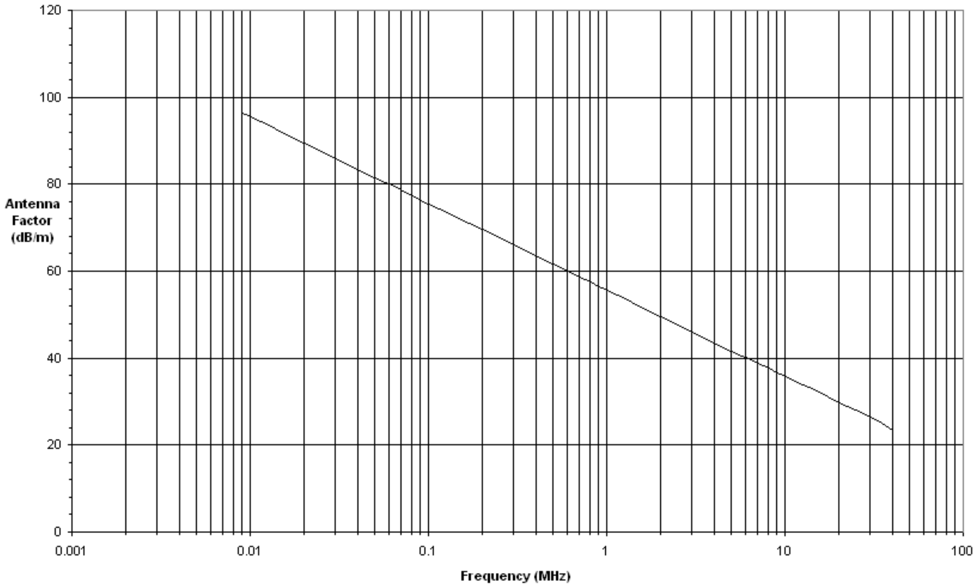


Figure 4.4 Antenna Factor of the 104 cm. Monopole Antenna

According to above chart, the AF (dB/meter) at 1 MHz is 55.6 dB/meter. A cable should be used to connect the antenna to the receiver (the RN Meter). A standard RG58 coaxial cable with an impedance of 50 ohms is used. The length of this cable is very important for the voltage to be read in the RN meter input. 3 meters of RG58 cables are used as standard to give a standard cable insertion loss of 0.5 dB.

So, 0.5 dB cable insertion loss is subtracted from 55.6 dB/meter and found as 55.1 dB/meter which is our final AF (dB/meter). Taking the inverse logarithmic function, the AF (1/meter) is found to be 568.

This value is interpreted as follows. If the 104 cm monopole antenna faces with an electrical field intensity of 1 uV/m, it will produce 568 uV on its terminals according to Equation 4.1. The AF value of 568 will be referred as a basis for our calculations.

4.2.2 Range Attenuators

4 levels of range attenuators are used in the RN meter. The adjustment of the attenuators is made with an 1 MHz sinusoidal noise. The variable resistors of each level are adjusted according to analogue meter's full scale. When the analogue meter went into full reading, the next level is adjusted so as to reset the analogue meter to zero reading. So, 4 different steps that are twice of the previous step are achieved. The steps can be observed on the RN meter.

4.2.3 Broadband Amplifiers

The weak signal coming through the rod antenna should be amplified and delivered to bandpass filters. This is achieved with a broadband amplifier. The broadband amplifier is composed of common emitter BJT amplifiers with negative feedback. This type of BJT amplifiers are widely used for high frequency radios. They are front amplifier circuits to have a low-noise and stable amplifying characteristics. The gains are arranged to have a full scale output of 200 uV/meter on the analogue meter. Typical common emitter amplifier circuit is given below.

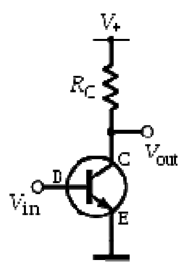


Figure 4.5 Typical Common Emitter BJT Amplifier without Biasing

4.2.4 Bandpass Filters

The requirement due to standard ANSI C63.2 is a narrowband filtering of signal before entering to weighing (the QP detector). The requirement is 4.5 KHz at the -6 dB corner frequencies. Two stages of filters are used to increase frequency selectivity. The center frequency of the stages are tuned to 1MHz in comply with the standard. The reason for 4.5 KHz (9 KHz in CISPR) will be given in further sections.

An active bandpass filter with high Q (the ratio of center frequency to bandwidth) is designed according to requirements of 1 MHz center frequency and the 4.5 kHz bandwidth. Q is used as an abbreviation of quality. The required Q level is found as 222 by dividing 1MHz to 4.5 KHz. The CA3140 OPAMP is used due to high frequency response requirement of the filter. CA3140 OPAMP supports input frequencies up to 4.5 MHz. Typical high Q active band-pass filer diagram is given below.

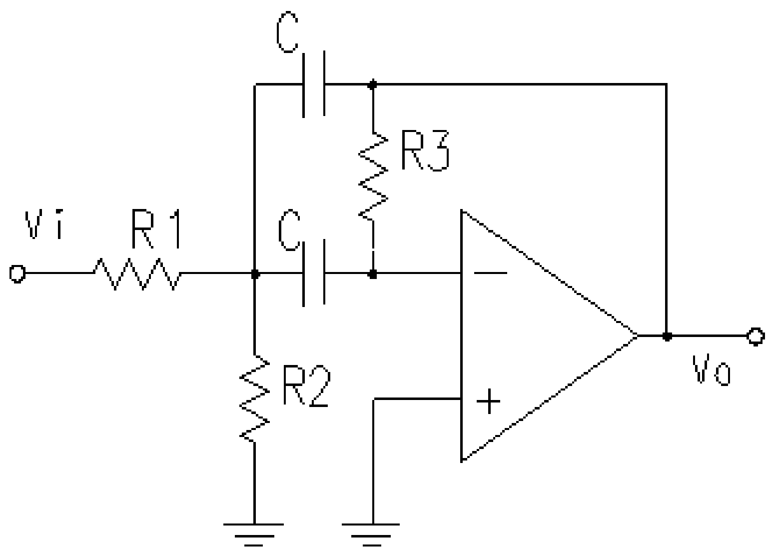


Figure 4.6 Typical High Q Active Bandpass Filter

4.2.5 Quasi-Peak Detector

A QP detector having a 1 ms charge and 600 ms discharge time is used for noise detecting unit. This is defined with the standard. Alternatively, peak or RMS detectors can be used as alternative metering equipments.

Quasi peak detectors are standardized for RN measurements. A quasi-peak detector is the detector that gives results in between the peak detector (measures the peaks of the signals) and the average detector (that measures the average value of the signal). The quasi-peak detector as its name resembles means the detector aiming to read the peaks nearly. It has been used because it is believed that it has a better indication of noise of interference to the human ear. The AM noises have a history that starts with the power line constructions. The power line noise has the characteristics to disturb AM broadcast stations. The noise can be heard and it decreases the quality of the station in the vicinity. With the quasi-peak, the disturbance of this noise to a human ear is aimed to be modelled. A quasi-peak detector is a simple detector with special time constants. It has charge and discharge times given in the standards. The QP detector can be described as a combination of peak detector followed by a lossy integrator. The peak detector keeps the peak level of the incoming signal and tends to keep the output constant. The second stage is the integrator that has a quick charge time and a long discharge time. If the incoming signal has repetitive pulses (as in the corona RN), the output is increased according to repetitive frequency of the incoming pulses. So, both peak level and the repetitive characteristic of the incoming signal are taken into account. The radio interference signals have repetitive pulse characteristics so that QP detector is the major measuring detector for interferences.

Typical diagram of QP detector is given below.

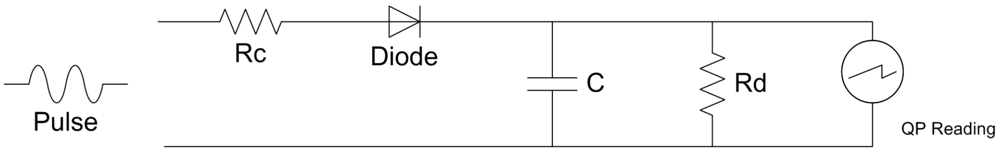


Figure 4.7 Typical QP Detector

A comparison of known detector outputs for frequency band 0.15 to 30 MHz is given in Figure 4.8. It can be seen from the figure that QP reading is in between the peak detector and the RMS and average detector.

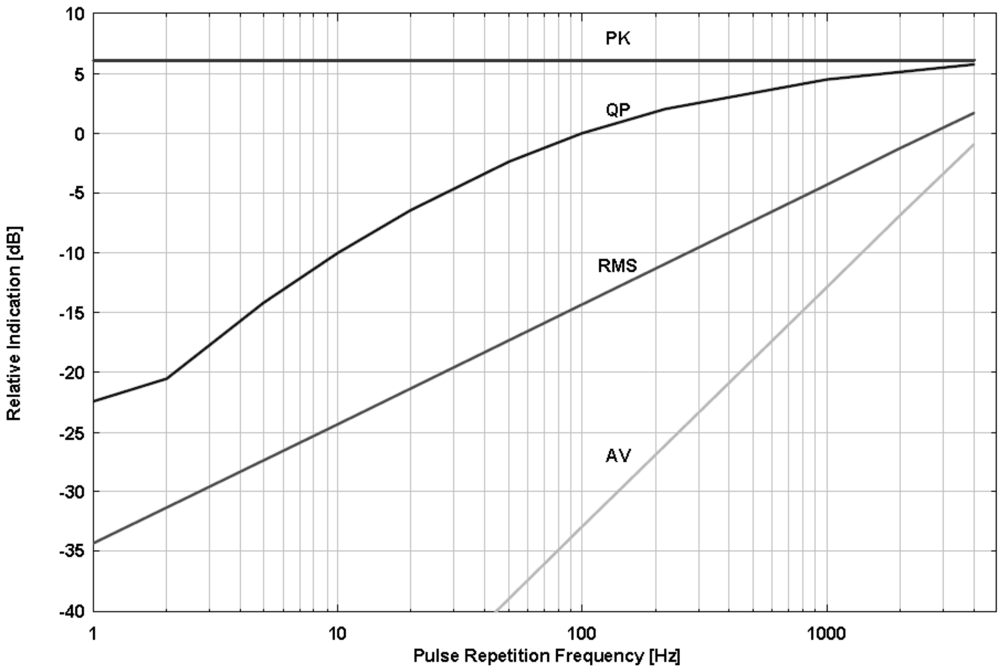


Figure 4.8 Comparisons of Outputs of Known Detectors

4.2.6 Current Buffer

A current buffer is used to minimize the loading effect of analogue meter to the output of QP detector.

4.2.7 Analogue Meter

An analogue meter having high internal impedance is used for monitoring the results. The results are measured in linear increase, not in the logarithmic scale. The meter is calibrated with the known input from a 1 MHz sinusoidal signal generator. The signal generator is connected to the antenna input of the receiver and full scale of the meter is adjusted to show 200 uV/m at first range. To do this the antenna factor calculated is used for the reference. So, the range of analogue meter is adjusted like below.

- Range 1 : 0-200 uV/m
- Range 2 : 200-400 uV/m
- Range 3 : 400-600 uV/m
- Range 4 : 600-800 uV/m

So, from equation 3.3, the RN meter is able to measure RN levels up to 58 dB above 1 uV/m @ 1MHz.

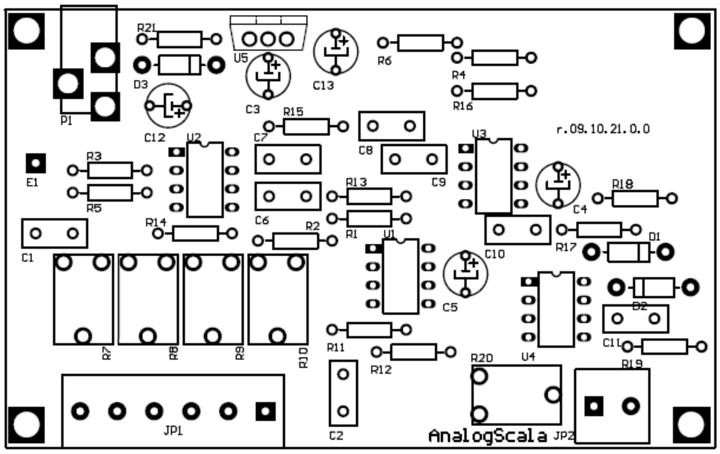
4.3 Circuit Design

The circuit according to given block diagram is designed and realized. The system is powered with 12 VDC power supply. The main circuit components are fed by 9 VDC. So, a voltage regulator is used.

All internal chassis elements and the circuit itself are connected to ground bar inside the chassis. The RF circuit inside the chassis is also put in another metallic chassis to increase Faraday Cage effect which will help to increase the noise immunity of the receiver.

4.4 PCB Design

The designed PCB layout and the picture is given in Figure 4.9.



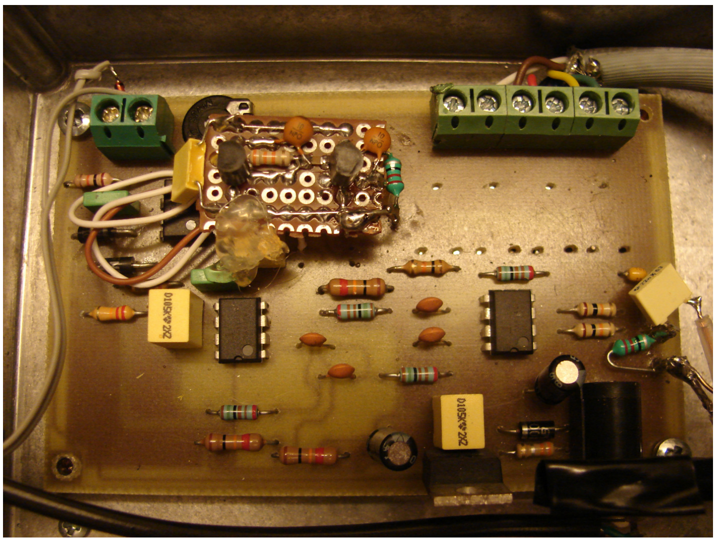


Figure 4.9 Main PCB Layout and Picture

4.5 RN Response in the view of Narrowband Filtering and QP Detector

Main design factors for the RN meter are the center frequency, the narrowband filtering and QP detecting. The reason for 1 MHz center frequency explained in Chapter 3. In this section, the reason for narrowband filtering and the QP detector usage (as the standards require) will be analyzed.

Each corona pulse has a unique rise and tail time and they can be expressed in mathematical formulas given below.

- For positive pulses : $i_+ = k_+ i_p (e^{-\alpha t} - e^{-\beta t})$
- For negative pulses : $i_- = k_- i_p t^{-3/2} e^{(-\gamma / t - \delta t)}$

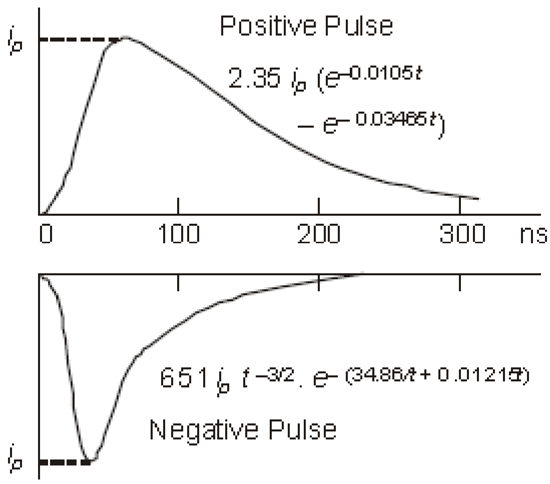


Figure 4.10 Typical Corona Pulses [13]

As it is discussed throughout the thesis, the real RN interference is found to be occurred in above damped exponential forms. The main idea of RN meter is to find a solution for pulse trains which are in forms of damped exponentials. So, a reading of a RN meter depends on;

- Pulse amplitude
- Pulse duration
- Pulse repetitive rate

Pulse amplitude and the pulse duration form the area of the pulse which gives the main amplitude for the reading. The response of the filter is directly proportional to area of the pulse.

Pulse repetition rate is also important for the meter reading to a definite extent. To understand this, the repetitive pulse spectrums should be investigated.

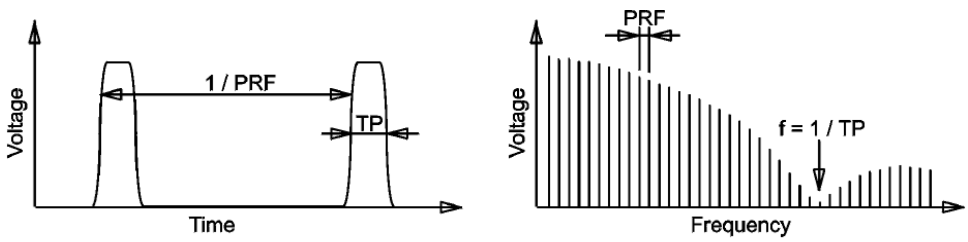


Figure 4.11 Repetitive Pulses in Time Domain and Their Frequency Spectrum

PRF is the pulse repetition frequency and the TP is the pulse duration. As the PRF increases, the frequency spectrum's envelope tends to be continuous. This forces to use a narrow bandwidth filter to catch a single frequency spectrum at a given center frequency (1 MHz in our case). So, the bandwidth should be adjusted according to PRF.

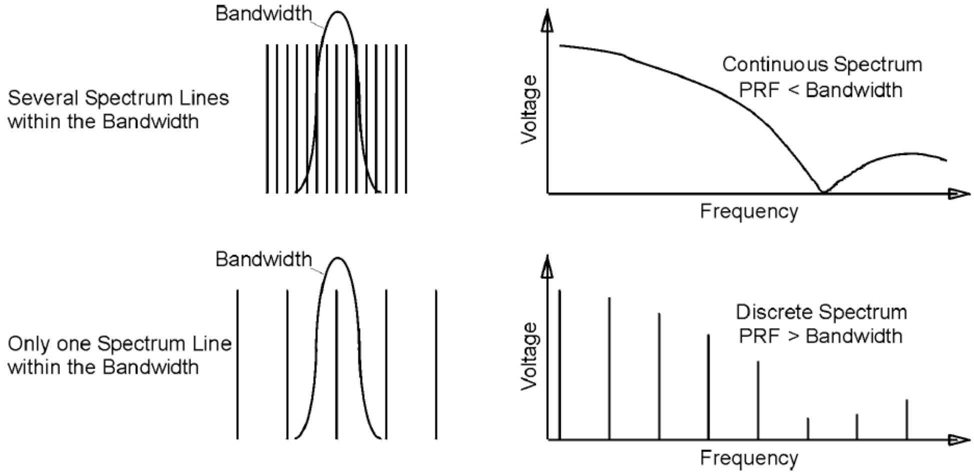


Figure 4.12 Bandwidth and PRF Relation

If the PRF is smaller than the bandwidth of the filter, a lot of spectral elements of the different pulses will be selected by the filter. This means a lot of spectral component will be effective within the narrow bandwidth. But, the envelope of the spectrum does not change. A lot of spectral elements will go into selection of bandpass filter due to increase in pulse repetition. So, this is the effect of increasing pulse repetitions.

If the PRF is greater than the bandwidth (as seen Figure 4.12), only one spectral element will fit in the bandwidth of the bandpass filter. This condition leads in a more precise reading.

So, amplitude-duration multiplication (the area of the pulse) in major determines the output of the detector. But, of course the pulse repetitions are also effective. The effects of pulse repetitions are lower than the pulse area.

The positive corona is the main noise interference factor for transmission line because of its powerful area of the pulse. The negative corona has a very low area of the pulse but it produces more pulse repetitions when compared to positive corona. Since the pulse area is the major factor affecting the detector output, the repetitive characteristic of the negative corona is not taken into consideration. So, the interferences from the negative coronas are neglected.

4.6 Pictures of the RN Meter

Some pictures of the realized RN meter is given below.

Figure 4.13 Front View of the RN Meter

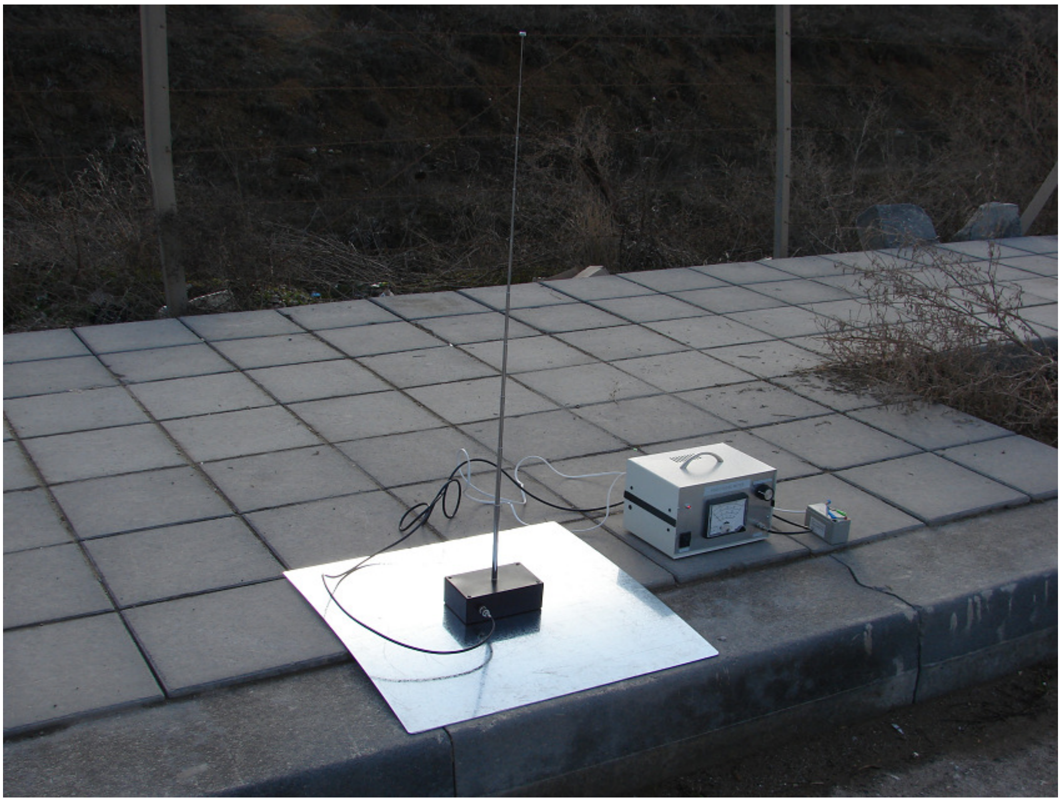


Figure 4.14 Realized RN Meter

CHAPTER 5

SAMPLE MEASUREMENTS

The RN meter is realized according to relevant standards and specifications given in the previous sections. All design constraints and the device components are based on regarding standards. Final adjustments were made at the laboratory environment. A finalizing issue is some sample measurements of the meter.

Since the corona on the power lines are statistical process, it is hard to observe real-time corona very often. Even if the corona appears (the hissing sound) the level of the line may not be adequate to be read on the meter. Taking these into consideration, a number of measurements were achieved.

5.1 Corona Measurements from a 380 kV Power Line

The corona can be observed on the EHV lines especially above 100 kV. A number of site measurements were held in Gölbaşı, Ankara. The measurements were done nearby the 380 kV transmission line going from GÖLBAŞI 380/154/34.5 kV Substation to Sincan Substation. Rainy days are intentionally chosen because of its effect to increase the corona probability.

5.1.1 Measurement #1

The measurement data;

- Location #1 : 39°48'16.82"N and 32°48'51.69"E
- Temperature : 8 ^{o}C
- Pressure : 1012 hPA
- Weather Condition : Rainy
- Altitude : 985 m
- RN Meter Center Freq. : 1 MHz
- QP Constants : 1ms charge and 600 ms discharge
- Antenna : A monopole rod antenna

Two types of noises were seen with the observation of audible noise. The corona and the gap-type noises were observed. Both the corona and the gap-type noise were heard at the same time but gap type noise was powerful as an audible source. The corona audible noise can be heard through the line but gap-type noise was directly coming from the tower. The noise was assumed to be coming from one of the insulators' connections. There was a steel fence barrier between the tower and the test area. It was not possible to measure exact distance from tower and the measurement points so estimated distances are used. The distances were taken by choosing tower base as the midpoint of test span. As it is discussed in the previous chapters, the corona electrical interference is lower than the level of the gap-type spark noises. The spark noises interfere with the full frequency band. So, the interference level of the gap-type spark was tried to be measured.

The test location is given below.

Figure 5.1 Location of Measurement #1 (Courtesy of Google Inc.)

The observed measurement is illustrated below.

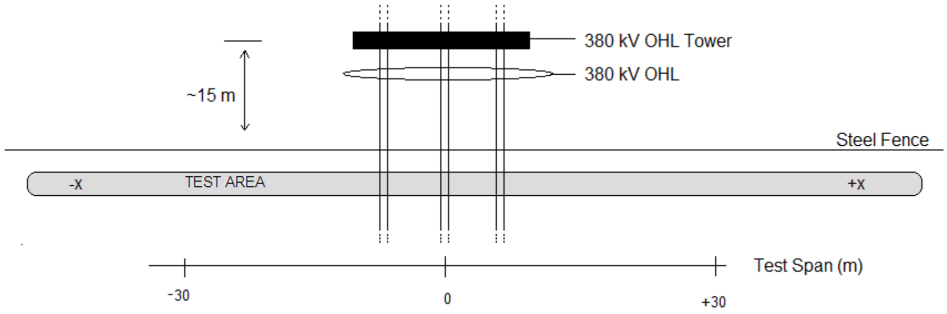


Figure 5.2 Measurement #1 Sketch

Figure 5.3 Measurement #1 Results

A meter reading between 70 uV/m to 140 uV/m was observed during the test. The decrease in the left hand span was sharper than the right hand span. This might be because of the physical location of the spark discharge. The antenna direction alters the reading so highest reading was tried to be read (vertical but with some slight angles). From these measurements it can be said that a radio receiver will be interfered with the existence of the sparks with a value of RN levels in between 36.9 to 42.9 dB above 1 uV/m.

Considering an existence of a radio transmitting radio station which is broadcasting at 1MHz (AM Broadcast) in the test area, the signal-to-noise ratio (SNR) gains importance. The signal strength of the radio station should be more than the found RN levels in order to have a quality of transmitting.

Due to nature of the noise meter, it is expected that the conductor corona has no contribution to this levels. The spark noise is the main factor for this meter reading because of its strength when compared to conductor corona. This test resulted in the powerful characteristic of sparks when compared to corona.

5.1.2 Measurement #2

The measurement data;

- Location #2 : 39°48'26.82"N and 32°48'20.75"E
- Temperature : 6 ^{o}C
- Pressure : 1008 hPA
- Weather Condition : Rain and Light Fog
- Altitude : 994 m
- RN Meter Center Freq. : 1 MHz
- QP Constants : 1ms charge and 600 ms discharge
- Antenna : A monopole rod antenna

Conductor corona tends to increase in foggy and rainy weather. Several trials have been done in different locations when the weather is fair. No corona reading could be taken from those locations. The measurement was done when the corona sound is heard in a foggy and rainy weather. The area chosen for measurement was an empty area. Any obstacle between the antenna and the line might affect the readings. The midspan of the two 380 kV OHL towers which are the elements of the 380 kV EHV feed line going from GÖLBAŞI 380/154/34.5 kV Substation to Sincan Substation is used as the start point. Two different measurement spans were done. The first is along a line parallel to the transmission line and along the line that is perpendicular to the transmission line (both sides).

Also, the environment should be clear of any other radio interference like spark type discharges. There was no spark type noise observed in the vicinity of the test. There were no electrical apparatus like disconnector, transformer, etc. close to the measurement location.

The measurement location is given below.

Figure 5.4 Location of Measurement#2 (Courtesy of Google Inc.)

The observed measurements are given below.

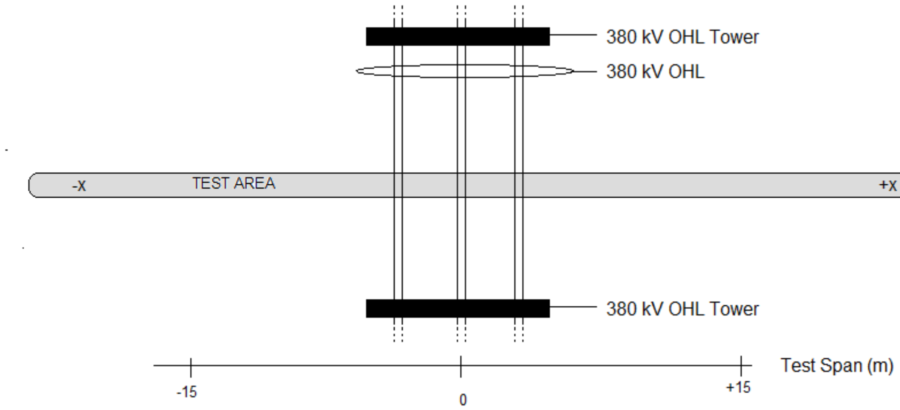


Figure 5.5 Measurement #2 Sketch

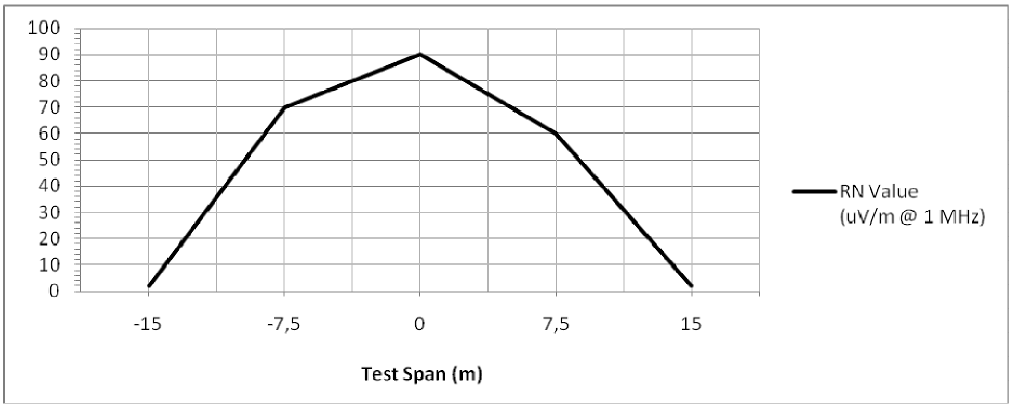


Figure 5.6 Measurement #2 Results

Very low level of corona has been observed during the measurements. The test performed perpendicular to the both sides of the OHL. The weak radio interference tends to disappear since the electrical field intensity decreases in proportion to square of the distance. The most powerful reading was taken below the center line as expected. During the transition from center line to the side lines a slight level reduce was observed. Going a bit far the level reduced very quickly due to inverse square proportion to distance. After 15 m from the center line, no readings could be taken.

So, the RN levels for the line are;

- RN = 39.08 dB above 1 uV/m at d=0,
- RN = 36.90 dB above 1 uV/m at d= -7.5 m (left side),
- RN = 35.56 dB above 1 uV/m at d= +7.5 m (right side),
- RN = 0 dB above 1 uV/m at d= -15 m (left side),
- RN = 0 dB above 1 uV/m at d= +15 m (right side).

Also, the level of corona through the direct under of the line (d=0 and going along the line) did not change as expected. It was measured in between 80-90 uV/m.

5.1.3 Measurement #3

Increasing the number of tests is so crucial that the corona noise has a random feature. So, another test has been achieved at test Location #1 in a different day. The measured data as follows:

- Location #1 : 39°48'16.82"N and 32°48'51.69"E
- Temperature : 11 ^{o}C
- Pressure : 1018 hPA
- Weather Condition : Heavy Rain
- Altitude : 985 m
- RN Meter Center Freq. : 1 MHz
- QP Constants : 1ms charge and 600 ms discharge
- Antenna : A monopole rod antenna

As given in Measurement #1, the Location #1 has a spark noises generated and heard from nearby the tower. Measurement #3 was intended to be achieved in a heavy rainy day that it might lead an increase in noise levels. The measurement held immediate after the rain stopped. The sound of corona and the gap-type discharge were heard again. The spark type noise still existed. There were no visual observations of the sparks. This measurement led most powerful result and the noise levels diminished at around 40-45 m from the tower. The location of the measurement is given below (same location with Measurement #1).

Figure 5.7 Location of Measurement #3 (Courtesy of Google Inc.)

The results were tried to be taken at more locations. The meter output table is given below.

Table 5.1 Measurement #3 Results

Test Span (m)	**RN Meter Reading (uV/m)**	**RN Meter Reading (dB above 1uV/m @1Mhz)**
-45	0	0
-40	30	29.54
-30	50	33.97
-20	110	40.82
-10	140	42.92
0	270	48.62
10	250	47.95
20	210	46.44
30	140	42.92
40	110	40.82
45	70	36.90
60	0	0

It should be noted that the distance taken is the lateral distance along the test span. This is not the actual distance between source and the receiver. All interference measurements are held according to measured location. The importance of the interference is the effect of its interfering power at a distant and known location so the interfering signal strength at a distance is important. The source interfering power can be calculated theoretically. This might give wrong results because the signal coming from the source can also be interfered with ground reflections or another obstacle. As the standards impose, the measurements are important for the received location. If an AM radio transmitter placed a nearby a transmission line, the noise level on the transmission line is not important but the level on the transmitter antenna. So that, the lateral distance basis are required by standards in this way. The actual distance can be found as follows. Taking tower height as h, test point as B, and the distance of mid point of tower base to the test point (B) as A, the actual distance is the hypotenuse of h and hypotenuse of A and B. This is the three dimensional diagonal hypotenuse.

The observed measurements are given below.

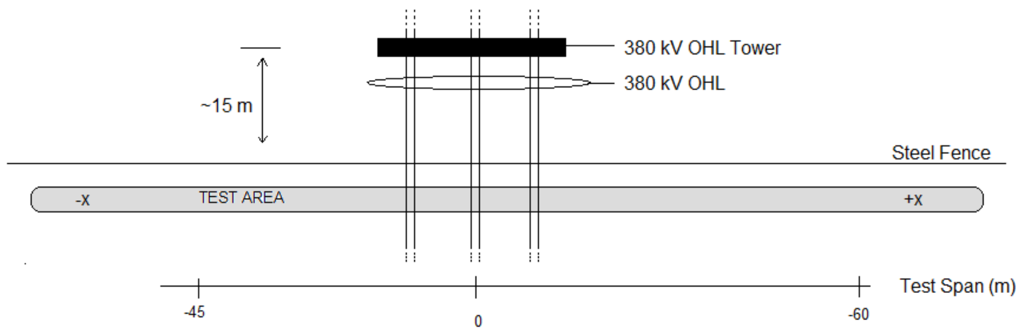


Figure 5.8 Measurement #3 Sketch

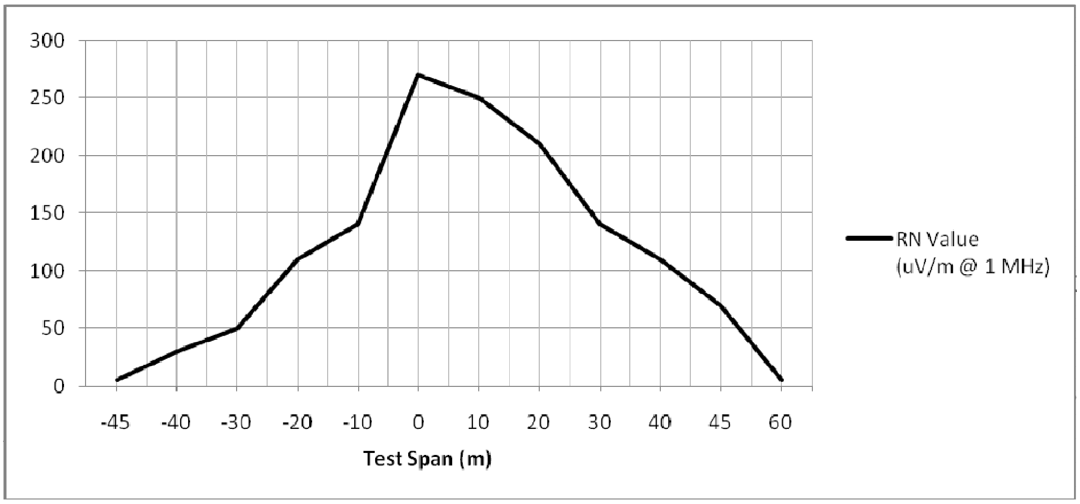


Figure 5.9 Measurement #3 Results

5.1.4 Measurement #4

The measurement data;

- Location #2 : 39°48'26.82"N and 32°48'20.75"E
- Temperature : 11 ^{o}C
- Pressure : 1018 hPA
- Weather Condition : Heavy Rain
- Altitude : 994 m
- RN Meter Center Freq. : 1 MHz
- QP Constants : 1ms charge and 600 ms discharge
- Antenna : A monopole rod antenna

As given in Measurement #2, the Location #2 was performing readable corona levels in the foul weather. Measurement #4 is intended to be achieved in a heavy rainy day that it might lead an increase in corona noise levels. The measurement held immediate after the rain stopped. The corona noise was observed at the test location. But, there were no corona visual appearance (the test held during daytime).

The test was held perpendicular to transmission line and along the transmission line. Higher corona level readings were taken during the test. The corona strength at each side of the line was almost similar. The line gave powerful corona readings due to heavy rain and moist. And also, the dirty environment (because of highway passing) might lead high corona values. The horizontal distance between the test span and the highway was around 150-170 m. The test span was held in the midspan of the transmission line where the conductor height is at minimum (directly under the line). This was to read better results from the line. But, when the measurements were held along the transmission line slight level difference (around 5-10 uV/m) levels were observed. A reduction in corona level due to conductor height change was expected. A slight reverse proportional decreasing effect because of noise source distance was observed.

The test location is given below (same location with Measurement #2)

Figure 5.10 Location of Measurement #4 (Courtesy of Google Inc.)

The meter readings are given in Table 5.2

Table 5.2 Measurement #4 Results

Test Span (m)	**RN Meter Reading (uV/m)**	**RN Meter Reading (dB above 1uV/m @1Mhz)**
-40	0	0
-35	25	27.95
-30	40	32.04
-25	60	35.56
-20	85	38.58
-15	110	40.82
-10	140	42.92
-5	185	45.34
0	190	45.57
5	185	45.34
10	140	42.92
15	120	41.58
20	100	40.00
25	95	39.55
30	70	36.90
35	55	34.80
40	45	33.06
45	25	27.95
50	0	0

The graphical interpretation of the readings as follows:

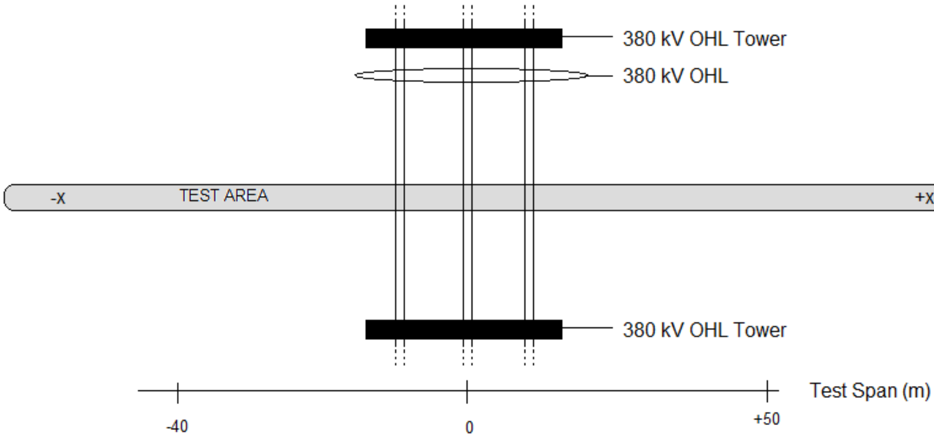


Figure 5.11 Measurement #4 Sketch

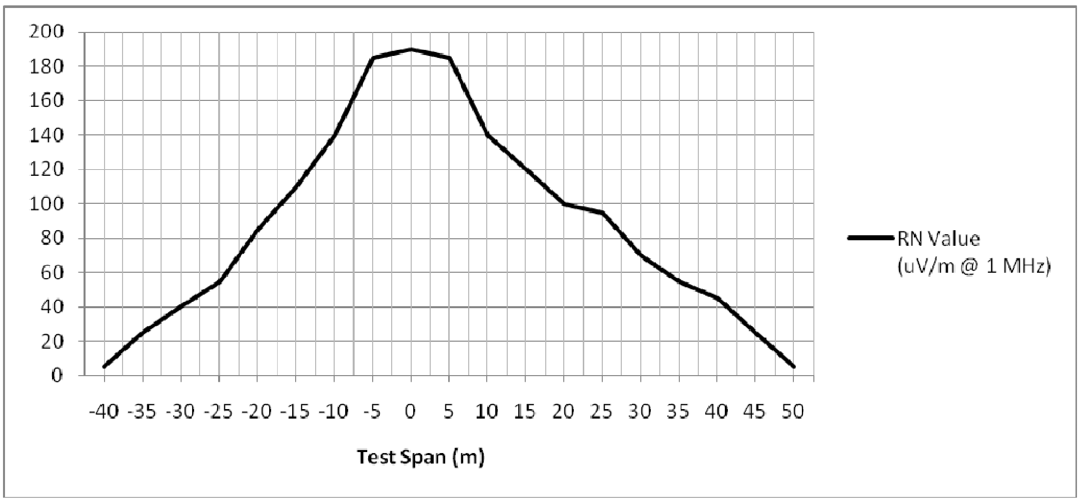


Figure 5.12 Measurement #4 Results

This test showed the best corona reading performance with the RN meter. Nearly 50 dB above 1 uV/m readings were observed at the site. The lateral plots given above are the expected results because the receiver going far away from the source. There were a lot of factors that affects the reading of the meter. These factors will be concluded in Chapter 6.

5.2 Measurement from a Corona Electrode

A test setup which is actually used for partial discharge measurements (PD meter) was used for this measurement. The test setup contains a Faraday Cage, a HV transformer, a HV capacitor, a calibrated corona discharge rod (corona electrode) and a calibrated PD meter. The schematic of the test circuit is given in Figure 5.13.

A HV transformer is used for producing HV for the system. The transformer has turns ratio of 1:227 which gives 50 kV output voltage when 220 VAC is applied. A HV voltage divider is used to read the HV level of the setup. So, the voltmeter reads the HV level.

A partial discharge measurement which is held according to IEC 60270 is aiming to measure harmful characteristics of partial discharges. Partial discharges age the insulation of a HV apparatus so it should be measured sensitively. The IEC 60270 offers the correlation of PD measurements with the quantity of apparent charge, so PD measurements according to IEC 60270 is expressed in pC. Also, a test setup is defined accordingly. A coupling capacitor is used to find the pC value in the test setup. A coupling capacitor of 1064 pF was used in this measurement. Coupling capacitor enables to convert the voltage value in to the charge according to below formula;

$$e = q / c \qquad (5.1)$$

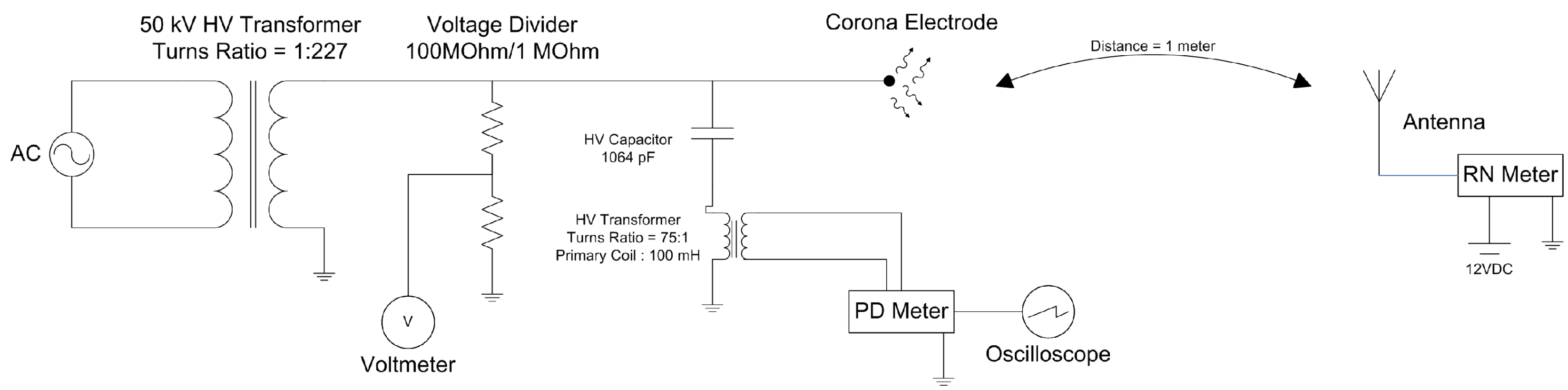


Figure 5.13 PD Measurement Setup for RN Meter Test

where;

q is the apparent charge in coulombs,

c is the capacity of the capacitor, in farads,

e is the voltage at the terminal of the capacitor, in volts.

By means of this capacitor, the PD activity was converted into voltage and became a readable voltage signal at the input of the PD meter.

A corona electrode that has known characteristics was used to produce corona (so the partial discharge). One of the characteristic of the corona electrode was the “Corona Inception Voltage (CIV)”. The CIV is the lowest value of the applied voltage that starts the known amplitude of “continuous” corona pulses. Even though the corona is random in nature, the controlled corona can be used to calibrate some HV apparatus due to its stable characteristics.

An oscilloscope was used to visually observe the amplitude and the rate of corona pulses.

The RN meter’s antenna placed 1 meter apart from the tip of the corona electrode.

The measurements gave some readings that are not linear with the pC levels of the PD meter. The measurements yielded below comments:

- The PD meter measures the charge of a corona pulse (“the current-time integral of a pulse” or “pulse area”) because the instant discharge of the pulse forms the PD activity. That is what harms a HV apparatus. But, the RN meter measures the charge (the pulse area) of the pulses with the pulse repetition (pulse weighing). If there is a single corona pulse with each cycle of power frequency (that is 50 Hz), there may be correlation between the reading of the PD Meter (pC) and the RN meter (uV/m). As the voltage increases, the PD meter and RN meter measuring mechanism yielded different results.

- During the measurement, the response of RN meter to the corona pulses was clearly observed. When the corona pulses went high in amplitude and the pulse repetition frequency increased (due to voltage increase) the RN meter readings responded as an increase.
- For a single corona pulse the PD meter reading was around 25 pC. At that point, the RN meter reading was around 5-10 uV/m. This situation is accepted as normal for a single corona pulse because of lossy network in between. For multiple corona pulses at higher voltage levels gave RN readings of 150 to 200 uV/m while the PD meter reading at around 60-80 pC. This was a result of increase in pulse repetitions as well as the corona pulse area (due to amplitude increase).
- The correlation in between pC and uV is an extensively studied subject for years. A number of papers were released on the subject. There are major factors affecting the correlation of these expressions. One useful paper given as reference [8] can be accessed for further reading.

The measurement was helpful to understand the response of the RN meter to intentionally made corona pulses. So, the theoretical design constraints that are defined by standards (according to nature of corona pulses and measuring mechanisms) were observed in practical. Corona mechanism response of RN meter was observed with the help of PD meter setup. Visual feedbacks of the oscilloscope were analyzed.

5.3 Pictures from Site Measurements

Figure 5.14 A Site Measurement Picture

Figure 5.15 A Picture from Location #1

Figure 5.16 A Picture from Location #2

CHAPTER 6

CONCLUSIONS

The main focus of thesis is to interpret corona in measurable quantities. Corona as a radio interference source brings some disadvantages when we think of a quality basis for electrical and wireless transmission.

The quality of transmission lines from the aspect of corona can be divided in to two main factors. The first is the power loss contribution of corona. As it is discussed in Chapter 2, corona results in power loss. This loss is unwanted since we loose the generated power. Global energy awareness leads into more strict power consumption and effective usage of electricity. If the power is lost by corona, some precautions should be taken. The author offers a comprehensive analysis of corona power loss for the Turkey's National Electricity Transmission Grid. The levels of corona loss, the statistical calculations should be made. These calculations should be done in scope of a legislative RN limit. So, all of Turkey's power lines may be healed according to corona power loss levels (as far as line and conductor renewal investments are economical). To do this, the realized RN meter in the scope of this thesis can be used. Further modifications on the RN meter might be needed for this comprehensive analysis. A regulation on the power loss of corona should be defined to limit the maximum loss due to corona. Although the transmission line designs are held to eliminate corona at fair weather, corona may appear due to some physical non-uniformity (due to dirt may be) on the line. For our measurements held in Gölbaşı, it has been observed that the corona in fair weather was at minimum as expected. When the weather goes to foul, the corona tends to increase which is of course an expected result. This condition should be limited to an extent that shall be defined with regulations for Turkey.

The other quality aspect of the corona is the generated RN. This RN occurrence should also be cured. The RN from the transmission line interferes with broadcast stations as well as other critical communication network of the country. The RN interferes with amateur radio bands, HF military radios as well as AM Broadcast Bands.

Amateur radio bands are very important because this network is formed with volunteer people and they are the alternative communication network in any case of disaster in the country. These amateur radios are widely used in occurrences of flood, earthquake and etc. In 1999 Gölcük earthquake, the amateur radios were widely used to share information vice versa. The SNR ratio of these radios is also affected with RN produced noises. The lower the RN, the better the RF transmission or reception.

HF military radios are the equipments that have no alternatives. They use HF frequency bands with AM SSB modulation technique. Due to these characteristics, they are highly vulnerable to RN noise. HF radios are able to transmit as far as 5000 km or more. They work with wave reflection characteristic of HF frequency. So, no line of sight connection is needed. Due its reflective characteristic, the HF signal can interfere with ground mounted transmission lines. During war-time some countries produces HF noise to diminish the HF performance of other country. The RN noise immune satellite phones can not be trusted as a major communication device because of security and reliability reasons. So, a country’s communication infrastructure is as important as a country’s transmission lines. These national assets should be used in harmony and regarding limits should be studied and released.

The author offers 57.5 dB above 1 uV/m @ 1MHz at 15 meters (which is 750 uV/m) as an RN limit for the transmission lines of Turkey. This clause is accepted by major counties in the world and some design papers are also impose this value as given in previous chapters. The 15 meter is the lateral distance (accepting the point below the middle conductor as d=0) from the nearest conductor. The measurements held in Gölbaşı, gave low corona levels when compared to above offered RN limits. A comparison of measured and the offered levels are given in Table 6.1.

Table 6.1 Percentage Comparison of Gölbaşı Measurements with Offered RN Limit

Measurement #	The RN value @ 15 m (uV/m)	Offered Highest Limit (uV/m)	Measured to Offered Percentage	Remarks
1	130	750	17.3%	Gap-Type RN
2	0	750	0%	Corona RN
3	220	750	29.3%	Gap-Type RN
4	120	750	16.0%	Corona RN

As the table imposes, the highest reading for Gap-Type spark was at %30 percent of offered limit and the highest reading corona noise was at

16% of offered limit. This shows that the transmission line that that used for our calculation has good corona performance even in foul weather. This also means of a low level of corona power loss. But, these tests should be done for all of transmission lines in Turkey. As a start, the 154 kV and 380 kV transmission lines which are likely to produce corona should be investigated by starting from the locations that those lines pass through the cities. The rural area calculations may follow.

The RN measurements may come into front because of EU Compliance Laws. As it is discussed in Chapter 3, the corona is treated as pollution from the view of Environmental Impact. The reports that are submitted to Environmental Impact Assessment and Planning Directorate (EIA) of the Ministry of Environment and Forestry contain corona impact as a pollution source. But, the RN limits for corona has not been defined, yet. In future, the RN level as an impact to environment is likely to appear and RN meters will be needed for measurement of these impact. This is important as we think of two quality measures of transmission line arising from the corona. If Turkey set the limits, a total healing of the transmission lines (as well as resistive losses) may come up. This healing, as always discussed, is beneficial for our country. The energy is one of the biggest concerns of a country.

The RN meter realized has achieved basic aims of this thesis. Corona measurements from the transmission lines were observed. The response of the meter to corona pulses was analyzed. The readings are based on standards imposed antenna and detection circuitry. And, the main characteristics like center frequency and the bandwidth is chosen accordingly. Since a metering device is major concern some reading uncertainties may occur naturally. These might arise due to operator experience (reading resolution of measured data), deviation of circuit components due to temperature change (amplifier and detector circuit stability), antenna polarization errors (should be straight up always), circuit internal noise, etc. These all uncertainties are common for measuring equipments but their effects are very less when proper measurement procedures are applied. Their effects can be taken into consideration only for more precise calculations.

The RN meter realized can also be used for other interferences that have powerful frequency spectrum containing 1 MHz. This means a sharp rise time for interfering sources. By this means, the electric field measurements can be done for other applications.

The RN meter realized can be developed for future works. The first thing can be done is changing the antenna. A loop antenna can be used instead. A loop antenna will measure the magnetic fields which are perpendicular to electric fields. The loop antennas tend to saturate at high levels of magnetic fields so near field calculations are hard to realize. And also, the operator should turn the antenna on its vertical axis to find the maximum interference levels. So, operator experience gains importance. The second development can be done by changing the discharge time of the QP detector and the bandwidth. CISPR QP discharge constant, which is 160 ms, and bandwidth, which is 9 KHz, can be used instead. By this, a comparison for CISPR and ANSI meters can be given at a fixed frequency. The third development can be changing the center frequency of the RN meter. Some measurements can be done at 500 KHz by changing the internal circuitry.

This thesis has roots from four main fields of Electrical and Electronics Engineering. Transmission lines and corona from Power Systems, antennas and broadcasting from Microwave, modulations from Telecommunication and amplifier and detector circuitry from Electronics Engineering are used in the scope of this thesis.

With the realized RN meter, the corona radio noise of any transmission line can be observed and reported as aimed.

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