CHAPTER 2

LITERATURE SURVEY AND THEORIOTICAL ASPECT

2.1 Introduction

There are some subjects and technical papers that are useful for supporting this study. The material of power plant reliability shows an available generator is one of the factors to keep and increase power plant reliability. The materials of generator structure consist of many critical parts and the stator winding is one of the important critical parts that has many troubles occurred during generator operating cause of partial discharge within insulation. The material of other subjects contain about partial discharge phenomena, method of partial discharge measurement, the suitable method of measurement and how to assess condition of insulation using partial discharge data from measurement. Some experienced technical papers give details on many case studies of stator winding insulation deterioration. These papers are used for supporting this thesis to select the suitable method of partial discharge measurement, install some couplers into the appropriate parts and guide to analyse and interpret the measured data.

2.2 Power Plant Reliability

The objective of an electric utility is mainly to provide electrical service to its customers in both economical and reliable manner. However, it is impossible to provide that service with 100% reliability because of random equipment failures. Power system generation involve many components that interact with each other. Some redundant components could be made, but some components are too costly to keep as spare parts.

The reliability of power system generation can be said in term of Probability of an event (failure or non-failure) and measured on scale from 0-1.

Generally, it is defined as: [**1**]

$$P = \text{probability of an event} = \frac{\text{event occurrences}}{\text{Total No. of events}}$$

$$\text{Then :} \quad P\ (\text{failure}) = \frac{\text{No. of failures}}{\text{Total No. of events}}$$

$$\text{or :} \quad P\ (\text{success}) = 1 - P(\text{failure})$$

As mentioned above, power system generation involve many components that interact with each other. The event of failure (or success) is based on two important definitions:

Independent Events: - Each event does not affect each other.

Mutually Exclusive Events: - One event affects other events.

Figure 2.2.1, shown example of a combined-cycle generating unit. The 400 MW combined-cycle unit consist of two 120 MW gas turbines whose exhaust into a heat recovery steam generator.

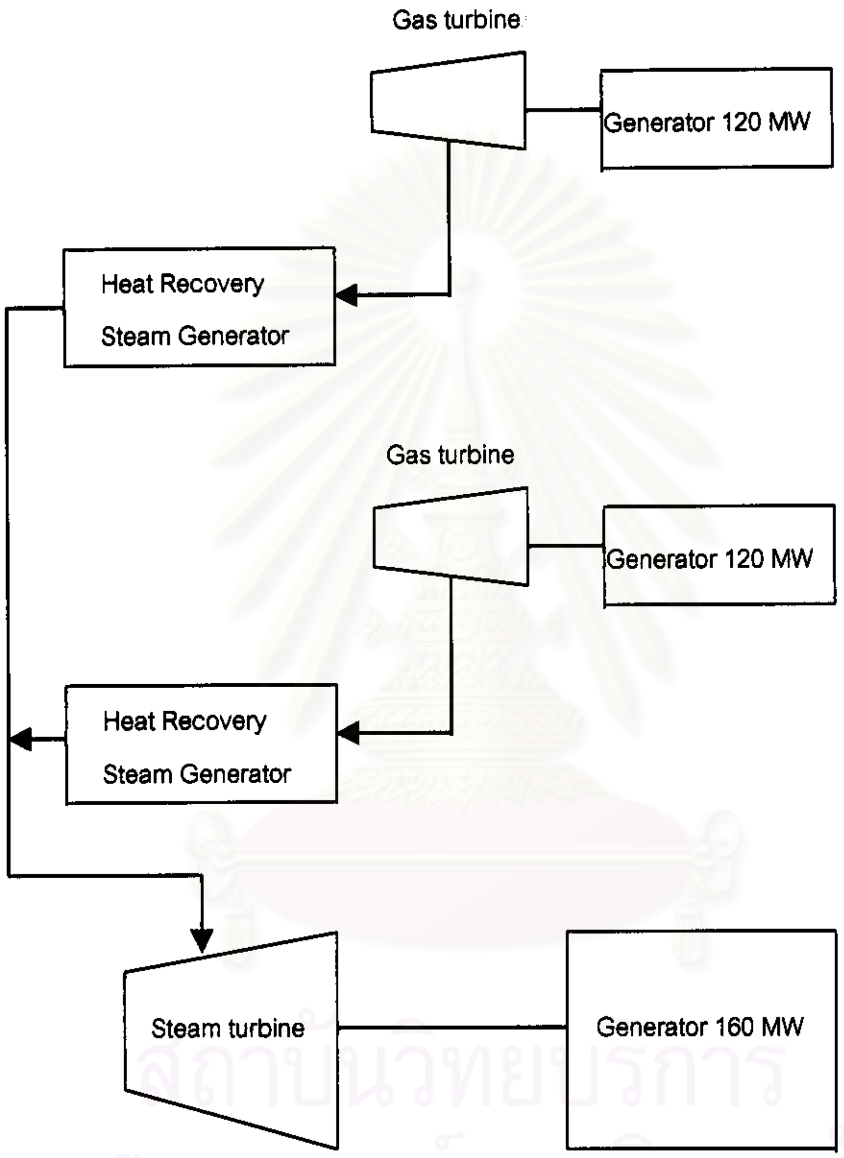


Figure 2.2.1 Combined-cycle Generating Units

In this case, the loss of one gas turbine generator affects directly the steam turbine generator but does not affect another gas turbine generator. The loss of gas turbine in each generating unit of 120 MW affects that generation unit only.

The above illustration shows that each component is important. The reliability of each generating unit depends on each component in that system. Generator is one of the most important components in a generation unit of power system generation. A generator failure can lead to a power system or subsystem failure.

Usually mechanical and electronic components failure depend upon equipment age or duty, and could be shown in the typical 'bathtub" curve as shown in figure 2.2.2

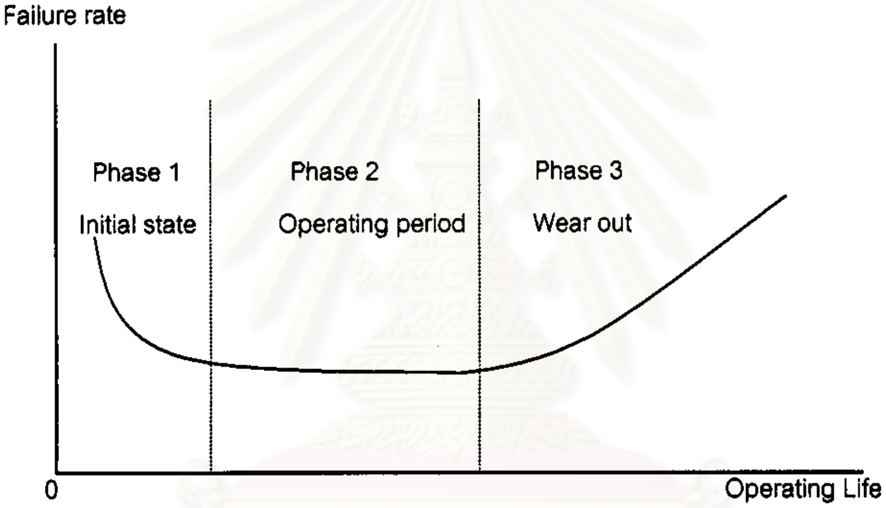


Figure 2.2.2 Typical bathtub curve for mechanical & electronic component [1]

Generator also exhibits the bathtub reliability trend. The low failure rate occurred at the initial state in phase 1 for first several years of operation. Then, the generator operates reliable until its age approaches 30 years in phase 2. After that, the generator enters the state of wear out in phase 3 and has high failure rate. In the same concept above, generic generator consist of many components interact with each other, any critical part failure can lead to generator failure and affect the generating unit reliability. The typical "bathtub" curve of any mechanical and electronic components show that, these components need a proper maintenance program to reduce failure rate.

Concerning a generating unit reliability and availability, a generator has several operating conditions. It can be in service and operating, be available for service and not operating (reserve shut down) or be unavailable for service (on outage). Usually, there are several contributors to outage:

Forced outage:- The event of component failure that requires unit shut down immediately.

Maintenance outage:- The unit shut down from service to perform maintenance work on specific component. This work done to prevent a potential forced outage.

Planned outage:- The unit shut down from service for inspection or general overhaul of major component or equipment groups.
There is systematical procedure and schedule of work.

Forced outage of a generating unit cannot be controlled because of random internal components failure or random external trouble, it is effective to make generating unit unavailable and reduce the whole power system generating reliability. Forced outage cause of internal component failure can be reduced or minimized by maintenance outage or planned outage. However, both maintenance and planned outage need time for doing the works that effect to generating unit unavailable. Reducing time of work lead to increase generating unit available.

Generator is the major component of generating unit that requires shut down for maintenance work. A generator consists of many parts interacting with each other such as stator winding, insulation system and etc. The major parts are stator winding and insulation system that is deteriorated or aging during operation. Using new technology of maintenance should reduce period of maintenance work. New technology help to find out the root cause of defection and monitor the status of the major part of generator, resulting which part need to repair or generator need to outage for correction or extend period of operation if the condition is normal.

All arguments mentioned above, intend to explain how a generating unit is reliable and available, any critical component could affect generating unit reliability and availability. A generator is the major part of generating unit that has many critical parts interacting with each other. New technology of inspection and maintenance could reduce time of work or extend period of operating time as long as possible, resulting high availability.

2.3 Generator Structure

Normally, hydroelectric generator and turbo electric generator have the same basic major structure as stator with stator winding and rotor with rotor field winding. The other parts are different and depend on driver of that generator. Figure 2.3.1 and 2.3.2 show the picture of two types of generator. Some mechanical parts as bearing, shaft, rotor body and stator casing are usually deteriorated due to operating and not the main cause of generator internal force outage. Stator with stator winding and its insulation deterioration are often found to be the main cause of generator internal force outage.

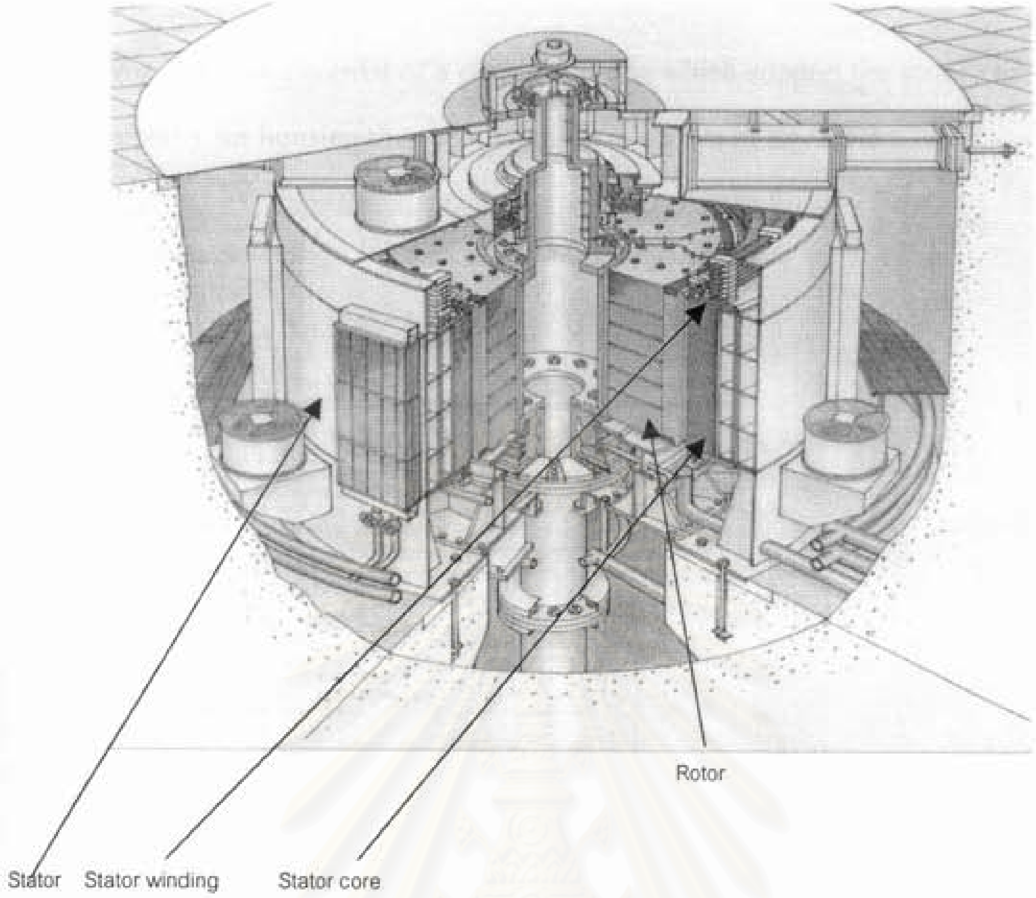


Fig. 2.3.1 Hydroelectric generator(source from Hydro Power Plant, Fuji Electric Co., Ltd.)

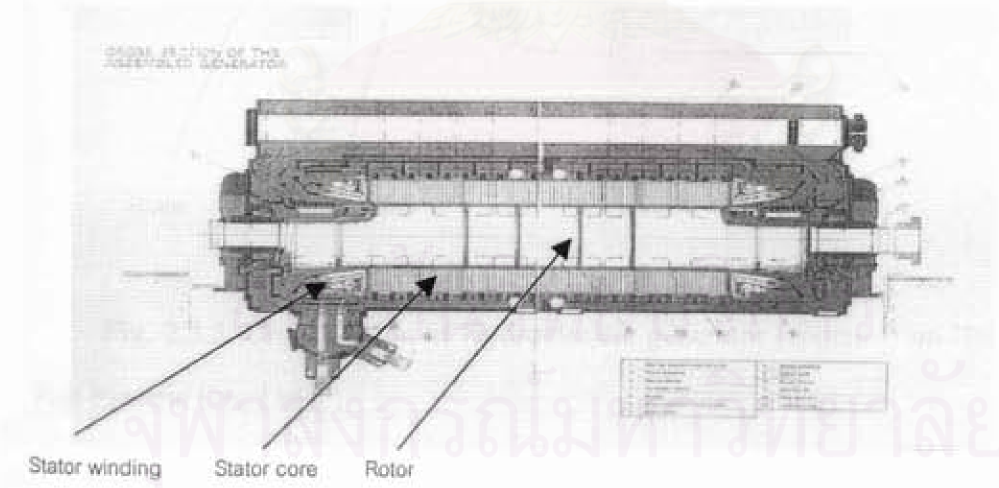


Fig. 2.3.2 Turbo-electric generator (source from Ratchaburi Power Plant, EGAT)

2.31 ***Stator*** The stator consist of a cast-iron frame which support the stator core having slot on its periphery for housing the stator winding as shown in fig. 2.3.3

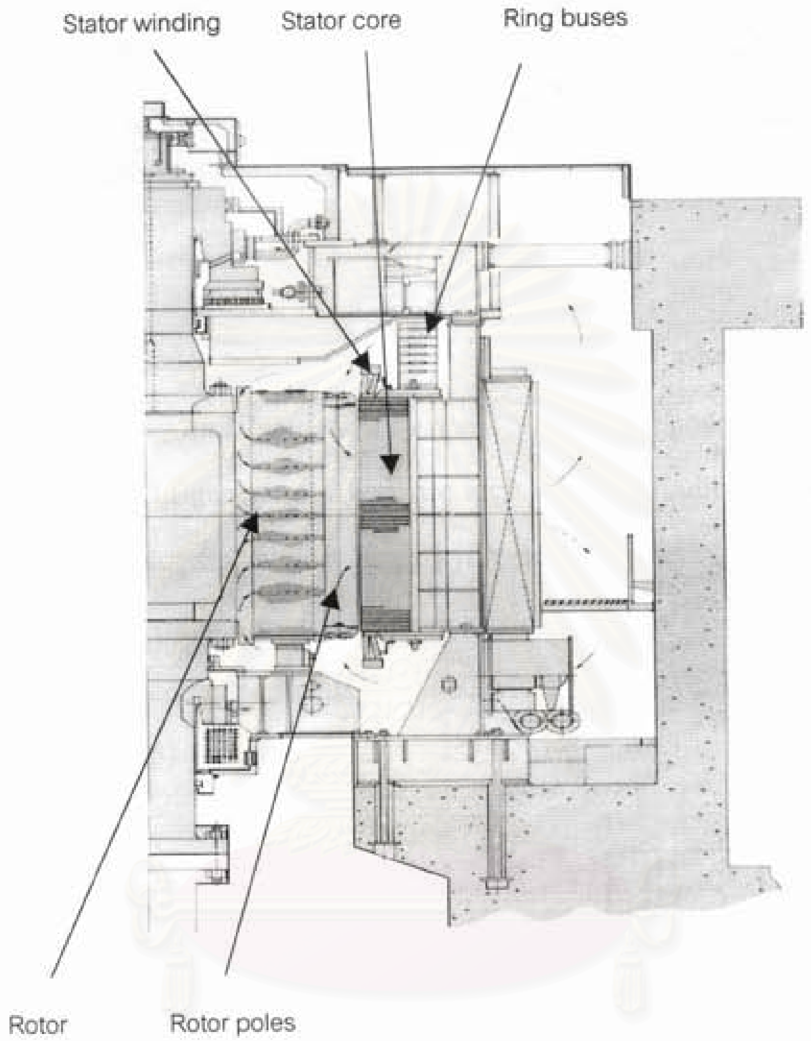


Fig. 2.3.3 Cross section of Hydroelectric generator (source from Hydro Power Plant, Fuji Electric Co., Ltd.)

The stator frame and the stator core : The stator frame is build of annular plates in order to absorb the radial forces from the stator core. The stator core consist of many laminate iron sheets which have insulation coated one or both side of them for elimination of eddy current during operating. These laminations are compressed between clamping plates by the use of axial through-bolts.(see fig. 2.3.4 and 2..3.5)

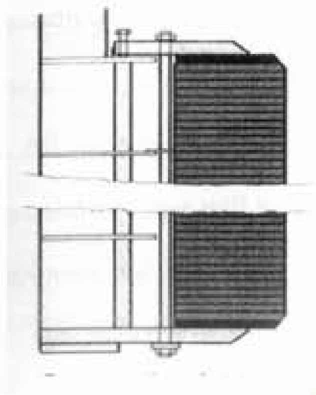


Fig.2.3.4 Stator core

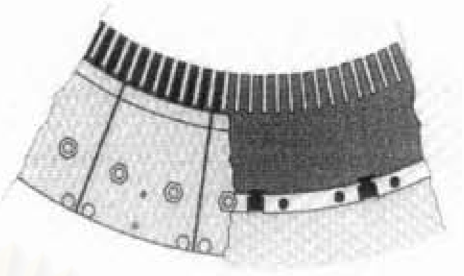


Fig.2.3.5 Stator Laminated sheet

Stator winding and Insulation system : These components could be said to be the critical component of generator. There are high voltage winding and low voltage winding for generic generator but almost large hydroelectric generators have only high voltage winding. The high voltage winding is normally designed as a double-layer symmetrical lap winding. The coils comprise stands insulated with epoxy or varnish impregnated glass fiber. (shown in Fig. 2.3.6)

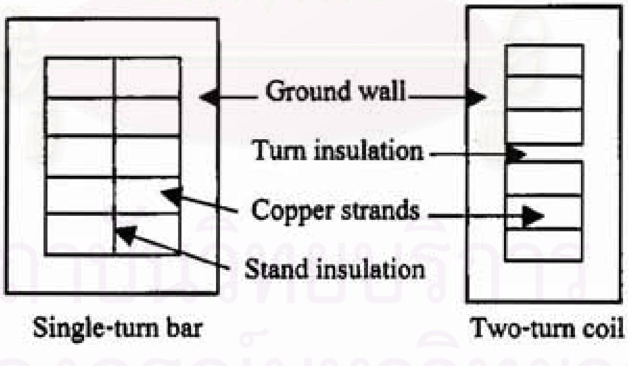


Fig.2.3.6 Cross section of generator stator winding

The coils are normally transposed according to the Roebel principle and are brazed at each end. However, in some cases, multi-turn coils are used. All inter connections are brazed for assuring good connection. Many kinds of insulation material are used as the main insulation system. Generally thermolastic is used as the main insulation system for most of hydroelectric generators. The main insulation system must have good electrical, thermal and physical properties in order to isolate all strands from ground, resist to temperature and vibration during operating. Generally base insulation materials are flecked mica with fiber glass backing and bond with several impregnated resin as epoxy resin, polyester resin and etc. All main insulation must have not any void inside. If there are some voids inside. The internal discharge will be occurred within the main insulation during operating and cause to deteriorate the insulation.

2.32 ***Rotor*** : The rotor consists of shaft, hub, rotor ring and poles (Fig.2.3.7). Normally large-diameter rotors do not have a continuous shaft, having instead a shaft attached to the rotor hub by a flanged joint. The poles are build of hot-rolled laminations with good magnetic and mechanical properties and are attached to the rotor rim. The field winding consists of rectangular coils backed together with the aid of the winding insulation. Generally, the winding insulation is made of class B materials. The coils are insulated from the poles by glass-fiber reinforced polyester.

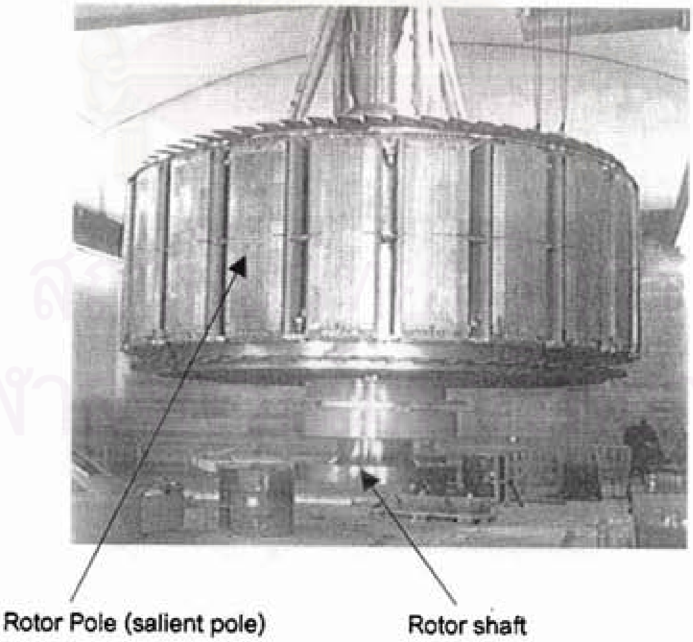


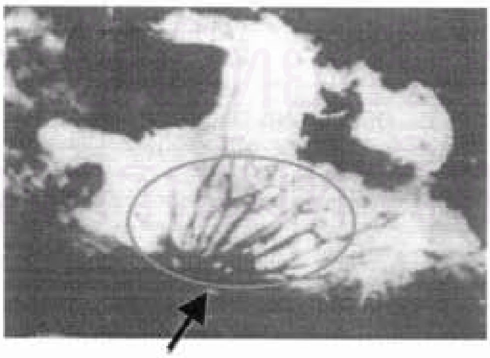
Fig. 2.3.7 Rotor of Hydroelectric Generator (source from Hydro Power Plant, Fuji Electric Co., Ltd.)

All mention above, showing some critical components of generator. Most internal forced outages come from insulation of stator winding failure. Poor main insulation of winding comes from having a lot of voids inside and easy to have internal discharge during operating under high voltage and high temperature.

2.4 Partial discharge within stator winding insulation

2.41 *Partial discharge phenomena*: IEEE. Publication 270, 1981 defined partial discharge that " A partial discharge is an electric discharge that only partially bridges the insulation between conductors. Such discharge may, or may not occur adjacent to a conductor." Partial discharges in gases around a conductor are sometimes referred to as "corona", but should not be applied to other form of partial discharges.

The partial discharges which are considered in generator's insulation system are localized electrical discharges in insulating media, restricted to only a part of the dielectric under applying AC or DC high voltage and only partially bridging the insulation between conductors.



Tree of discharge

Fig. 2.4.1 Partial discharge phenomena occurred within solid insulation

Partial discharges may occur in cavities in solid insulation in gas babbles in liquid insulation or between layers of insulation, which has different dielectric characteristics. They may occur at sharp edges or points of metallic surfaces. Discharges mostly occur in the form of individual pulses, which can be detected and measured as electric pulses. They involve only small amounts of energy that may lead to progressive deterioration of dielectric properties of insulating materials.

2.42 *Partial discharges in Generator* Insulation system of generator stator winding mostly comprise of several materials such as mica flecks, glass fibers, polyester fibers, etc. Each material has its own dielectric property, which is different to each other. As definition of partial discharge at the first stage, partial discharges in stator winding insulation are phenomena that few parts of insulation system become to be conductor but do not effect to the whole system to fail to be insulation. The phenomena could be simplify explained as following:

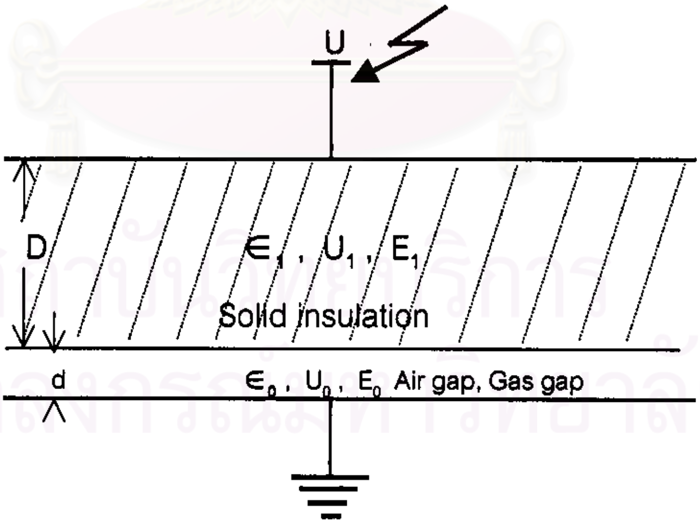


Fig. 2.4.2 Two electrodes, which have solid and air gap inside.

Between two electrodes, which have AC high voltage applied across, there are two layers of insulation materials. One is the solid insulation with D thickness and $\in_1$ permittivity (dielectric property of insulation), an another is air gap with d thickness and $\in_0$ permittivity (see Fig. 2.4.2).

AC voltage distribution can be defined as following:

$$U_1 / U_0 \quad = \quad \in_0 / \in_1 \cdot D / d$$

and

$$E_1 / E_0 \quad = \quad \in_0 / \in_1 \qquad [2]$$

Where:

U_1 = Voltage drops across solid insulation material.

U_0 = Voltage drops across air gap.

$\in_1$ = Permittivity of solid insulation

$\in_0$ = Permittivity of air

E_1 and E_0 = Electric field strength of solid and air respectively.

From above equation, if permittivity of solid material is 5 times of permittivity of air. The voltage drops across air gap " U_0" will be 5 times of voltage drop across solid insulation, and will be more higher if thickness of air gap " d " is very thin. If the voltage U_0 is higher than breakdown strength of air (30 kV / cm), gas will ionize and conduct (discharge). Then the voltage that across air gap will decrease and ionization will stop. After that the voltage U_0 will be increase again and make the gas to ionize. These repetitions still be occurred under applying AC high voltage and generate heat from gas ionization.

Partial discharge within stator winding insulation system occurred cause of imperfection of insulation, poor designed in winding insulation system and winding distribution is not suitable. The area that has dominant partial discharge is the location, which has high voltage different of winding and ground or winding and adjacent winding. There are some dominant partial discharges within stator winding, which deteriorate insulation system and lead to insulation failure. They occur at slot portion, coil-end portion, joint area of slot portion and coil-end portion. Some generators have found partial discharges occurred at the surface of coil-end and jumpers.

Partial discharges occurred at slot portion of generator Partial discharges at slot portion are discharges of gases in air gap and void at some locations as following:

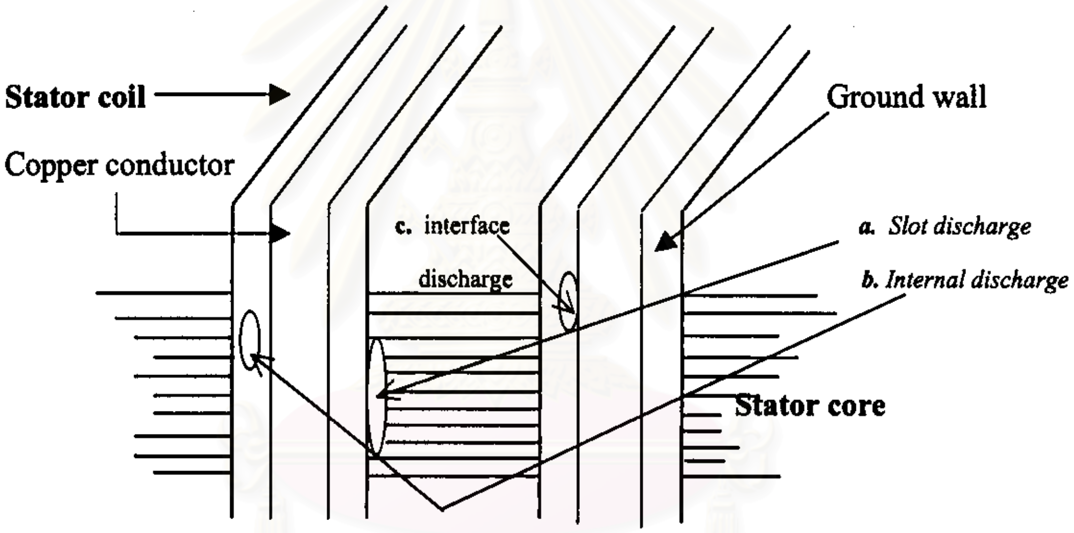


Fig. 2.4.3 Location of partial discharges at slot portion

a. Partial discharges, which occurred between surface of coil and stator core (see Fig. 2.4.3), usually called “slot discharges”. Improper stacking of lamination sheets causes some voids or air gaps occurred between coil and stator core and allowing voltage across the air gap that will be sufficient to breakdown the air, resulting in a partial discharges (slot discharges).

b. Partial discharge within internal main ground wall insulation of coil (bar) usually called " internal ground wall discharges". Voids in the ground wall could be created by poor impregnation of the bonding varnish or resin during manufacture or other aging mechanism, usually related to thermal cycling during operation. That cause delaminating of insulation layers (see Fig. 2.4.3 - *b*). The voltage across these voids occurred and will be sufficient to breakdown the voids (air), resulting internal discharges.

c. Partial discharge at conductor surfaces Usually called "copper insulation interface discharge". Some voids can occur in the region between the ground wall insulation and conductor stand insulation (see fig.2.4.3 – *c*). These are the spaces created by stand fillets in all types of coil and not adequately filled during manufacturing by impregnating varnishes or resins. Voids can also be created during operating by thermal cycling, which may cause the copper conductors to separate from the ground wall insulation. Partial discharge induced in these voids occurred as the same cause of internal discharge and slot discharge.

Partial discharges at the joint area between slot portion and coil-end portion, which have their high potential voltage and high electric field strength.(see Fig. 2.4.4)

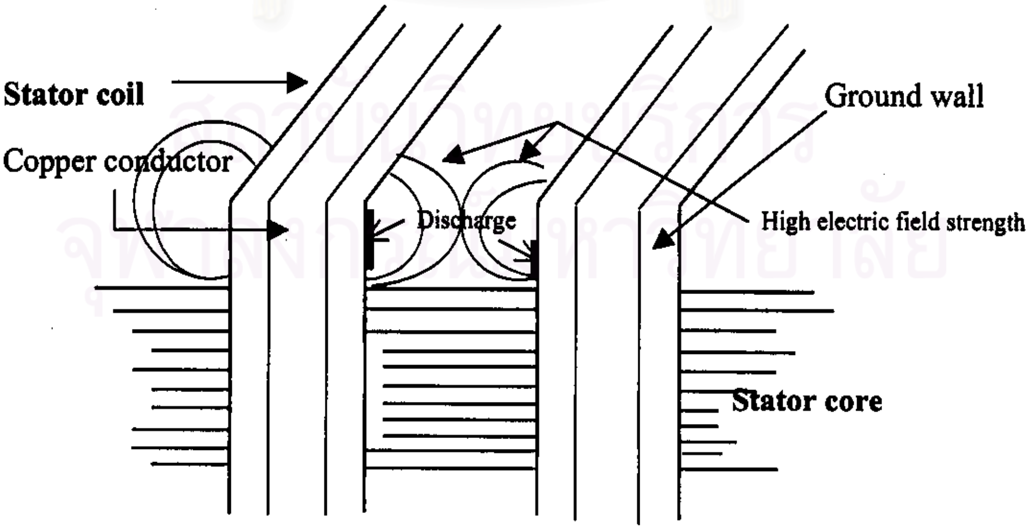


Fig. 2.4.4 High electric field strength yields to generate partial discharges around surface of coil at the end of slot portion.

By electromagnetic theory, Potential strength at any edge of part of metal always very high and any part of insulation material which far from ground will has equal potential to the conductor [2]. Then, air around that area will be breakdown and deteriorate the surface of coil at that area. Usually, there is conducting paint applied to the surface of coil at the slot portion and applied high resistance paint at the surface of coil at end part of slot portion for protection that phenomena.

d. Partial discharges between coil-end and jumper

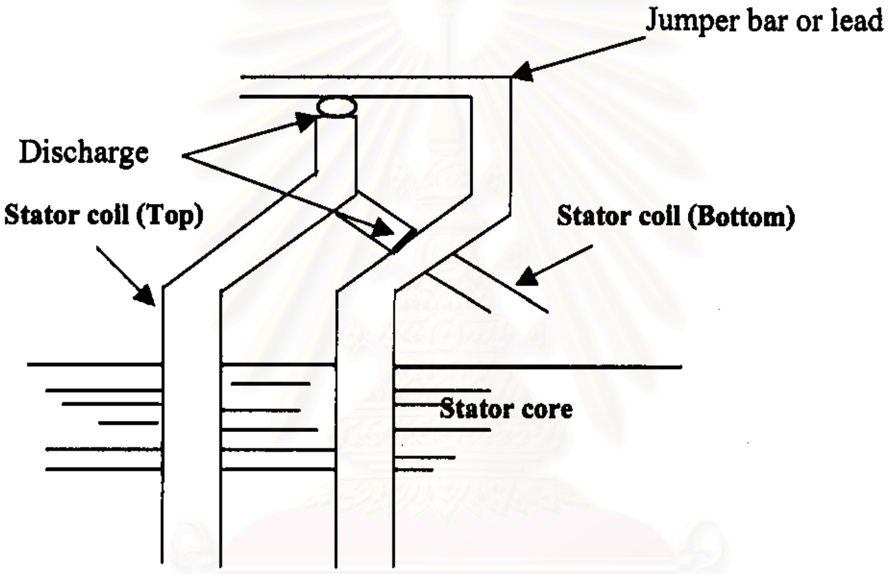


Fig. 2.4.5 Partial discharges around coil - end and jumper

Some generator have improper winding configuration that have narrow gap between end cap of coil and jumper lead which has high potential voltage, or between coil-end and that jumper and causing discharges at those area.

2.5 Method of Partial discharge measurement

Generally, there are two type of partial discharge measurement, off line and on line partial discharge measurement on generator

2.51 ***Off line partial discharge measurement on generator:*** The off line measurement of partial discharge at standstill has the advantage that tests can be performed relatively quickly under defined conditions. Disconnection from the power system and absence of electromagnetic disturbances generated during operation (e.g., static excitation) permits useful measurement to be carried out with relative simply apparatus. Under IEEE standard Publication 270 of Partial discharge Measurements, definition, method of measurement and circuit measurement can be described below:

Partial discharge is an electric discharge that only bridges the insulation between conductors. Such discharges may or may not, occur adjacent to a conductor. Partial discharge occurring in any test may be characterized by different measurable quantity such as charge, repetition rate and etc.

Charge (q) of a partial discharge is that charge which, if injected instantaneously between the terminal of the test object, would momentarily change the voltage between its terminal by the same amount as the partial discharge itself. The charge is expressed in picocoulombs (pC).

Repetition rate (n) The partial discharge pulse repetition rate (n) is the average number of partial discharge pulses per second measured over a selected time.

Measuring circuit Partial discharge are electrical sparks which occur in gas voids within the insulation when the voltage is high enough. The spark is a fast current pulse, which travels through the stator winding. The larger the partial discharge pulse, the higher is the current pulse (also voltage pulse) that reaches the terminals of the winding. To measurement these pulses, a high voltage capacitor is used to block the power frequency voltage and allow the high frequency pulse signal to reach a partial discharge detector (usually, high frequency oscilloscope instrument). The measurement circuit is shown in Fig. 2.5.1

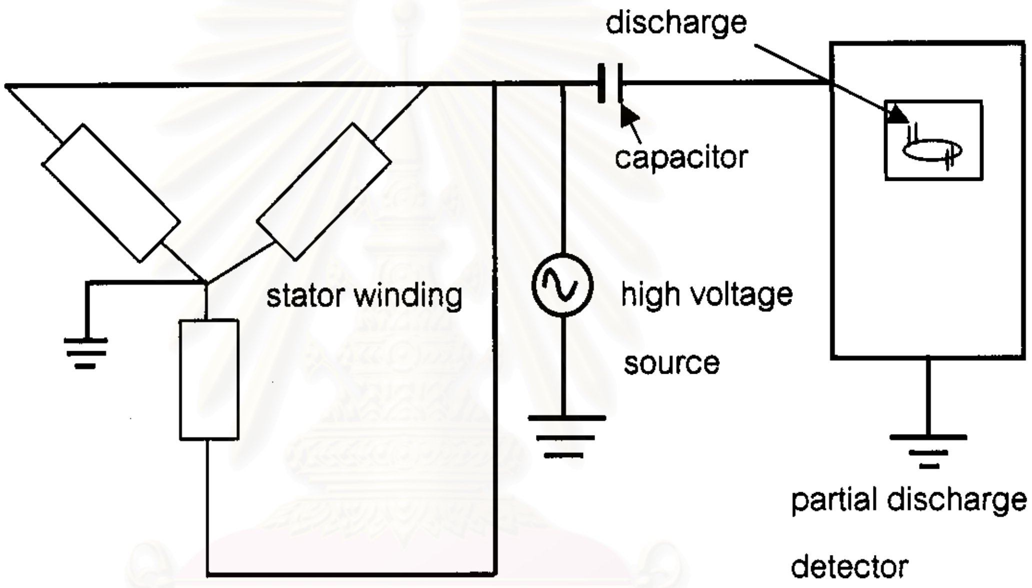


Fig. 2.5.1 Simple circuit measurement of partial discharge on standstill generator

The partial discharge pulse signals are displayed on an oscilloscope screen. The pulse magnitudes are measured in millivolts (mV), it is conventional to calibrate the pulse magnitudes in term of picocoulombs (pC). In the off line conventional test, the winding must be energized to normal voltage with a separate voltage supply to start partial discharge occurring. In this test condition, interference from high frequency electrical noise is at a minimum. The conventional test requires isolation of the winding from ground and AC high voltage source is energized to at least one phase winding to rated line to ground voltage. On generators, this test is normally done on each phase with the other two grounded, which requires that the phases be disconnected from one anther at the neutral.

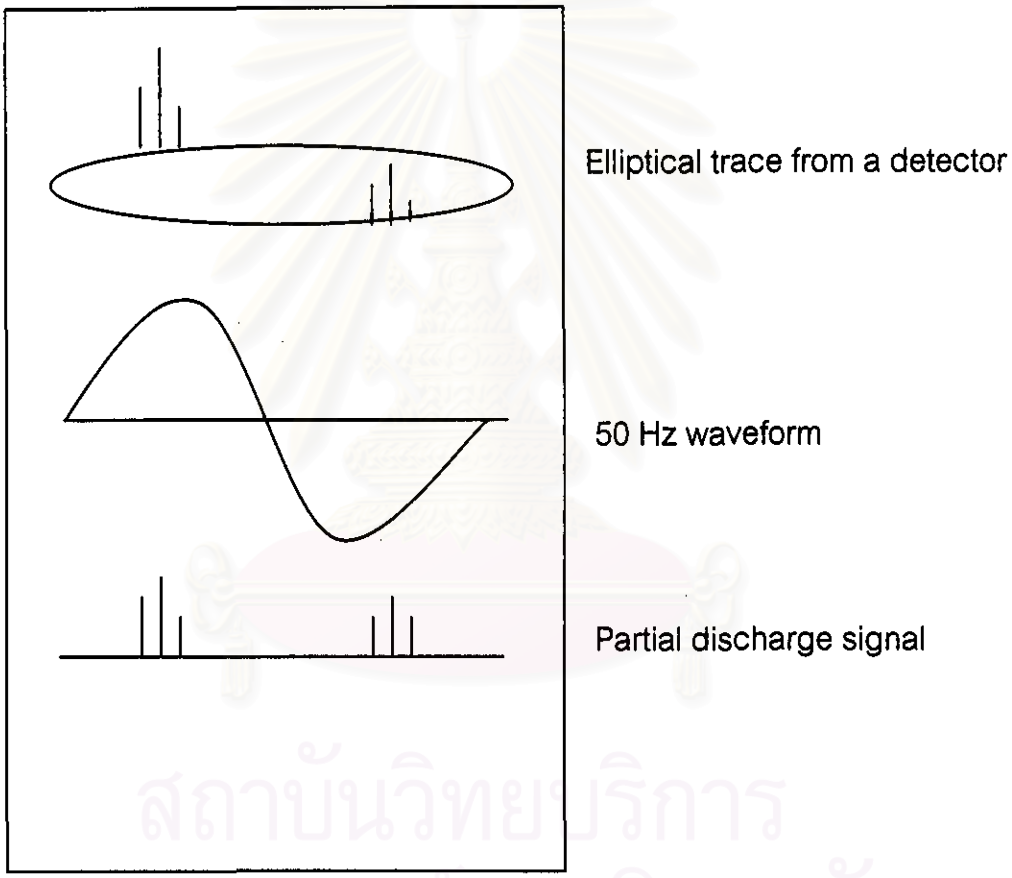


Fig. 2.5.2 Display from conventional dual – channel oscilloscope

Partial discharge pulse may be observed directly on the oscilloscope display and pulse data may be processed by a pulse height analyzer to yield pulse counts, pulse magnitudes, comparisons of positive and negative pulses, etc. The usual test procedure is to gradually raise the AC voltage until partial discharge pulses are observed on the oscilloscope screen.

The voltage at which partial discharge pulse starts is noted, is called the discharge inception voltage. When the test voltage reaches normal rated voltage, the highest partial discharge pulse magnitude is then read from the screen and recording shall be done. As the test voltage is decreased, at the voltage which, partial discharge pulse disappear is called discharge extinction voltage.

2.52 *On line partial discharge measurement on generator* Most utilities, partial discharge testing is conducted with the generator shut down. An external AC high voltage supply energizes the winding for measuring procedure. Although this form of partial discharge test is useful in determining whether problems are occurring, it does has its advantages. Of most concern to utilities is that the test requires at least a one day outage. Another major disadvantage of the off line test is that, since certain types of discharges may not occur when the generator is not operating, some types of insulation problems may go undetected. In particular, Vibration and heat do not on the stator winding when generator is shut down. Although the slot discharge which are the major cause of insulation problems may be noted reliably detected. Also end-winding discharges may not occur in off line tests, because the three-phase voltage distribution is not normally simulated as operating status. As disadvantages of off line partial discharge tests, the on line partial discharge test for use in large generator is developed. The Ontario Hydro Research Division (Ontario Hydro, Toronto, Canada) initiated developing on line partial discharge test for hydroelectric generator. The concept design of measurement method is very useful and there are many utilities and generator manufacture companies bring this concept to develop by themselves for measurement and maintenance.

2.53 *Method of test and measurement circuit* There are many types of on line partial discharge test. All of them use the same concept that, using sensors attached with insulation bar or nearest to pick up partial discharge signal and sent to measuring unit. The basic circuit measuring is shown in fig. 2.5.3

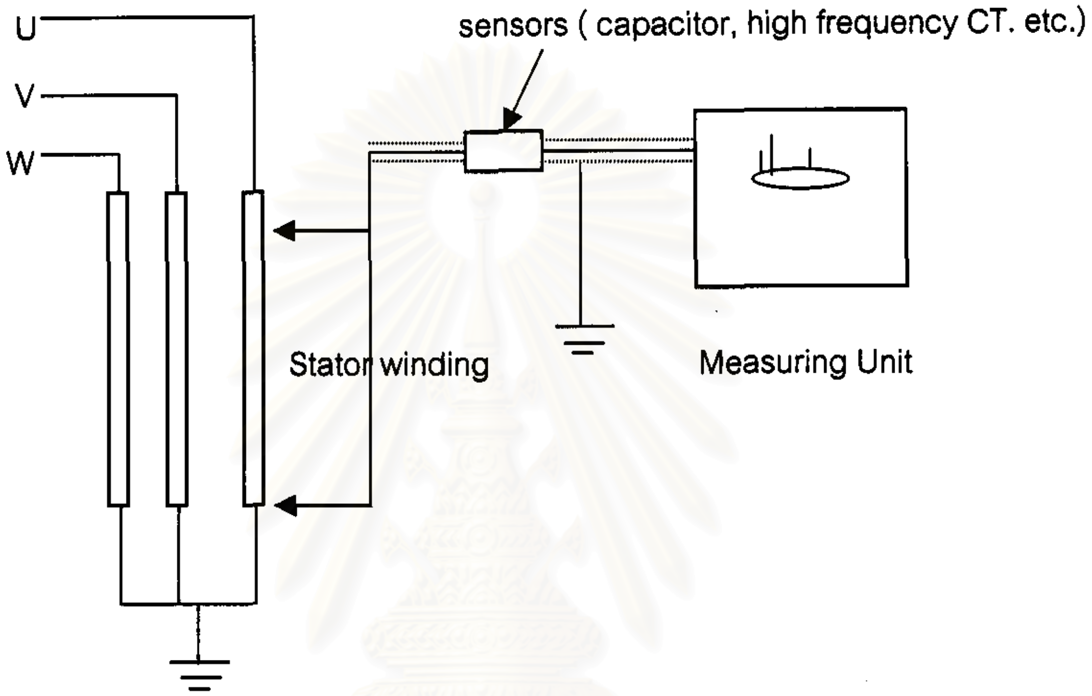


Fig. 2.5.3 On line partial discharge test on generator

In order to achieve true pulse of partial discharge occurred within stator winding during operation. Ontario Hydro studied and developed method of measurement by using 80 pF high voltage coupling capacitor as the sensor [3], these couplers are attached to stator winding at the stator bar which near terminal or lead of stator winding, as shown in Fig. 2.5.4

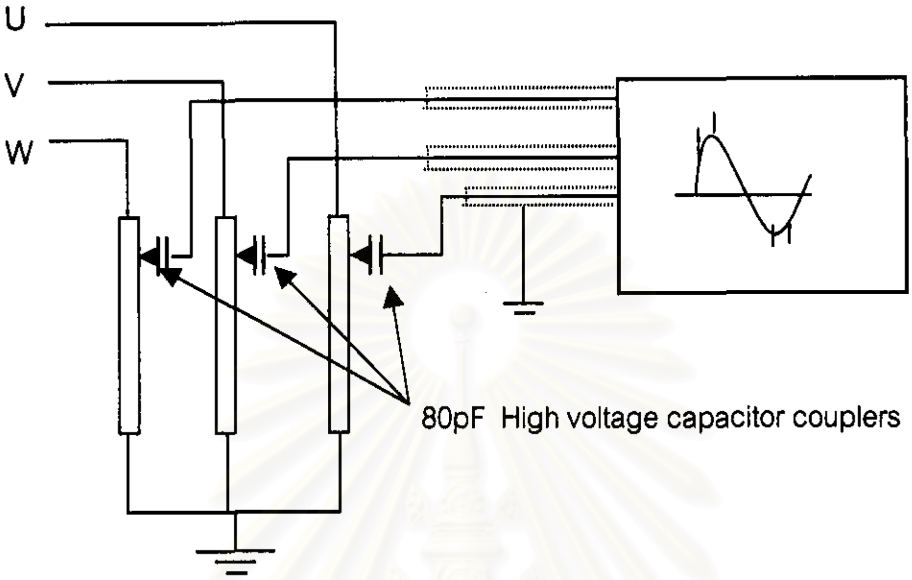


Fig. 2.5.4 80 pF couplers sensors are used for picking up the discharge pulses

The measuring unit (usually, oscilloscope) show partial discharge pulses both positive and negative pulse with amplitude and magnitude includes repetition rate same as off line method. Each of the coupler acts as pass band filters 30 kHz to about 30 MHz. The output are high frequency pulse signals associated with partial discharge in the stator winding and to aid identification of the partial discharge pulses, a phase corrected 50 Hz signal proportional to the generator terminal voltage is also displayed on the oscilloscope.

Output partial discharge pulses as shown in fig. 2.5.5 are collected and perform into the form relationship of pulse magnitude (mV) and pulse frequency (number of pulse per second), both positive and negative pulse as shown in Fig. 2.5.6

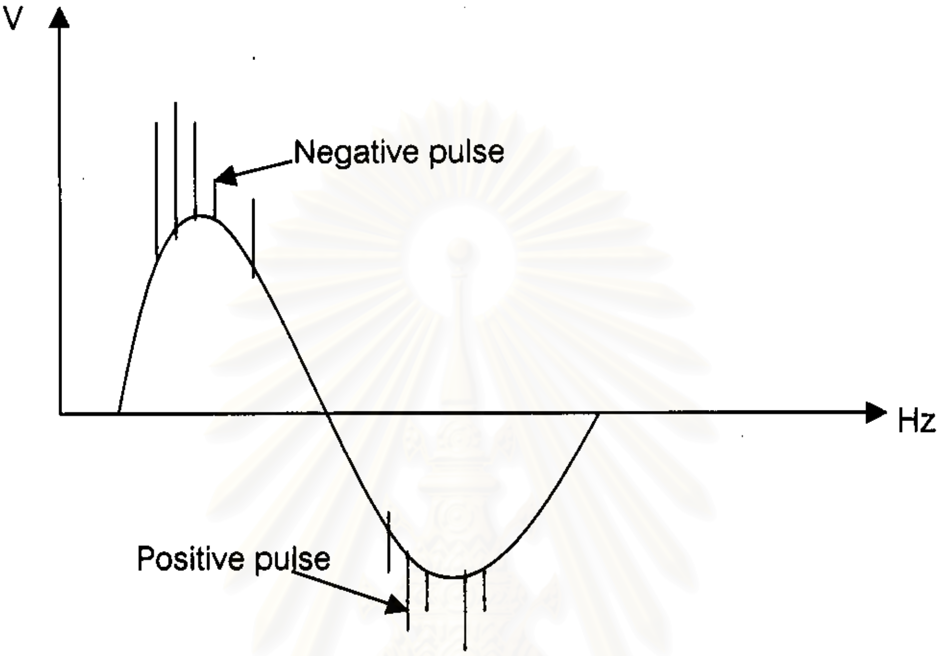


Fig. 2.5.5 Conventional measuring unit showing partial discharge pulse relate to applied AC 50 Hz high voltage cycle.

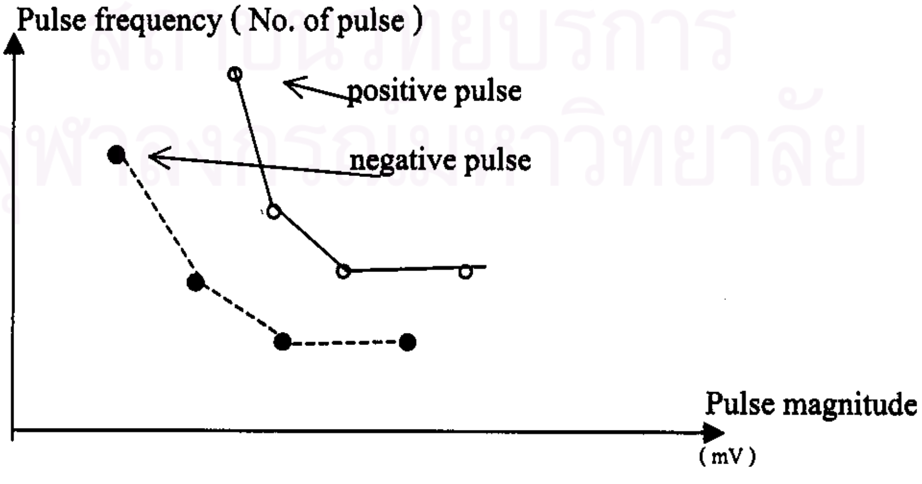


Fig. 2.5.6 Typical form of on line partial discharge measurement

2.54 ***Interference*** The most disadvantage of on line partial discharge test are electrical interference such as noise from both internal and external generator, excitation noise and etc. During generator operating, there are a lot of electrical noise occurred in stator winding and output results include both partial discharge pulses and noise pulses. To eliminate these pulses, Ontario Hydro was developed method of measurement by using two coupling capacitors [3] installed at the same location of winding parallel paths together in each phase as shown in Fig. 2.5.7

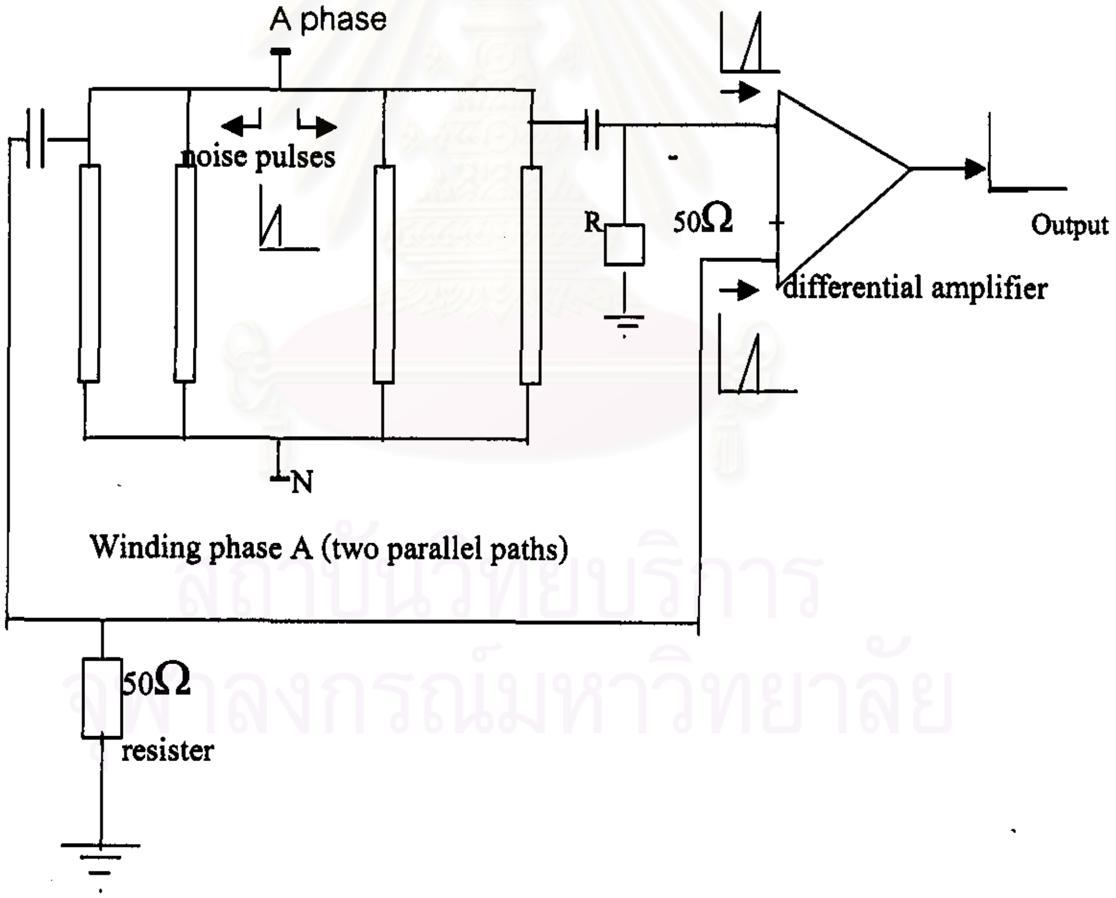


Fig.2.5.7 Noise pulses from generator enter to two input of differential amplifier at the same time and then they are eliminated by differential amplifier.

The noise pulses rejection basis is the time required for a pulse to propagate along the circuit of winding, usually 0.3 meters per nanosecond of propagation velocity. A noise pulses entering a generator phase from the power system splits and travels along each half of the circuit ring bus(Fig. 2.5.7). If the lengths of circuit ring bus of each parallel path are equal, also the coaxial cables connecting the couplers to measuring unit are the same length. Then the same noise pulse could travel to measuring unit at the same time on the two inputs of the differential amplifier in measuring unit. The result is zero output from the differential amplifier, none of noise pulses in output. If the length of circuit ring bus which installed the couplers are not equal, the noise pulses appear on the two inputs of differential amplifier at different time. The length of coaxial cable of each coupler should be trimmed or adjusted to equalize travel time.

The partial discharge pulse closes to one of the coupler yield a net response from the output of the differential amplifier. When the partial discharge pulse occurred in the parallel paths of winding and be detected by the coupler of that path and appears on one of inputs of the differential amplifier. The same partial discharge pulse travel into circuit ring bus enters to another coupler and appears on another input of the differential amplifier at the different time cause of unequal length of path and resulting output signal of partial discharge.

There are several measurement units for measuring of partial discharge within stator winding, mostly give the out put form of partial discharge activity pulse in term of partial discharge pulse frequency relate to pulse magnitude. The useful measurement unit is developed by Ontario hydro of Canada called Partial Discharge Analysis – Hydro-generator (PDA-H) and the output are shown in Fig. 2.5.6 that showing partial discharge pulse both positive and negative pulse in time interval of one second in measuring procedure.

The form or pattern of partial discharge output could be determined under the characteristic of pulse as frequency or number of pulse occurred per second mean the quantity of pulse and the magnitude of pulse could be the high of partial discharge activity, etc. There are many experience information of several utilities as Ontario Hydro, ABB company, and etc. those provide many results of testing and their interpretation. Almost of experience information are very useful to guide and support the project of this thesis.

2.6 Literature survey for experience technical papers

2.61 Experience with on-line generator partial discharge tests (M. Kurtz, G.C. Stone, W.F. Janaway, Ontario Hydro, Toronto, Canada) The experience paper of partial discharge test on on-line hydroelectric generator was wrote by the staff of Ontario Hydro. The high voltage insulation in stator windings gradually deteriorates due to mechanical, thermal, electrical, and environmental stresses. Many organizations have found that partial discharges are a symptom of winding deterioration. Over 40 years, Ontario hydro has used partial discharge tests on several types of generator. The tests required considerable expertise operator at the early stage, then Ontario hydro with supporting of Canadian Electrical Association have developed tests that are accessible to nonspecialized maintenance staff. Some highlights and their descriptions could be described below:

The conventional on-line test method In the early stage, Ontario hydro used the three 25 kV, 375 pF capacitors that were temporarily connected to the generator terminals to pick up partial discharge pulses . Each of the portable couplers was connected to a simple five-pole RC filter that had a pass-band from about 30kHz to about 30 MHz. The output of the filter contained the high frequency pulse signals associated with partial discharge in stator winding, which were displayed on a 100 MHz analogue oscilloscope. To aid identification of partial discharge pulses, a phase corrected 60 Hz signal proportional to the generator terminal voltage was also displayed on the oscilloscope. To test a generator, a suitable location for applying the 375 pF portable couplers was determined (usually at the drop leads into the generator potential transformers). With the generator operating normally, one coupler was connected per phase to each of generator output terminals. Partial discharge tests was done with full load and no load conditions, the measuring also repeated at no load and disconnected from power system for less electrical interference. Monitoring the change in partial discharge magnitude from low generator power to full power permitted the identification of loose windings. Then the portable couplers were removed from the terminals of generator at low power condition. The test was performed twice per year on hydroelectric generator by the same operator, who was skilled in extracting the generator partial discharge signal from noises (exciting signal, arcing from slip ring, etc.). The five hydroelectric generators were repaired cause of slot discharge and mechanical abrasion and damaged stator windings. The repairing was performed and several types of semi-conducting material were applied to protect slot discharges. The on-line partial discharge tests were done and accumulated data for several years, the test results and interpretation as a function of time. Both before and after repair are shown in fig.2.6.1 and 2.6.2.

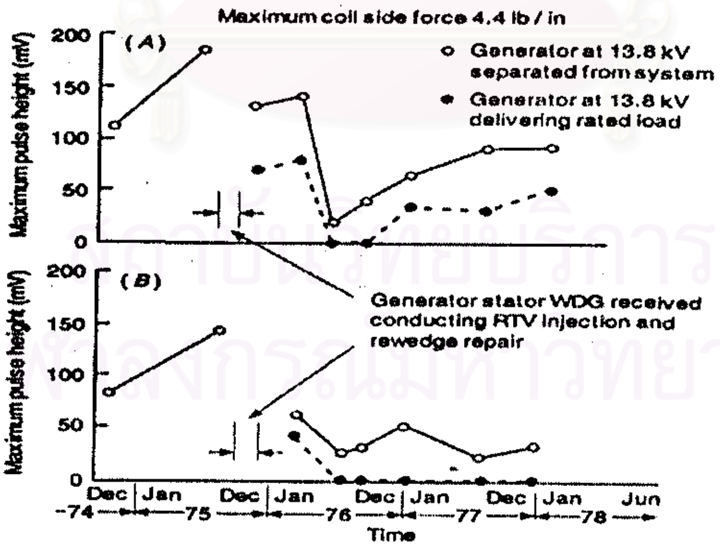


Fig. 2.6.1 Variation of discharge magnitude with time, A, unit1; B, unit2.

(source from Ontorio hydro research division, June 1992)

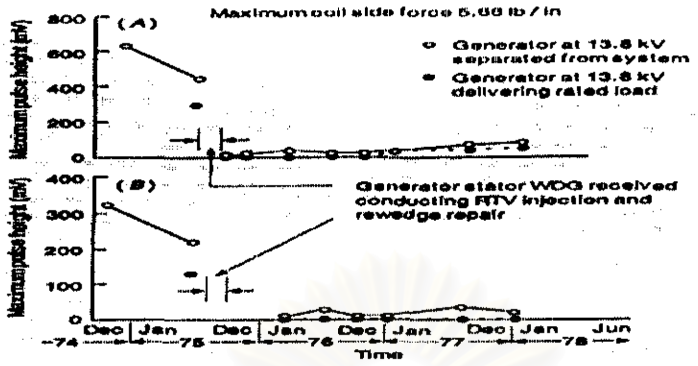


Fig. 2.6.2 Variation of discharge magnitude with time, A, unit 3; B, unit4 (source from Ontorio hydro research division, June 1992)

Consideration of these graphs shows that the repairs were initially successful in reducing the discharge activity in the slots from the high levels measured prior to repair. The test enabled Ontario Hydro to reduce its hydroelectric generator repair and rewind costs significantly in the 1970s and 1980s, since several years warning of problems, such as loose wedges and delaminating deterioration, permitted timely and inexpensive corrective maintenance to be carried out. The key parameter that correlated with stator insulation condition in hydroelectric generators was the peak observable magnitude of the positive and negative partial discharge at normal generator operating voltage. The actual magnitude of partial discharge from a test was less important than the change or the trend in partial discharge over the years. Doubling or tripling of the peak partial discharge magnitude over a few years indicated that the insulation was deteriorating significantly.

The partial discharge Analyzer test The main difficulty in performing on-line partial discharge test was not how to detect the partial discharge signals, but was in how to separate the electrical noises from partial discharge pulses. Ontario Hydro found that in a hundred of tests in several generators, the noises were found and sometime higher than generator partial discharge signals. Only the specialized operator can differentiate between partial discharge and electrical noise, permitting an effective on-line test. On above problems and concerns, Ontario Hydro under Canadian Electrical Association (CEA) researches the method to, measure and eliminate electrical noise from on-line partial discharge test. By using at least two 80 pF, high voltage coupler capacitors are permanently installed at the end of the circuit ring buses that connect the various winding parallel path together in each phase. The noise rejection basis is the time required for a pulse to propagate along the circuit ring bus with a propagation velocity of 0.3 meters per nanosecond. A noise pulse enters to a generator phase from the power system and travels along each half of circuit ring bus or parallel path (fig. 2.6.3). If the length of each half ring bus is equal and the length of each coaxial cable from each coupler is also equal, then the noise will travel to the two input of differential amplifier at the same time, resulting zero noise output from differential amplifier in measuring unit.

The partial discharge pulse occur at the winding close at one of the couplers (fig. 2.6.4) and is detected immediately by that coupler and appears at one of the inputs of differential amplifier. The same partial discharge pulse propagate along ring bus to the other coupler of the pair and take more few time, resulting appear at the another input of differential amplifier in different time. This difference in pulse arrival time at the amplifier results in a net pulse output from the amplifier.

In summary, noise interference is eliminate and there is not output from amplifier, but the partial discharge pulse occurring near any one of the couplers can appear at the output. No need to use specialized operator to do the test every time.

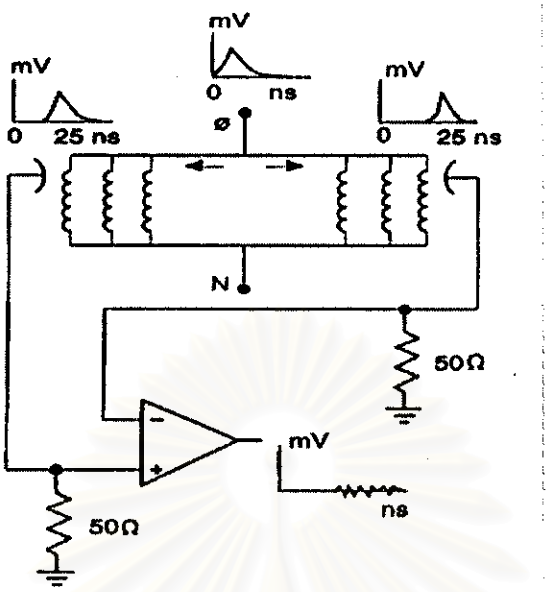


Fig. 2.6.3 Rejection of common mode electrical noise while maintaining sensitivity to winding discharges is obtained by electrical balancing the coaxial cables connecting the couplers to the external differential amplifier. A noise pule from the power system arrives simultaneously at the inputs of the differential amplifier, resulting in no output (source from Ontario Hydro Research Review, No.6, June 1992).

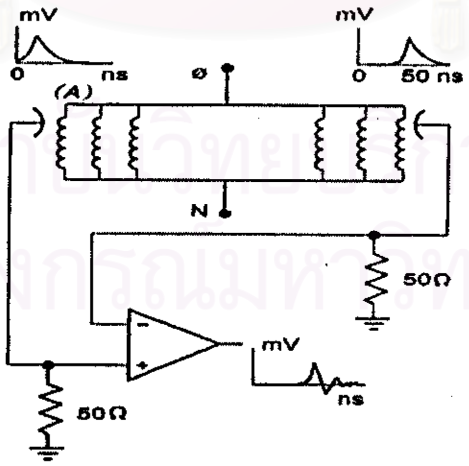


Fig. 2.6.4 A discharge pulse (near A) yields a non-zero output since the electrical signal arrives at the positive input of the differential amplifier well before it arrives at the negative input (source from Ontario Hydro Research Review, No.6, June 1992).

Ontario Hydro developed the partial discharge analyzer instrument, which include differential amplifier module for noise elimination and measuring unit. The output data show in form of partial discharge pulse frequency (number of pulse per second) respect to magnitude of pulse in specific time interval (usually one second). By the past experience that Ontario Hydro installed permanent couplers into stator winding for all hydroelectric generator of Canada and using developed partial discharge analyzer to measure and analyze data. The typical output and pattern of graph can be shown in fig. 2.6.5 and fig. 2.6.6.

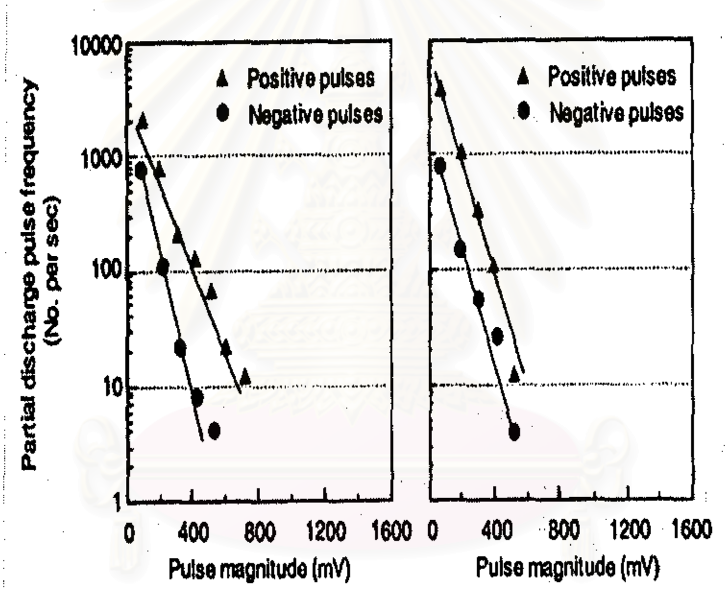


Fig.2.6.5 Barrett chute Unit 4 , showing the data that were recorded with partial discharge analyzer, while the generator operated at 60 MW and 63°C. The winding insulation is epoxymica paper and is about 14 years old (source from Ontario Hydro Research Review, No.6 June 1992).

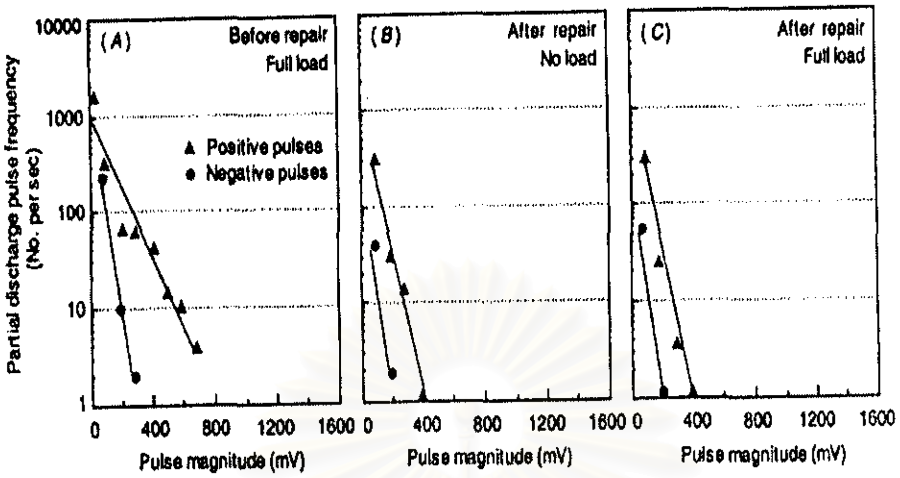


fig.2.6.6 Partial discharge Analyzer test results before (A) and after (B and C) the winding maintenance on Saunders Unit 8. The tests were performed after repair with the generator at full power (58 MW and 68°C) and at no load (source from Ontario Hydro Research Review, No.6 June 1992).

The Partial discharge analyzer test is most useful in tracking Partial discharge activity and in comparing identical generators. Fig. 2.6.6 show another hydroelectric generator of 13.8 KV,60 MW tested results that overall partial discharge pulse-count was decreased as well as the difference between the positive and negative counts resulting from the semiconductive paint repair is evident. The change in partial discharge depends on a function of load that is interpreted to be a characteristic of a tight winding.

2.62 Permanent Coupler Capacitor The main problem of partial discharge measurement is electrical noise elimination. Under experience over 40 years of partial discharge measurement of Ontario Hydro, using a pair of coupler capacitors install into the lead of each parallel paths. The noise pulse can travel along the terminal of generator and is detected by coupler capacitors and to be eliminated by comparison of differential amplifier. Each of the coupler acts as a band pass filters 30 kHz to about 30MHz that cover the range of partial discharge pulse frequency. To match that band pass filter, 80 pF capacitor is selected. The 80pF coupler capacitor can be made from any kind of materials that can withstand the high voltage higher than the rate terminal voltage of generator and does not generate partial discharges by itself.

The experience technical paper of CEA-EPRI and Ontario Hydro 1986 (by T.E. Goodeve, the engineer of Electrical Hydraulic Plant Equipment of Ontario Hydro Canada) recommended type of coupler, technique in fabrication and installation of the interesting low cost 80 pF capacitor. The capacitor is made from XLPE high voltage cable that could be shown in fig.2.6.7

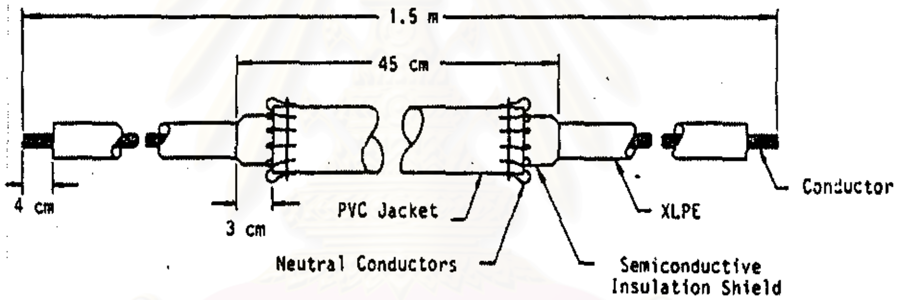


Fig.2.6.7 A low cost efficient cable-type permanent coupler capacitor (source from Experience with on- line generator partial discharge tests paper, September 1981)

Ontario Hydro suggests the standard 2/0-aluminum conductor 28 kV, concentric neutral, cross-linked polyethylene insulated power cable to fabricate a high voltage capacitor. The specific characteristic achieved shall be detailed that:

a. 80 pF could be achieved by trimming the length of the cable.

b. Terminated both ends of the cable for preventing of discharge occurred due to sharp edge of material.

c. Apply dc high voltage 50 kV test voltage to prove that the cable can withstand that testing.

d. Apply ac high voltage to find the extinction voltage that exceed 15kV rms and low power loss in cable insulation.

e. The 50Ω coaxial cable is connected to the shield of the cable

The coupler capacitor can be made in form of loop type or line type depends on the space of installation area on generator.

2.63 Coupler installation Ontario Hydro recommended technique of coupler installation into a stator winding in order to achieve the suitable location for picking up partial discharge pulse (Partial discharge analyzer couplers installation experiences, consideration and techniques by T.E. Goodeve, 1986, CEA-EPRI-Ontario Hydro, Canada). The general hydroelectric generator could be divided the structure frame of stator into three types:

a) A generator whose stator frame and wrapper extend above the level of the circuit rings.
b) A generator whose circuit rings sit fully exposed on the top shelf of the stator frame.
c) A generator whose has not circuit rings or circuit rings of very short length.

There is rather difficult to install couplers into those frame types above. It is recommended to disassembly end cover and some parts of wrapper. Some special supports shall be made to fix or support couplers far from stator frame for prevention of interference from those parts. In the other way, uses open loop - type of couplers and supported by the wrapper itself (see fig. 2.6.8 and fig. 2.6.9).

For a generator with no circuit rings or has single circuit, a pair of couplers should be install near the terminal lead of generator, which one coupler fixes to the terminal and another fixes to the stator lead nearest the terminal of the same phase.

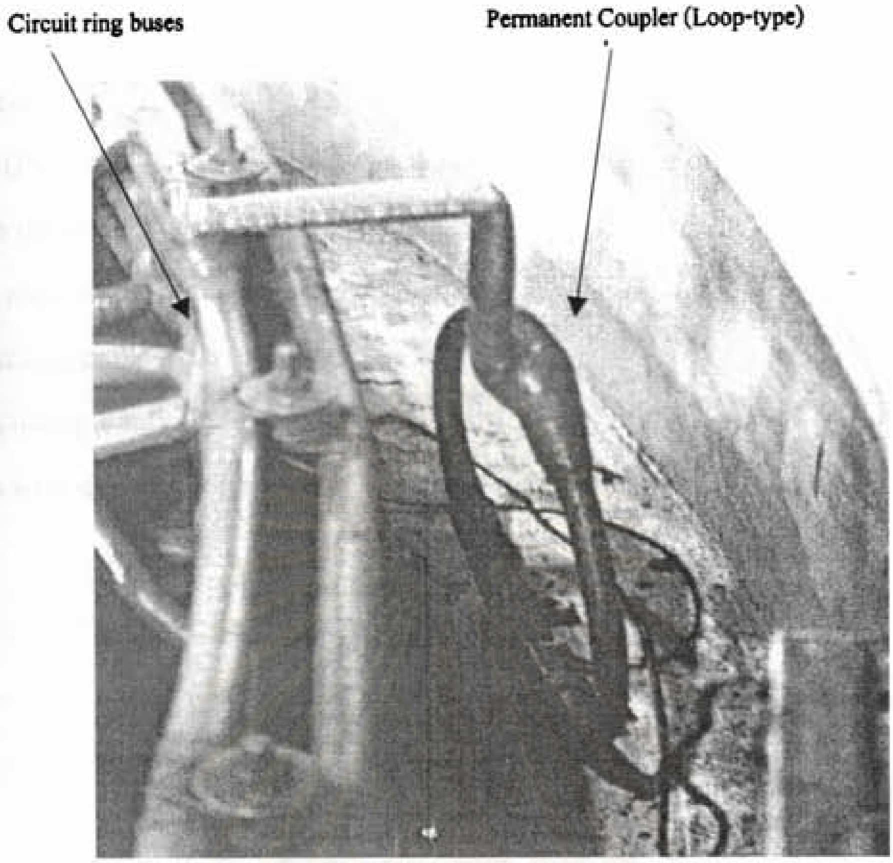


Fig.2.6.8 Loop-type coupler

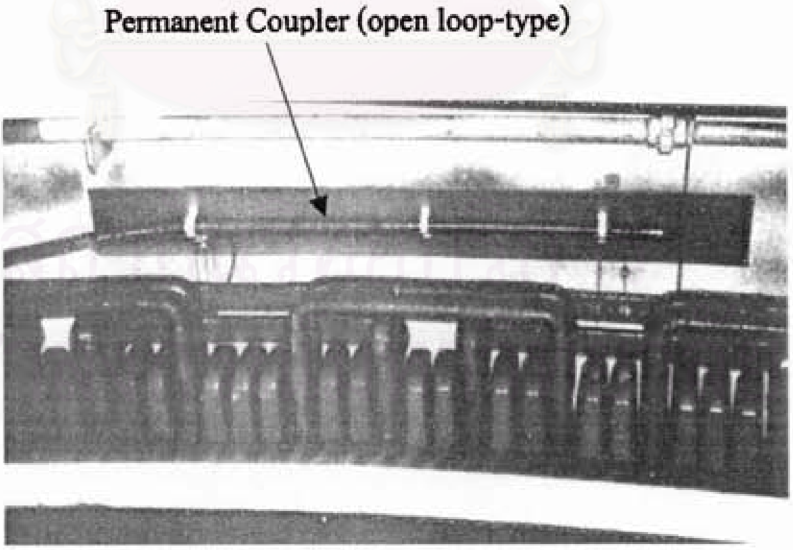


Fig.2.6.9 Open loop-type

The couplers are connected to the circuit rings at point where the phase parallel connection furthest from the line entrance (generator terminals) is connected to the parallel rings (Fig.2.6.10). This location was selected under reason of:

a) To minimized coaxial cable lead length.

b) It reduced the requirement to "store" excessive lead length for balancing purposes since circuit ring paths were usually closer in length.

c) Winding configurations were such that less physical interference from leads and other items were experienced which would make installation more difficult.

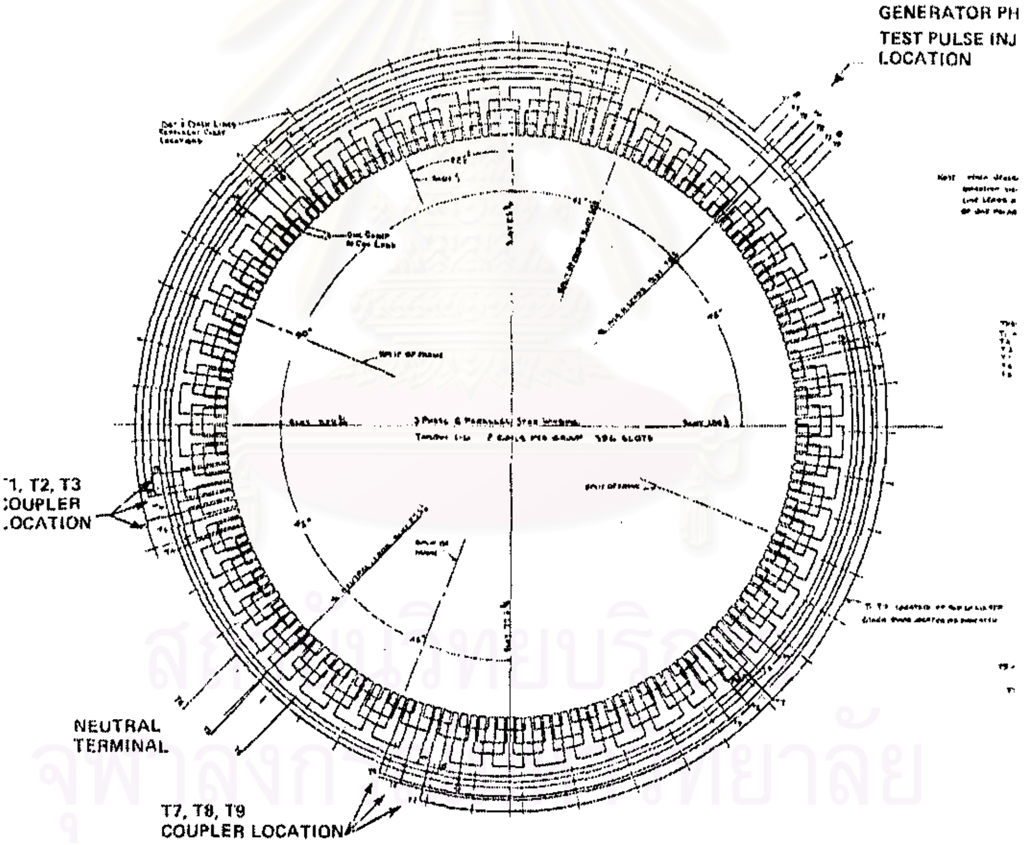


Fig.2.6.10 Winding diagram of hydroelectric generator

The coaxial cable lead to the terminal box should be 50Ω, RG58 – type and be routed along with the thermocouple/RTD leads of the generator. Flexible conduits are used to support these coaxial leads. The excess lead length used for balancing purposes can be tied in open loops along the core top in the same location as the leads.

2.64 Coaxial Cable Trimming T.E. Gooeve, Engineer Electrical Hydraulic Plant Equipment, Ontario Hydro suggested the principle of coaxial cable trimming method that could be described below:

The ability of the partial discharge to accurately count those pulses resulting from discharges within a generator winding or slot while rejecting pulses resulting from external "noise" rests with accurate trimming of the coaxial leads. The recommended instruments are high frequency oscilloscope (dual trace 200MHz or better), signal generator for generating the 10kHz pulse with 9-10 volt magnitude, 400 nanosecond rise time and 9 nanosecond fall time.

To perform the actual trimming of the coaxial leads the signal generator is connected to terminal phase conductor. 10kHz pulses is injected into the phase winding. Using 200MHz oscilloscope to pick up that pulse at both leads of couplers for each phase. Under 10 kHz and 50Ω coaxial cable, resulting about 3 feet length will delay time of 1 nanosecond. On CRT screen with dual mode shown different time of each signal, matching lead length (equalizing pulse time-of-arrival) can easy be done to within 2 nanoseconds for a typical response (fig. 2.6.11)

After the coaxial cables have been trimmed they are soldered into place in the terminal box, in pairs, with a 680 ohm, 0.5 watt resister across the output.

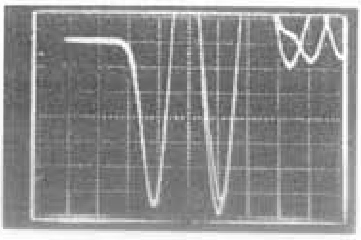


Fig. 2.6.11 signal output after trimming

2.65 Partial discharge Identification of Deterioration Mechanisms: Partial discharge testing has been used for over 50 years to measure the quality of electrical insulation and to detect if insulation deterioration has occurred in high voltage apparatus. The goal of testing usually to find some manufacturing problems for new apparatus and to find and detect deterioration while the apparatus was in normal use. Partial discharge testing can be done either off-line or on-line. Under the success in research of on-line partial discharge testing by Ontario Hydro and Canadian Electrical Association, the most widespread application of partial discharge testing is for detection deterioration in rotating machines. The signals were measured on limited bandwidth of oscilloscopes and special measuring unit developed by Ontario Hydro. The installed permanent couplers detect partial discharge pulse and electrical noise. The electrical noises are eliminated by a differential comparison of pulses (as described in section 2.5 of the thesis). Normally, partial discharge activity is measured in term of picocoulomps (pC) and, large numbers of pC indicate more partial discharge activities. For on line partial discharge measurement, the signal pulse is measured in terms of millivolts. This is an arbitrary quantity, which depend on the effective capacitance of the generator and associated connected equipment. Thus the unprocessed results from the partial discharge test on a particular generator can only have significance in comparison with previous tests on the same machine (ie. The rate of change of partial discharges with time) or other phases or parallels on the same machine, or with test result from similar generators. The output result is shown on the graph in correlating test curves with observed machine condition has confirmed a direct relationship between the position of the test curve on the graph and the winding condition.

Figure 2.6.12, increased partial discharge activity, and hence more insulation deterioration, is indicated by a shift of the line to the right. Furthermore the evident is strong that the relative position on the graph of the "positive pulse count" and the "negative pulse count" curve versus pulse magnitude is indicative of the location or nature of the partial discharges.

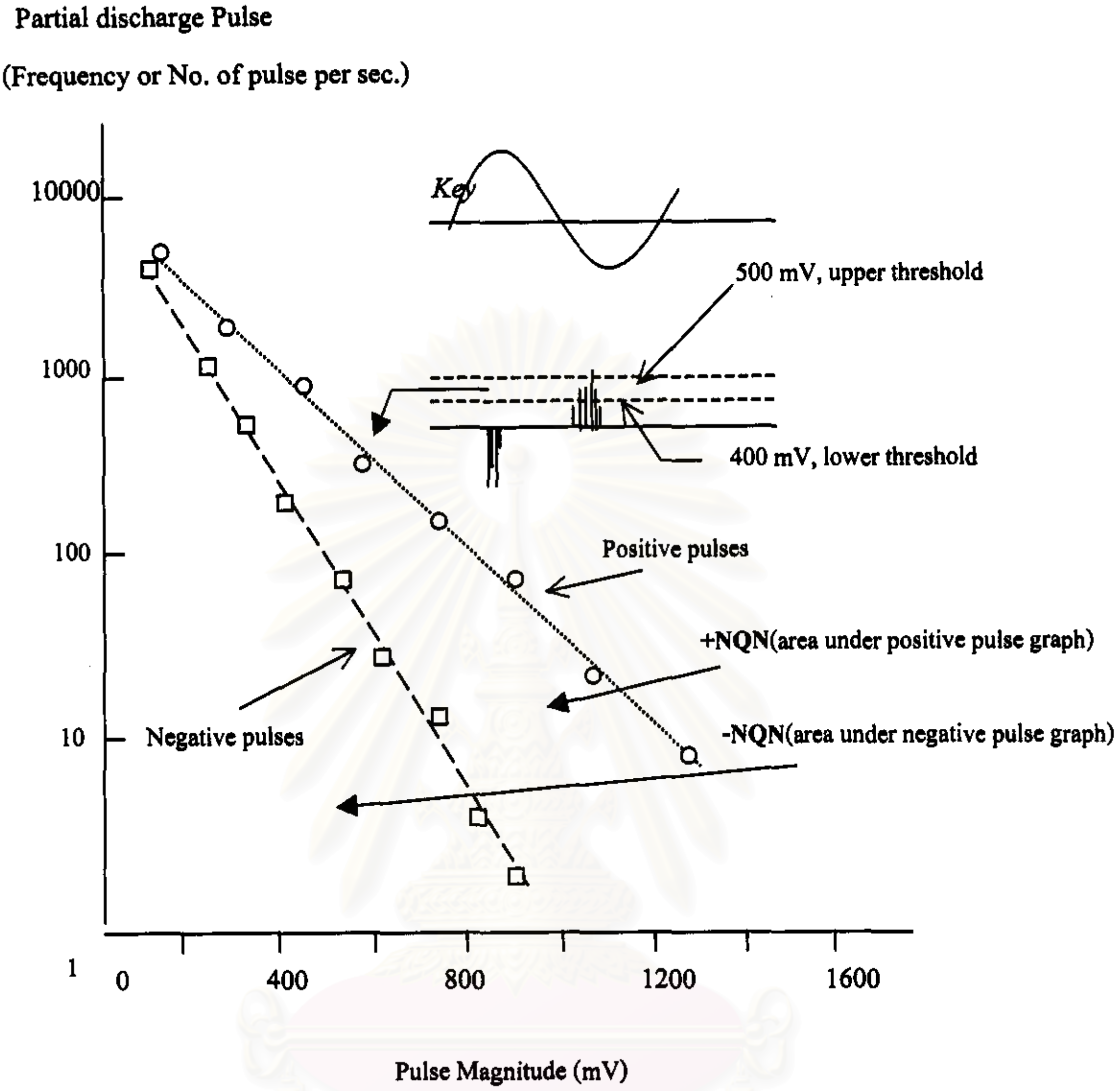


Fig. 2.6.12 Typical output from the partial discharge test

The output data is not only measured in term of millivolts and quantity as numbers of pulse per second but the overall partial discharge activities of each phase or parallel circuit is also very important. It indicates several significant condition of winding, and to be measured in term of ***Normalized Quantity Number*** **(NQN)** and the area under the relevant partial discharge graph determines NQN.

G.C. Stone from Iris Power Engineering Inc. Canada, the technical paper presented in Iris Rotating Machine Conference, June 1999 has explained the deterioration mechanisms of generator insulation that:

In stator windings, the main insulation is now made of mica paper, impregnated with epoxy or polyester. Although the organic epoxy and polyester materials are easily degraded by partial discharge, the mica is essentially impervious to moderate levels of partial discharge. As a result of the presence of mica, the partial discharge in itself does not necessarily lead to failure of the winding. In fact, most stator winding rate 6 kV or more have at least low levels of partial discharge occurring during normal operation, without any adverse consequence.

Most stator windings fail as a result of long term thermal aging, load cycling, or the coils being loose in the slot [3]. For these mechanisms, partial discharge is a symptom of the thermal or mechanical deterioration of the winding. Partial discharge occurs because these mechanisms create air pockets. Usually, the greater the deterioration, the larger the air pockets, and thus the larger is the partial discharge. However, the thermal or mechanical stresses, and not partial discharge mainly determine the actual rate of deterioration. Since the partial discharge is not the direct cause of deterioration, the time to failure is not related to the partial discharge causing the insulation deterioration.

For example, if thermal deterioration is occurring, the bonding between the mica tape layers is lost, allowing air gaps to occur, and thus partial discharge. Partial discharge is the symptom of the presence of thermal deterioration. However, the magnitude of the partial discharge can be small, if only small gaps are occurring, even though the insulation has become very brittle and could crack easily. If the partial discharge is increasing over time, the gaps are getting larger, indicating more thermal deterioration. Thus, an increase in partial discharge over time indicates that more thermal deterioration has occurred. However, the actual magnitude of partial discharge is unrelated to how long it will take the insulation to fail, since the partial discharge is not the main agent causing the deterioration. Similarly, if coils are loose in the slot, the main cause of deterioration is the abrasion of the insulation, as the coil rubs against the laminated stator core. The rubbing away of the insulation allows an air gap, and thus partial discharge, but the root cause of the mechanism is the movement, not the partial discharge. Again, partial discharge is just a symptom. If the partial discharge increases over time, then more insulation has been abraded away. Since with these two mechanisms the partial discharge is just a symptom, there is no reason to believe that if the partial discharge gets above a certain level of pC, that the winding has a large risk of failure.

There are a few failure mechanisms that can occur in stator windings in which partial discharge is the main cause of deterioration. These include partial discharge occurring in large voids next to the copper conductors, caused by poor impregnation of epoxy or polyester during manufacture. Partial discharge occurs in the voids, and if the voids are large enough, the partial discharge pulses will be large enough to gradually eat through a few layers of mica paper tape turn insulation, leading to a turn insulation fault. The large the voids, the large the partial discharge pulses, and the faster the failure. Thus, the partial discharge magnitude is an indicator of the time to failure. Similarly, if the endturns of a stator winding are polluted and electrical tracking is occurring, the insulation will track quicker if the discharges are larger. Thus, with the contamination failure mechanism, the partial discharge magnitudes are a good indicator of how fast a winding will fail.

The deterioration mechanisms of stator winding could be identified in several significant parts of winding, the ability of measurement in both positive and negative discharge pulses independently, include under various load condition yield significant deteriorated mechanisms of winding.

Semi-conducting Coating/Slot Discharge : This mechanism is very dangerous since it can synergistically combine the effects of electrical and mechanical stresses to erode the outer layers of the ground wall, resulting in rapid failure. Partial discharge test data plots will give *positive pulse predominance* for discharge activity located at the insulation, semi-conducting coating, ground plane interface. For repeatability, these tests must be performed at the same steady state temperatures for the no load and full load condition, ie, within five degrees Celsius. If the winding is loose, there will also be a change in partial discharge test's data magnitude. Ozone may also be present in large quantities if the deterioration is widespread.

Internal partial discharge : Discharge can occur within the ground wall insulation at delaminations or areas where the bonding material is missing or incompletely cured. Internal partial discharge is particularly common in order insulation systems such as micafolium and asphalt-mica. The main characteristics of this mechanism are that *the positive and negative partial discharge activity is about equal.* The discharge activity is more sensitive to winding temperature than to load changes.

Copper/Insulation Interface Partial Discharge : These discharges occur at the interface of the copper strands and the turn insulation in multi-turn coils. For roebel bar windings the copper strands interface directly with the ground wall insulation. As this condition, the partial discharge test data plots will give *negative pulse predominance.* This condition has been observed on 25 to 35 year old asphalt-mica insulated, multi-turn windings as well as poorly bonded epoxy/polyester insulated, roebel bar windings of 3 to 10 years of age. The observed behavior of the asphaly multi-turn windings has been to progress through to turn to turn coil failures and eventually to a complete rewind in year 35 to 45. For the roebel bar winding, such a condition has led to premature rewinds by year 5 to year 12.

Loose Wedging, Loose winding/Tight Winding: A loose or tight winding can be determined by comparison of the no load and full load partial discharge positive test data.

For a tight winding, *the full load test data, when superimposed upon the no load test data, will coincide with it or be very closely parallel to it. The pulse magnitude and frequency will, in most cases, be low.*

For a loose wedging-loose winding, *the no load and full load partial discharge data plots will diverge away from one another with the magnitude and frequency increasing for the full load condition.* Such a winding upon physical examination, will indicate other factors indicative of a loose winding such as depth packing migration out of the slot, loose end wedge migration, etc. If this condition has existed for some time, there may also be visible signs of depth packing, wedge burning, and mechanical abrasion of the coil side semi-conducting coating and insulation. In the worst observed cases, coil side end-head lashing breakage has also been experienced.

2.66 Experience of interpretation in partial discharge pulses output

J.F. Lyles, G.C. Stone, and M. Kurtz, Ontario Hydro, Canada presented their experience paper about partial discharge diagnostic testing on hydraulic generator on Feb.1988 in CEA. The diagnostic results achieved from many hydroelectric generators of Canada, which before and after the repair of stator winding. The experience information is most useful to assess the condition of winding and could to apply to the project of the thesis, and some significant information can be listed below:

i). Identification of deterioration mechanisms

a). *Semi-conducting Coating/Slot Discharge*: The test results from Sir adam Beck Niagara II GS. Unit A (Fig.2.6.13) shown significant graph as indicated by the positive (+ve) pulses predominance, and during repairing found many coils that surface damaged in slot portion on the red phase split 2.

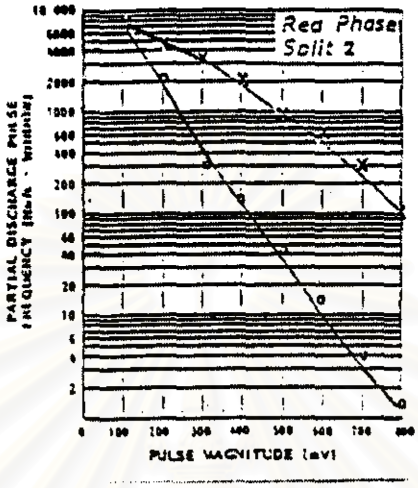


Fig.2.6.13 Sir Adam Beck Niagara II Gs Unit A (source from presentation report by J.F. Lyles and staff in CEA on Feb.1988) shown significant of slot discharge.

b). *Internal Ground wall partial discharge*: The internal discharge can occur within the ground wall insulation at delaminations or incompletely cured. Test data of Decew Falls GS Unit B (Fig.2.6.14) indicates that the positive (+ve) and negative (-ve) partial discharge activity is about equal and these discharge are more sensitive to winding temperature than to load change.

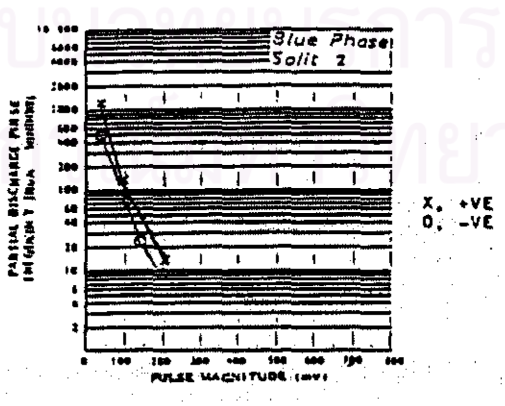


Fig.2.6.14Decew Falls GS Unit B (source from presentation rept., by J.F. Lyles and staff)

c). *Copper stack/Insulation Interface partial discharge*: Test data from Blenhelm-Gilboa Unit C indicates negative (-ve) pulse predominance (Fig.2.6.15). The machine is about 30 years old with asphalt-mica insulated and polyester/epoxy insulated multi-turn winding. During repairing work, the copper surface which interface with main ground wall insulation found some abrasion and oxide occurred.

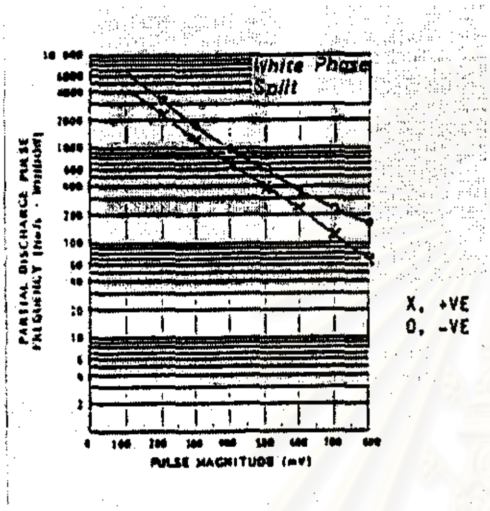


Fig.2.6.15 Blenheim-Gilboa Unit C

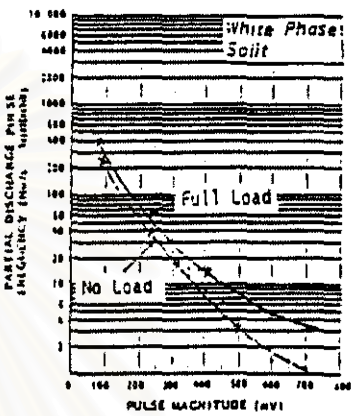


Fig.2.6.16 Arnprior GS Unit D

d). *Loose Winding/Tight Winding*: Using comparison of the no load condition and full load condition, the deviation of positive partial discharge pulse graph from no load and full load indicate loose or tight of winding. The coincidence of two graphs indicates tight of winding and the divergence of these graphs indicates loose of the winding. Test data of Arnprior GS Unit D (Fig.2.6.16) shown divergence of two positive partial discharge pulse graphs and loose of winding cause of loosen wedges were found in repairing work later.

ii). Normalized Quantity Number (NQN)

The NQN is a measure of integrated discharge activity given by the area under the relevant partial discharge graphs. It is more easily to track the winding condition over time, the partial discharge graph can be summarized as a single number as NQN.

J.F. Lyles, G.C. Stone and M. Kurtz use the NQN of each test data to trend the condition of that tested winding. It should be recognized that the NQN value couldn't be used in isolation. It must always be used in association with the relative positions of the +ve and –ve partial discharge pulse curves plotted from no load and full load test data.

Fig.2.6.17, presents +ve NQN data long term monitoring plots for two Ontario hydro muti-unit stations. One is incorporating thermoplastic and the other thermoset stator winding insulation systems. By over long term experience on testing of many hydroelectric generators of Canada, the value NQN can be related to a probable winding condition for a given insulation system as described in Charts I and Charts II. The charts also relate maximum coil side force/inch length to corrective action time as per Ontario Hydro's experience for thermoset systems.

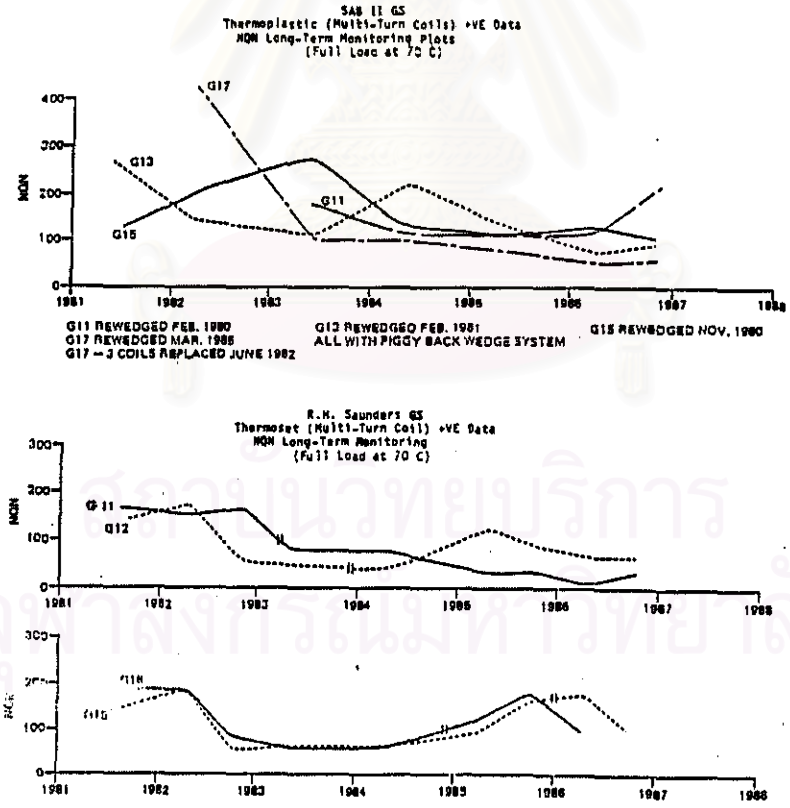


Fig.2.6.17 Long term monitoring of NQN on thermoset and therplastic insulation systems

Ontario Hydro
PDA Normalized Quantity Number
(NQN) Insulation Damage Releationships
Based on Operational Experience*

Chart I

		Polyester and Epoxy Insulation Systems			
		Normalized Quantity Number (NQN)	Comments Regarding Most Likely State of the Winding	Maximum Bar Force [8]	Corrective Action Time
		0 to 100	Winding will be tight and in good condition. +VE and -VE NQN typically of equal magnitude.		
Semi-Conducting Coating Erosive Discharge	Repair Prob of Success 90 to 99%	101 to 250	Very early semi-conducting coating damage will be present in the top 10% of any circuit string. +VE and -VE NQN not equal. +VE NQN probably 15% to 20% greater in magnitude.	2.0 lbs/inch 2.5 to 4.5 lbs/inch 4.5 to 6.0 lbs/inch and greater	3 years 18 months 9 months
	Repair Prob of Success 75 to 90%	251 to 400	Semi-conducting coating damage will be present in the top 20 to 25% of any circuit string. Damage will be easily visible on affected coil sides. Some early internal ground wall or conductor insulation interface delamination is highly probable on 25- to 30-year-old windings. +VE NQN probably 30 to 40% greater than -VE NQN.	2.5 to 4.5 lbs/inch 4.5 to 6.0 lbs/inch and greater	15 months 6 months
(a) Semi-Conducting Coating Erosive Discharge Std Corrective Repair Has High Prob of Only Temporary Halt to Surface Deterioration. Complete CRTV Injection Corrective Repair [8] Has Achieved a High Success Prob for Ontario Hydro. (b) In Loose Windings High Prob of High Intensity Slot Discharge Present.		451 and above	Same as for 251 to 400 NQN range, except a larger area of the winding will be involved. For long stator core machines 90 inches (228.6 cm) and greater, internal copper stack insulation interface delamination will most probably be present on 8- to 10-year or older windings. Standard corrective action will have a high probability of producing only a temporary halt to the surface deterioration involved. Our experience has been that only a complete CRTV injection at every core package - coil side interface achieved a high success probability when NQN has been greater than 451.	2.5 to 4.5 lbs/inch 4.5 to 6.0 lbs/inch and greater	9 months 3 months

* couplers located at the end of the circuit ring bus

Chart II

	Considering Asphalt-mica and Mica-folium Systems	
	Normalized Quantity Number (NQN)	Comments Regarding Most Likely State of the Windings
Semi-Conducting Coating Erosive Discharge. Ground Wall Void Discharge Activity is the Primary Mechanism of Insulation Deterioration.	0 to 200	Winding will be tight. However, there will be signs of internal void development for the 125 to 200 range windings. Winding should be rewedged with a piggy-back wedge system if it is 20 to 25 years of age. Typically, +VE and -VE NQN are of equal magnitude.
	201 to 500	Winding will be in the 30 to 35 year + class, and will be experiencing a higher level of internal void development than those on the NQN 125 to 200 range. Depending upon the winding's histogram, and if its NQN falls between 201 and 350 a rewedge operation may be possible in order to extend its life to 50 years. Typically, +VE and -VE NQN are of equal magnitude.
	501 and above	Winding will be experiencing significant internal delamination and in fact, may have already experienced turn to turn failures. If winding has reached 35 years of service, then consideration should be given to rewinding unit within the next 10 years.