CHAPTER 3

MEASUREMENT AND ANALYSIS OF ON LINE PARTIAL DISCHARGE OF HYDROELECTRIC GENERATOR UNIT 2 OF SIRIKIT POWER PLANT

3.1 Introduction

The concept of on line partial discharge measurement and analysis was proposed to the manager of the Electrical Maintenance Division of the Electricity Generating Authority of Thailand (EGAT) and the project was setup an on line partial discharge measurement and analysis at one hydropower plant, Sirikit Hydropower Plant. Using EGAT's Electrical maintenance budget, a set of measuring unit was bought from Ontario Hydro Canada and the author was authorized to implement this project.

Sirikit hydropower plant is one of the largest hydropower plants of EGAT. It is located in northern of Thailand. Sirikit hydropower plant was established in 1974, which is 26 years old. There are four units made by Mitsubishi co., Japan, which unit 1, 2 and 3 have been in serviced for over 26 years and unit 4 is the new machine, which just has been operated for four years (1996). The generators unit 1, 2 and 3 were selected to implement the partial discharge analysis to measure and monitor the condition during operating period and use some tested results to assess and correct some specific parts of stator winding on overhaul period.

Generator specification: (units 1, 2, and 3 have the same specification)

Manufacturer:	Mitsubishi Co., Japan
Rating:	132,000 KVA, 13,800 Volt, 5,522.5 Amp.
	3 phase, 50 Hz., 0.95 pf., Rating continuos
Insulation:	Class B, Polyester mica type
Stator winding:	Lap winding type with 3 parallel circuits per phase and star connection

The types and suitable methods of partial discharge measurement are selected and apply to the generator base on consideration with specification of each generator and knowledge from literature on chapter 2. The measurement unit is bought from Ontario Hydro as PDA-H model and all permanent couplers were fabricated by EGAT(the author and his maintenance peoples) itself. The measurement was done during machine operating and the inspection has been done in the recent period of overhaul to confirm the results of test before overhaul.

The project procedure could be shown below : (Fig. 3.1.1)

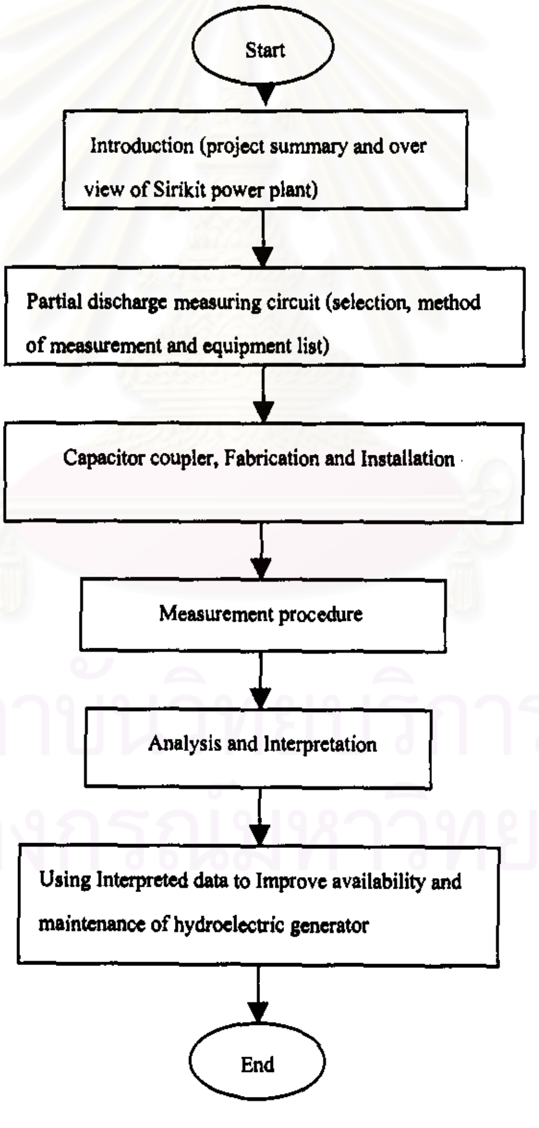

Fig. 3.1.1 Procedure of Project

3.2 Partial discharge measurement circuit

The partial discharge measuring circuit for on line measurement is shown in figure 3.2.1. High voltage 80 pF capacitor couplers are selected to connect directly to each parallel circuit of stator winding. By this method all electrical pulses could be directly detected by these couplers. To eliminate electrical noises from measuring, at least two couplers are installed and using comparison method to send all signals into differential amplifier of measurement unit.

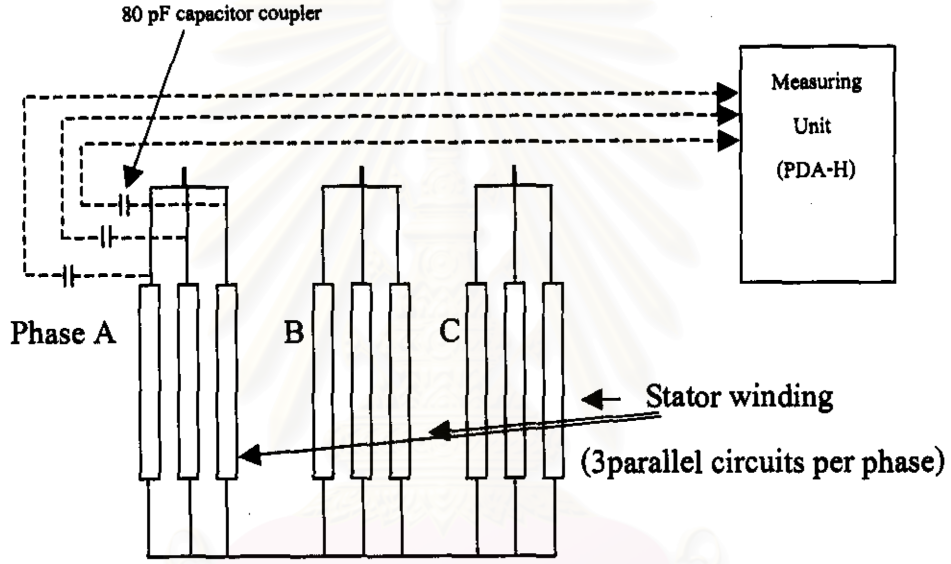

Fig.3.2.1 The On line partial discharge measuring circuit on generator, 80pF coupler is connected to the lead of each path (shown in phase A, phase B and C are the same)

The measuring unit is Partial discharge Analyzer model "PDA-H"(shown in Fig.3.2.2) which has comparison method of electrical noises elimination concept that suitable for multi circuits of a hydroelectric generator. The output data are number of partial discharge pulses of each magnitude in mV of negative pulse and positive pulse includes quantity of pulses as – NQN and +NQN.

Censer devices are high voltage 80 pF capacitor couplers, which are connected directly to stator winding. These couplers must have electrical properties as high breakdown strength, low power factor and corona free etc. The coupler can made from many kind of insulation material and the low cost

Coaxial cable is the low impedance communication cable (50Ω coaxial cable is selected) using for transfer partial discharge pulse to measuring unit and less attenuation.

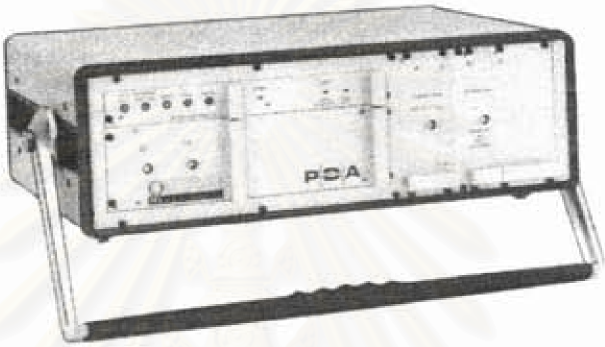

Fig.3.2.2 Measuring Unit "PDA-H", which using comparison method to eliminate noises from received data.

The output data are shown in term of numerical numbers and need to be plotted a graph by hand. The graph will show the relationship of pulse frequency (number of pulses per second) and their magnitude (Fig.3c sample test data). The PDA-H provides software to process the output data automatically that can inform the output as partial discharge graph in a few minutes after measuring. Fig 3d shows sample of test data output in graph form, the significant points are pattern of graph and amount of both +NQN and –NQN.

SAMPLE PDA TEST DATA

PDA Test unit #_____ Station__________ Temp_____
Ref no = 118 Phase _____ Date _________ Load_____

2 TIMES GAIN

	Coupler 1 Pos	Neg	Coupler 2 Pos	Neg
100 mV	2743	1496	3721	1061
	2614	1372	3410	1017
	2486	1361	3192	982
	2816	1477	3377	870
	2859	1319	3000	945
200 mV	820	92	1092	210
	795	96	1011	207
	881	77	1046	197
	763	81	936	194
	791	99	1000	179
300 mV	153	22	421	64
	137	19	417	62
	131	24	427	66
	148	21	392	58
	154	17	419	68
400 mV	52	6	132	21
	56	6	137	17
	61	3	140	18
	40	4	128	20
	50	5	178	19
500 mV	22	3	72	11
	24	1	61	9
	19	3	69	10
	18	1	68	8
	17	1	73	8
600 mV	10	1	33	5
	8	2	37	3
	8	1	26	5
	10	2	30	4
	11	0	29	3
700 mV	6	0	12	1
	4	1	13	4
	5	0	11	2
	9	0	16	3
	3	1	8	1
800 mV	3	0	6	0
	2	0	3	0
	1	0	7	1
	4	0	5	0
	1	0	6	0
900 mV	0	0	3	0
	0	0	2	0
	0	0	1	0
	0	0	1	0
	1	0	3	0
1000 mV	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0

Fig.3.2.3 Original Output data printout

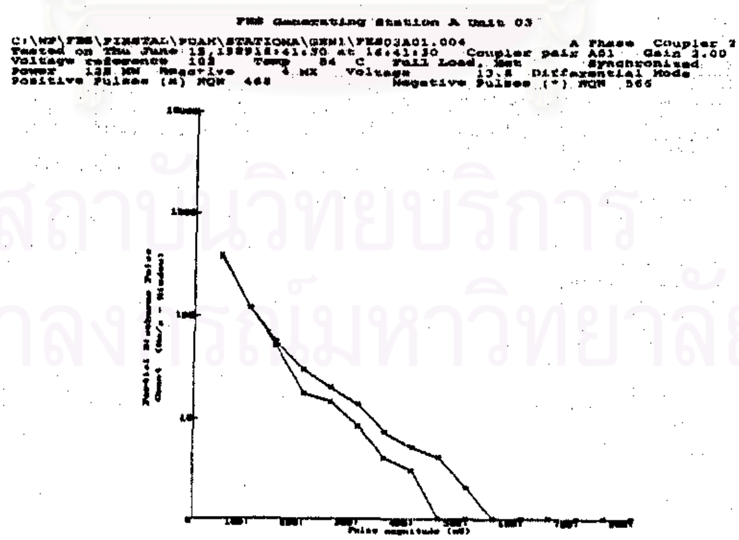

Fig.3.2.4 Output data in form of partial discharge graphs, the significant points are pulse frequency and its magnitude that sign something of insulation conditions.

3.3 Type of coupler, coupler fabrication and installation

Type of coupler: The selected type of coupler is 80 pF capacitor, made from 25kV power cable "XLPE" insulation. The characteristics of this XLPE cable are high dielectric strength, corona or partial discharge resistance, complete with continuously copper shield. The coupler can be made to the form of loop-type coupler, or open-loop type coupler, which depend on location of installation. Fig.3.3.1 shows cross section of XLPE power cable.

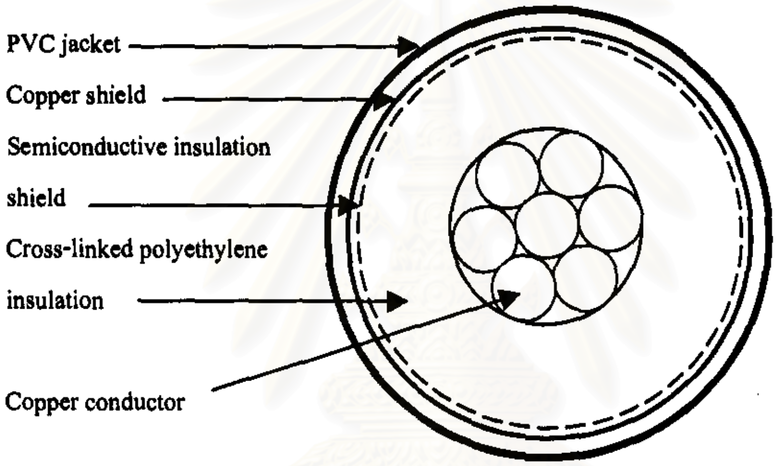

Fig.3.3.1 Cross section of XLPE power cable 25 kVrms.

The power cable can be made to be required capacitor. The copper conductor and copper shield act as electrode plates of capacitor, XLPE insulation acts as dielectric media of capacitor. The capacitance depends on the length of cable. This capacitor is low cost and has good electric properties.

Coupler fabrication: Some pieces of 25 kV XLPE power cable were selected from EGAT's inventory store and were cut into suitable length. The fabrication of capacitor could be done by the following procedure:

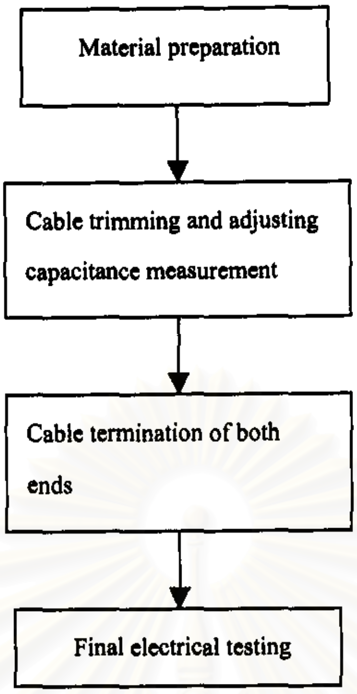

Fig.3.3.2 Fabrication procedure

<u>Material preparation</u>:

Copper Fabrication (approximate quantities per coupler)

a). 35 square mm. Copper conductor 25 kV XLPE power cable .... 1.5 m.

b). 3M high voltage termination kit (no.2220) for above 25 kVrms......... 1 set

c). coaxial cable RG58 c/u 50 ohms .... 50 m.

d). Insulation tape:-

Glass fiber tape 20mm.wide .... 1 roll

Silicone tape (self- fusing) .... 1 roll

Insulation varnish (class f)... 1 can

<u>Cable trimming and adjusting capacitance measurement</u>:

Cut power cable into approximately length 1.5 m., trim the PVC jacket both ends of cable such that 39 cm. remains centered on the cable. Cut copper shield until remains 10 mm from the jacket both ends of cable (see Fig.3.3.3). Trim the semiconductive insulation shield until remains 4.75 cm. from both ends of the jacket. Using Capacitance Bridge meter to measure the capacitance between the copper shield and the copper conductor that should be 78-80 pf. If it is over capacitance, trim the jacket and copper shield off a little bit and measure again until achieve required value.

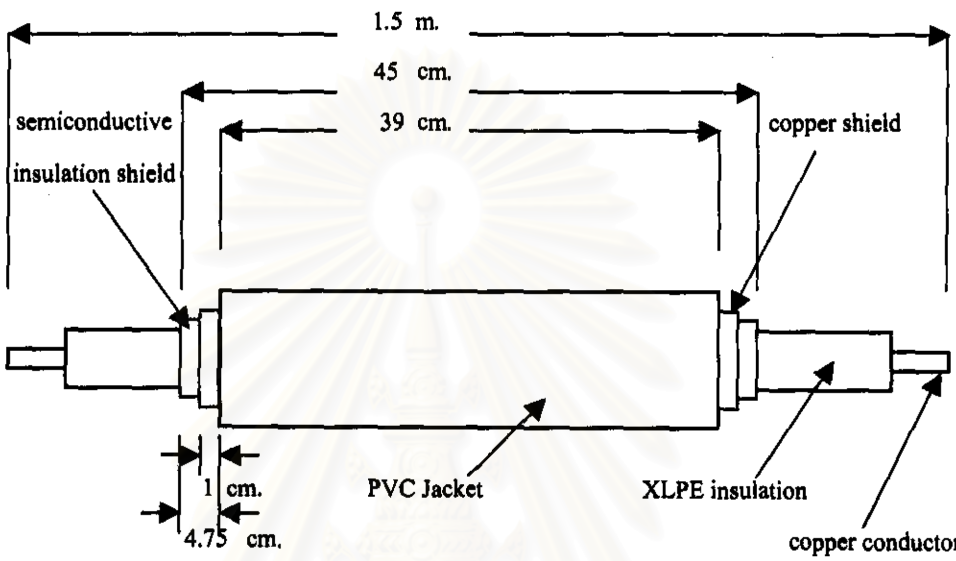

Fig.3.3.3 39cm of PVC jacket length of cable will achieve 78-80 pF capacitance

Cable termination:

Terminate each end of the cable with an approved stress-grading tape termination (using 3M scotch 2220), as shown in Fig.3.3.4

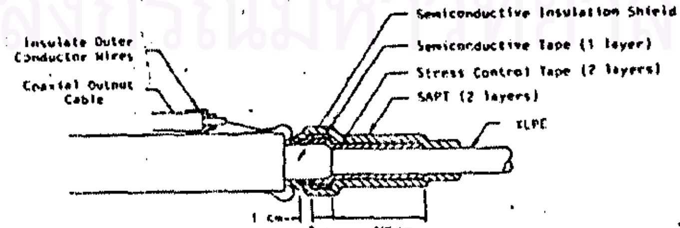

Fig.3.3.4 Termination of each end of the cable, using 3M termination kit and apply insulation tape as detail in instruction of the kit.

Connect coaxial cable to the copper shield of the cable by following the detail of termination kit instruction.

Finally, apply two layers of half-lapped Self-Amalgamating Polymeric Tape (SAPT) over the termination and over the remaining exposed XLPE. This tape must be stretched to half its width. Leave the coupler's copper shield exposed. The cable-type coupler is now complete and ready for tests.

The nine capacitor couplers are fabricated as shown in Fig 3.3.5, which have not coaxial cable, after passed the final electrical testing 50 m. coaxial cable is connected to each coupler as shown in Fig 3.3.6

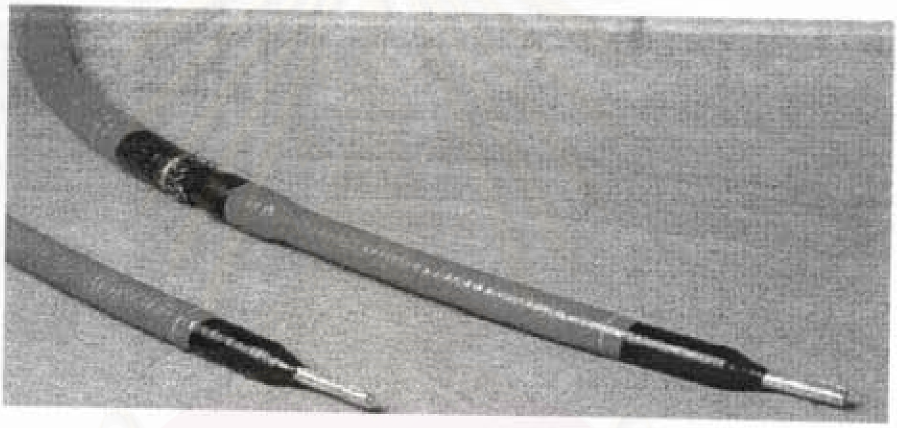

Fig.3.3.5 Complete capacitor coupler (without coaxial cable connected), ready to final tests.

Fig. 3.3.6 Complete 80 pF coupler, ready to install on stator winding

<u>Final Electrical tests:</u>

Final testing for all capacitor couplers is listed below.

a). Capacitance measurement

Using Capacitance Bridge, resulting 80.9 pF mean average values of 9 couplers as shown in Appendix, data test 1

b). Power loses of insulation

Using 10kV Insulation Analyzer, resulting 0.34% pf. mean average values of 9 couplers. (see Appendix, data test 2)

c). Dielectric test for 48.62 kVdc. Withstand test voltage

Using DC. High-potential tester by applying 48.62 kVdc. Test voltage to copper conductor of each coupler and copper shield connect to ground for one minute, resulting all coupler passed this test, mean average current leakage about 3.5 mico-Amp. (see Appendix, data test 3).

Coupler Installation: From winding diagram of generator unit 1, 2, and 3 of Sirikit hydropower plant, three units have the same winding diagram, same winding configuration. There are three parallel circuits of each phase, nine couplers are required to install for each unit of generator. Fig. 3.3.7 shows winding diagram of Sirikit hydroelectric generator unit1 (unit 2 and 3 are the same) and Fig.3.3.8 shows some location of stator winding, which suitable to install couplers.

The stator winding has long circuit ring buses and there are enough areas beside these ring buses, so that the loop-type coupler is suitable to install into the ring buses. The schedule of coupler installation was set up under agreement of Sirikit power plant division and starts the schedule in the major overhaul period of each unit. The installation was complete in end of the year, 1997. The detail of coupler installation were described following:

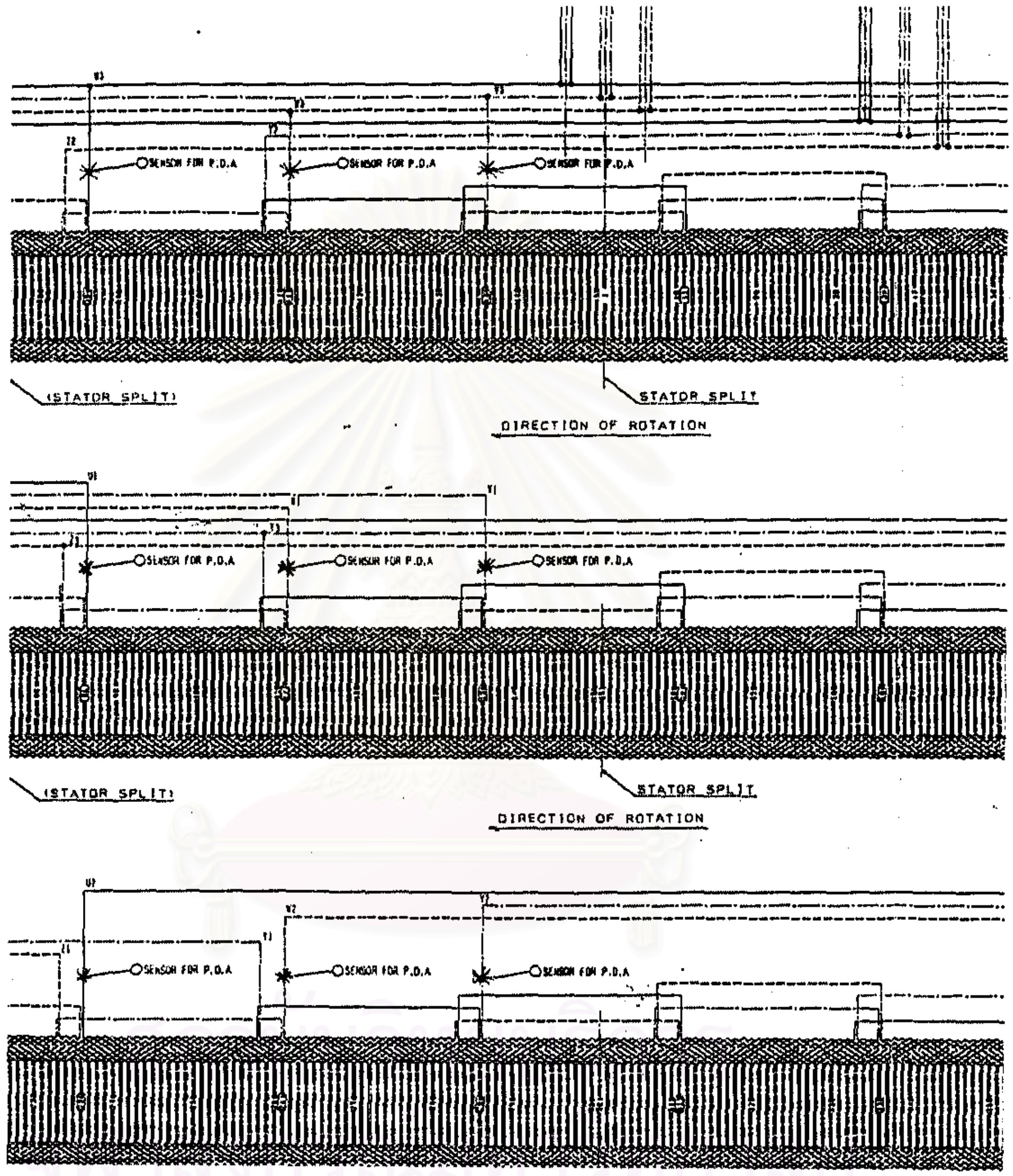

Fig.3.3.7 The winding diagram of Sirikit hydroelectric generator unit 1 (unit 2 and 3 are the same)

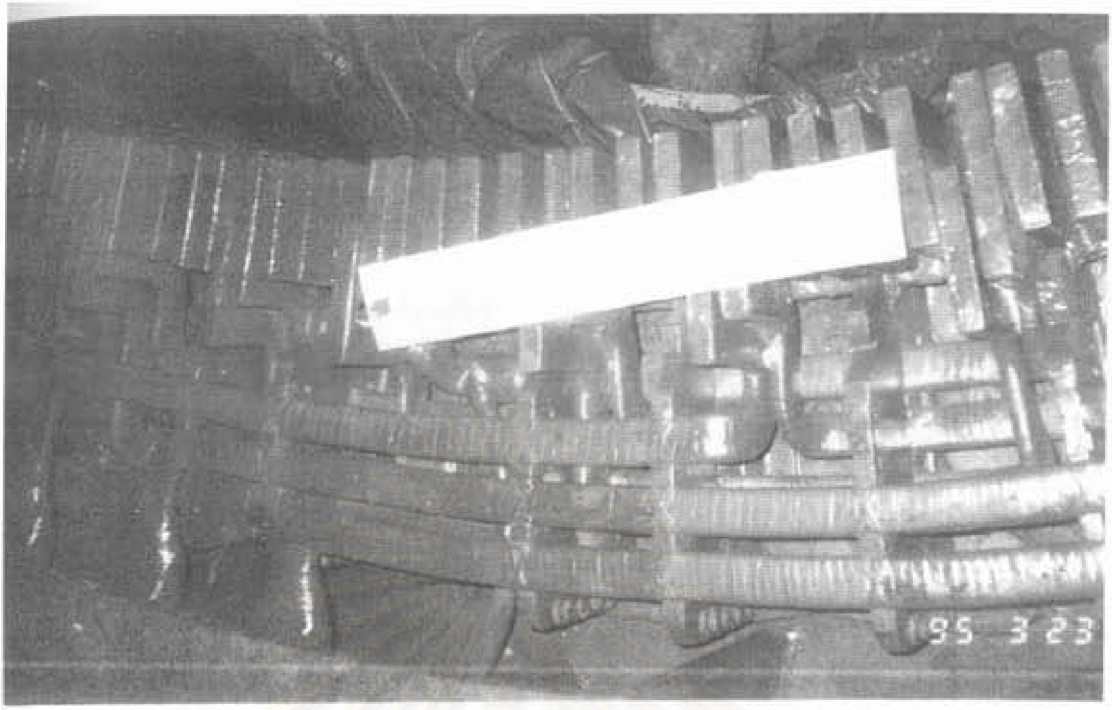

Fig.3.3.8 Some location beside circuit ring buses that suitable to install couplers on generator unit1 (unit 2 and 3 are the same).

The procedure of coupler installation is:

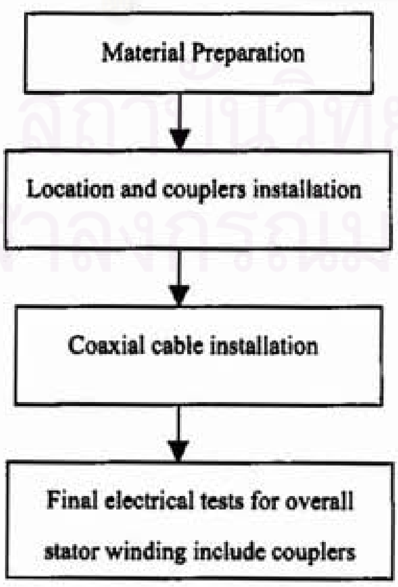

Fig.3.3.9 Coupler installation procedure

<u>Material preparation</u>:

a). Tested 80 pF couplers (nine couplers per unit)

b). Insulation tapes:

- mica tapes 2-3 reel per coupler

- glass fiber tapes 1 roll per coupler

- epoxy varnish 1 small can per coupler

c). Coupler supporters U clamp 1 each per coupler

d). Flexible conduits 50 m. per three couplers

e) Terminal box 1 each.

<u>Location and Coupler installation</u>:

Location: As mention at first stage, the generator has long circuit ring buses per phase and has enough space beside those circuit ring buses. The circuit ring bus of each parallel circuit of each phase is about 3 m. length. The suitable location is each of the joint of circuit ring bus and lead of parallel path of winding (see Appendix, winding diagram for coupler installation). The loop-type coupler is suitable to install in to any parallel path of winding.

Installation: Joining the two end of the coupler together, forming either an circle (loop-type). The coupler joint was connected directly to each of the copper bus near or nearest the joint of lead parallel path of winding. The coupler was clamped to the stator frame with U-clamp and far from the stator frame 30 cm. or over (see Fig.3.3.10)

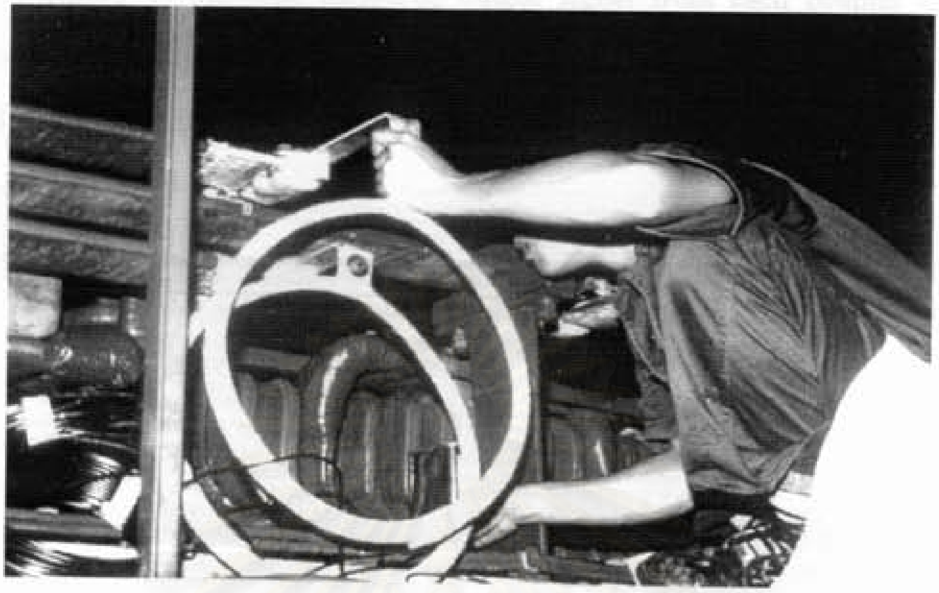

Fig.3.3.10Coupler was connected directly to circuit ring bus (unit 1 – coupler installation)

Insulated the connection joint with mica tape 5-6 layers of half-lap together with applying epoxy varnish to layer by layer and masked with 2 half-lap layers of glass fiber tape. The insulation took 3-4 hours for curing.

Coaxial cable installation: Coaxial cables (RG58A/U) are employed to convey the partial discharge signals from the coupler to a termination box mounted outside generator's housing. The length of coaxial cables is important and will be adjusted or trimmed for noise elimination.

Located the termination box at beside the door of generator's housing, which was 1.5m. far from stator frame (unit 1, 2 and 3 were the same.)

Using three flexible conduits lied at the same way of RTD conduits. Provide each end of flexible conduit near three couplers of each phase winding and the other ends put into termination box.

Inserted all coaxial cable to flexible conduits, three coaxial cables per flexible conduit. Provided long length about 5-7 m. per cable before connects to termination box.

Coaxial cable trimming, Injected 1KHz signal to each phase lead of generator. Using high frequency oscilloscope measured output signal from each coupler of that phase. Compared each signal, trimmed coaxial cable that the signal came later until got the output signal came with in the equal time shown on screen of oscilloscope (see Fig.3.3.11, Fig.3.3.12 and Fig3.3.13)

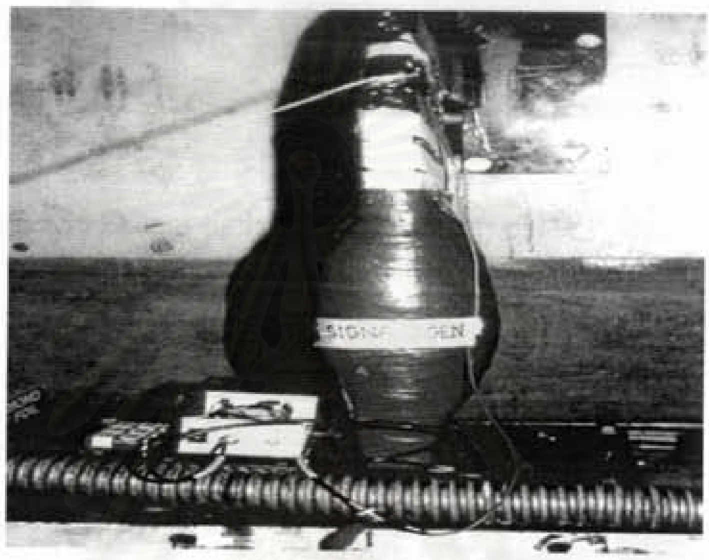

Fig. 3.3.11 Injected signal into each phase lead of generator (unit 1, 2 and 3 were the same).

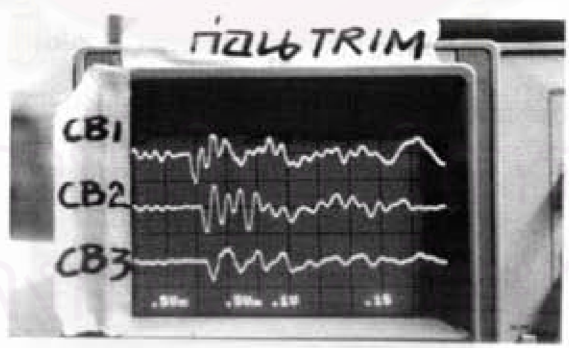

Fig.3.3.12 Output signals of three couplers of Phase C before trimming

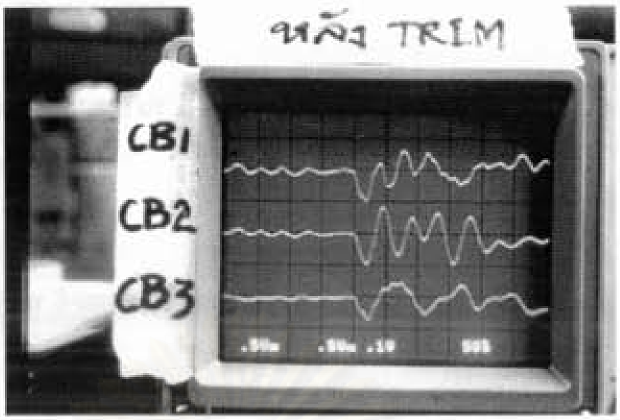

Fig. 3.3.13 Output signal of three couplers phase C after trimming.

Fig. 3.3.14 Measuring unit and Coaxial cable trimming instruments

Connected all coaxial cables to termination box, which provided BNC jacks for connection of measuring unit (circuit diagram shown in Appendix, Termination box chart)

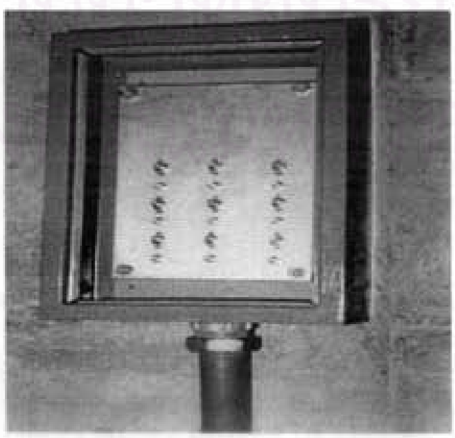

Fig. 3.3.15 Termination box, provided 9 BNC jacks

Final electrical tests for generator stator winding include couplers:

Applied DC. Test voltage of 1.7(2E + 1), :- where, E = rated voltage of generator (ANSI C50.10 - 1977)

E = 13.8 kVac (for 3 units of generator) :- then, Test voltage = 48.62 kVdc

Applied 48.62 kVdc. to each phase winding for one minute to ensure that any part of stator winding include couplers can withstand operating voltage while machine operation. The result of test was accepted (shown in Appendix A, Generator Stator test sheet).

3.4 Measurement procedure

Normally condition bases of generator during operation are temperature and vibration that effect to partial discharge within stator winding. The partial discharge tests should be taken under 4 conditions. These include no load cold tests, full load cold tests, full load hot tests and no load hot tests. Typically all 4 partial discharge tests are taken at the first time the measurement is used on a generator. This will establish a base line against which future partial discharge tests can be compared. Then every 6 months or sooner, depending on the severity of the deterioration, a full load hot test is taken. This is usually sufficient to determine whether the insulation system is stabilized or deteriorating.

The procedure of tests can be set up according to condition of operation step by step as follow:

No load cold condition: Purpose to view partial discharge activity at low temperature and less vibration effected.

Full load cold condition: Purpose to view a change of partial discharge activity due to vibration from full load operation but temperature does not change.

Full load hot condition: Purpose to view partial discharge activity, which is effected from both high vibration and high temperature from full capacity operating.

No load cold condition: Purpose to view partial discharge activity at high temperature and less effect from vibration.

Test data compiling and interpreting: Compile all data of each testing, analysis and recording as database for comparison with next testing of same machine or other identical machines.

The next testing (4-5 months or as schedule), all partial discharge tests must be taken under similar loading, temperature and voltage condition.

The 4 partial discharge tests are detailed as follows:

a). <u>No load cold condition</u>

Generator connects to system at rated voltage but with 0 MW and 0 MVAr. Partial discharge tests are taken on each phase.

b). <u>Full load cold</u>

Full load is applied to generator. Partial discharge tests are taken on each phase. These must be completed as rapidly as possible, typically within 15 minutes of applying load, to minimize temperature changes. It may be necessary to perform the partial discharge tests without inputting the stator temperature and load as obtaining these values may take too much time.

c). <u>Full load hot</u>

The generator is allowed to come to thermally stable conditions, usually 4 hours. The load should be maintained as steadily as possible to minimize internal temperature changes. Load condition should be the same as full load cold test.

d). <u>No load hot</u>

Load is reduced to 0 MW and 0MVAr. The tests are taken on each phase. This must be completed as rapidly as possible, typically within 5 minutes of reducing load, to minimize temperature changes. Again, it may be necessary to perform the partial discharge tests without inputting the stator temperature and load as obtaining these values may take too much time.

During each partial discharge test a voltage reference number is recorded. This is a number between 0 – 225 that corresponds to the phase voltage. This number should not vary more than 20% from one test to another. A large change in the voltage reference number indicates a change in the electric field and makes comparisons between partial discharge tests difficult.

For Sirikit hydroelectric generator 3 units, after installation couplers were finished. The schedule of tests were set up to be taken every 4 months of each unit or sooner as depending on Demand of load managed by EGAT's Power system control division.
The 4 conditions of tests were taken at the first time on unit 2. The second time were done in 5 months later under in the similarly conditions. After a year ago, the period of overhaul of each unit was started. The investigation was done to confirm the results of tests, and correction was done under recommended from the tests.

The method of tests can be explained as below:

Unit 2, partial discharge test procedure

No load cold condition, the generator unit 2 was connected to the system at rated voltage with 0 MW and 0 MVAr, connected two coaxial leads to termination box at coupler CB1 (B phase coupler 1) and CB2 (B phase coupler 2), by PDA-H measuring unit and started to measure. The tests were taken at other couplers, such as CB1 together with CB3, CA1 with CA2, CC2 with CC3 and etc. until finished all of couplers (usually 15-20 minutes). The data results were printed out in from of graph of partial discharge pulses and all of them could be saved into hard disk or floppy disk as required. (See Fig. 3.4.1)

Then, full load was applied to generator, with the temperature was not increased (not more than 5% changed from no load cold condition) and the ***Full load cold condition*** tests were taken on each phase with coaxial lead connection as same as no load cold tests.

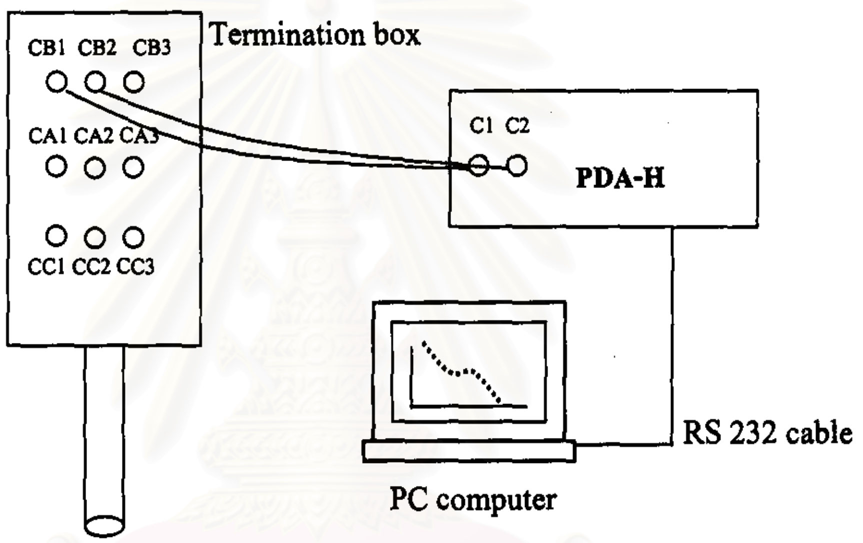

Fig. 3.4.1 Connection of two coaxial cable leads for each condition of testing

When finished the full load cold tests, the generator was allowed to keep full load 2-3 hour until the temperature became stable at about 75-80 degree Celsius. After that, ***Full load hot condition tests*** were taken with the same coaxial lead connection method. The load was decrease until 0 MW, 0 MVAr with the temperature still did not change, ***No load hot condition tests*** was conducted immediately.

All data could print out automatically when each condition of tests had been completed, and also all of them were saved in floppy disks during each testing. The test data of each test condition in term of graph pictures could be received by processing from software program on the computer.

3.5 Analysis and interpretation

The scope of analysis and interpretation of measured data are consideration of characteristic of partial discharge pulse activities. In the fact that, most stator winding fail as a result of long term thermal aging, load cycling, or coils being loose in the slot. Vibration and operating temperature at several load conditions are the main effective causes to deteriorate winding insulation system. These mechanism cause air gap to occur and generate partial discharge. The partial discharge is a symptom of thermal or mechanical deterioration of the winding and as described, the vibration and heat or temperature cause to generate partial discharge activities. Then, the data of partial discharge pulses should be determine according to the load condition base on vibration and heat or temperature. The significant deterioration of stator winding and partial discharge symptoms could be listed together with their analysis and interpretation as below:

Semi – coating / Slot Discharge and coil looseness: This deterioration of winding are usually found on a lot of generators. These mechanisms are very dangerous that cause to damage the outer layers of ground wall of winding, resulting in rapid failure.
The interpretation of this case is to consider the data output that will show *the positive pulses of partial discharge are predominance for discharge activities*.
The loose wind is the main cause to deteriorate the surface of winding. The interpretation of data output is to determine *some positive pulses of partial discharge symptom on full load condition (high vibration) compare with positive pulses on no load condition (less vibration). The higher deviation means higher vibration of winding occurred.*

Internal Partial Discharge : This deterioration on the main ground wall insulation cause of delaminating of insulation layers due to thermal aging and heat cycling from operation. This deterioration occur in the main ground wall, then effect of vibration dose not cause to delaminate of insulation layers. Heat is the cause that generate delaminating mechanism of insulation, then the data output can be interpreted that *both positive and negative pulses are not predominance for discharge activities but usually have the same equal. The quantity of magnitude and pulse rate show how much of partial discharge occurred.*

Copper / insulation Interface Partial Discharge: The deterioration occur on the surface of copper stand and internal layer that delaminate from each other and generate partial discharge pulses. The cause of delamination is heated cycling that comes from load cycling. The interpretation is consideration of *the negative pulse activities is predominance. The higher magnitude and pulse rate mean the higher deterioration.*

Surface discharge on coil-end portion, jumper and between upper and lower coils: The deterioration occur on the surface of adjacent coil, which have high voltage different to each other, and jumpers are the same as. The pollution such as dirt, lub.-oil and moisture, etc. are the main cause to generate the discharge on it.

The interpretation is consideration of *total amount of partial discharge activities (NQN), which achieved from calculate the area under each positive graph and negative graph. The amount is not so important, but the trend of them is very important that indicate how dirty and pollution of winding.*

After the partial discharge tests of unit 2 was taken on the procedure described above, after that the interpretation was conducted and followed the procedure mentioned above. The details and results are presented on the chapter 4 following.

3.6 Using Interpreted results to improve availability and maintenance of hydroelectric generator

The availability of machine means to provide that machine ready to operate at any time or operate that machine as long time as possible without damage or accident occurred. To keep the generator has high of availability. The interpreted results can be divided into two sections. One is used for monitoring the condition of specific parts of generator while operation. The another is used for maintenance program such as correction the specific damaged parts of generator on period of major overhaul.

To monitor the specific condition of generator during operation: To beware internal force outage of generator, the schedule of partial discharge tests should be planned to frequency test at every 3-6 months for new generator with about less than 10 years old. For long term serviced generator that more than10 years old, the frequency in testing should be done as every 2-3 months.

a). *To monitor slot discharge and coils looseness:* The significant interpreted results as slot discharge and loose of coils are important to determine the actual condition of winding. Compare the results for each test, the rapid change indicate serious condition and need to repair as soon as possible. This deterioration is the main cause of internal forced outage at normal operation. For old generator that over 20 years old, the results are usually very high and the appropriate maintenance plan must be done

b). *To monitor total amount of partial discharges:* The significant interpreted result as amount of both NQN occurred and the trends of them indicate total partial discharge activities have been occurred. Rapid change indicates insulation aging, more pollution inside and need to recondition at next over haul.

c). *To monitor internal discharge:* The interpreted results of internal discharge indicate insulation aging and it is very difficult to correct or improve it. This result uses to compare with the next test's result for creation the trend of them and plan to rewinding when this trend indicates high deviation from existing values.

To use the interpreted results for correction and improving specific deteriorated parts of winding: To keep the generator continuous operate without internal fault, the appropriate maintenance must be set up and apply to generator. In order to keep the less time of schedule with economic and efficiency, the interpreted result of deterioration on specific parts must be applied in the procedure of overhaul. The details can be listed below:

a). *Material preparation:* Some spare parts and consumable materials are higher cost to keep them in stock and have long time for delivery when purchase. The interpret results will detail specific deteriorated parts, then planner could prepare the appropriate spare parts and consumable materials, resulting in keeping schedule on time.

b). *Special tool and method of correction preparation:* The interpreted results indicate specific parts for repairing and improving. Planner knows where is damaged and how its damaged, the preparation of specialist people include special tools can be done at early stage.

c). *Extend period of operation and shift the schedule of generator maintenance into appropriate time:* All interpreted results are represent of deteriorated parts of winding that are the main cause of internal forced outage in normal operation. For normal operation of generator, if the on line test's results indicate normal conditions several times of testing. Planner can shift the schedule of overhaul generator and allow generator is in service for long period as possible.

On line partial discharge tests were taken on hydroelectric generator unit 2 and the data graphs received from 4 condition of testing on each coupler. All of them and interpreted results are reported in the next chapter 4.